Considerations for the Cornell ERL Linac

CHESS & LEPP

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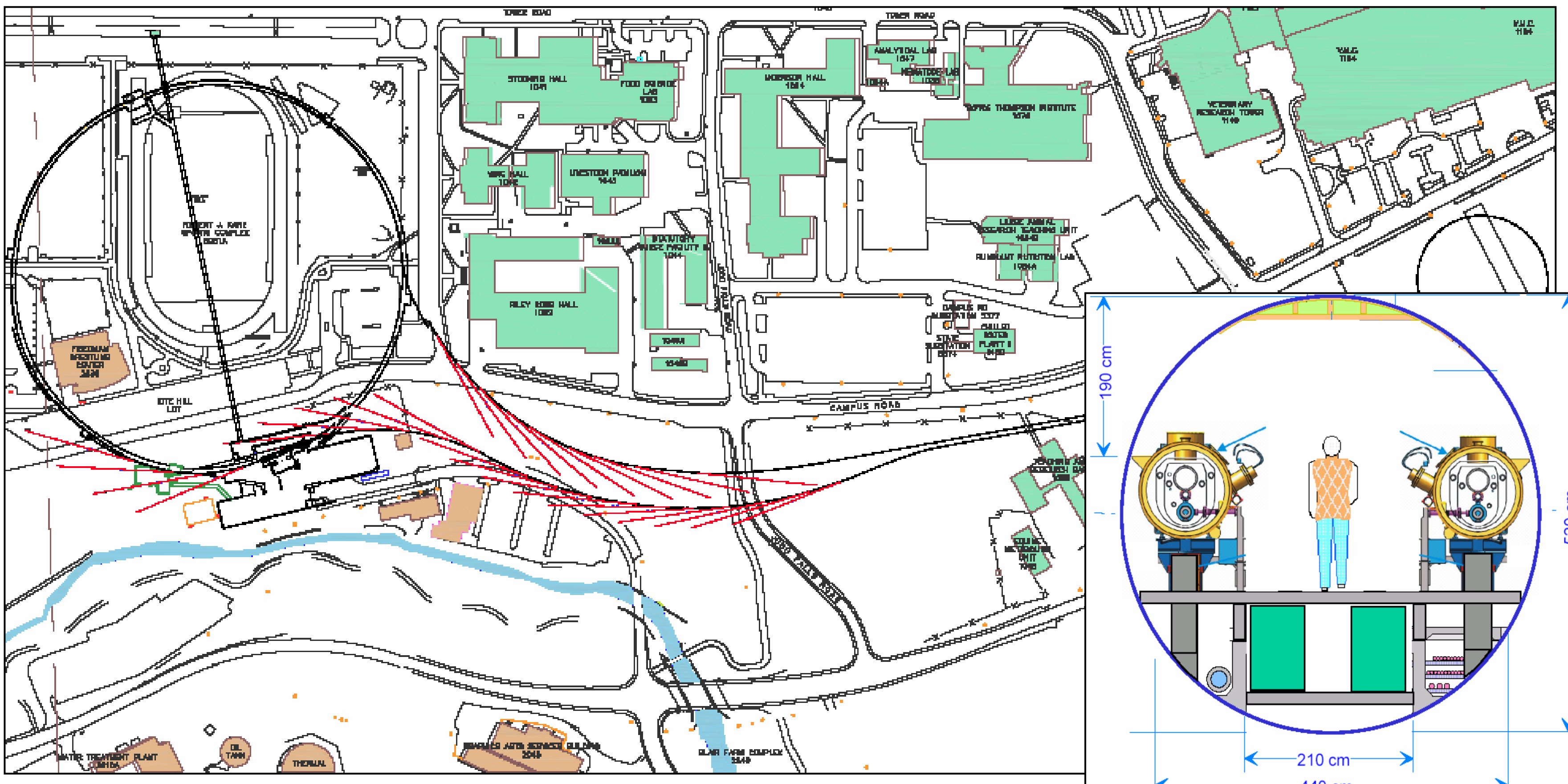

ERL Cryomodule Challenges

Operate high voltage SRF cavities CW

- Very reliable operation essential
- Avoiding excessive cryogenic loads
- Minimize RF drive power

Accelerate a high beam current

- Avoiding beam instability and excessive HOM losses
- Dispose high HOM power safely

Preserve beam emittance

- Small wake fields
- Good cavity alignment
- Small transverse kick fields
- Beam especially vulnerable in the low energy injector

Operation with very large loaded Q

- Control for very small resonance width
- Minimization of microphonics

ERL vs. ILC Linac vs. Rings

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ERL vs ILC

Average HOM power ∝ q_{bunch} x I
⇨ factor 100

Peak HOM power in resonant excitation ∝ I^2
⇨ factor $4\cdot10^6$

2K dynamic cavity load ∝ $E^2\cdot$duty factor
⇨ factor 50

Cavity bandwidth ∝ $1/Q_{ext}$
⇨ factor 0.05

ERL vs. Rings

Average HOM power ∝ q_{bunch} x I
⇨ factor 0.05 (but at 300K)

Peak HOM power in resonant excitation ∝ I^2
⇨ factor 1

2K dynamic cavity load ∝ $E^2\cdot$duty factor
⇨ factor 10

Cavity bandwidth ∝ f/Q_{ext}
⇨ factor 0.01

Some ERL linac parameters

- Single-Pass Linac Max Energy: 5 GeV
- total linac length: 711 m
- Geometric fill factor: 44 %
- Injection Energy: 15 MeV
- Single-Pass Average Current: 100 mA
- Bunch Charge: 77 pC
- Bunch Length in Linac: 2 RMS ps
- Single-Pass Bunch Rep. Rate: 1.3 GHz
- Total number of cavities: 390
- Cavity frequency: 1.3 GHz
- Active Cavity Length: ≈ 0.8 m
- Number of Cells: 7
- Average Accelerating gradient: 16 MV/m
- Max. Accelerating gradient: 20 MV/m
- E_peak/E_acc: <2.4
- B_peak/E_acc: shape
- Average Unloaded Quality (Q_0): $2{\cdot}10^{10}$
- Min Unloaded Quality (Q_0): $1{\cdot}10^{10}$
- External Quality (Q_ext): $6.5{\cdot}10^{7}$
- Full Bandwidth (f_0/Q_L): 20 Hz
- Impedance per cavity (circ. Def.) 400
- Lorentz-Force Det. Constant: 1
- Expected peak Detuning: <20 Hz
- Cavity Loss Factor (V/pC): 11
- Cavity offset tolerance: 1 mm
- Cavity angle tolerance: 1 mrad

- Average HOM Power: 170 W
- Max. HOM power per load (design): 200 W
- Operating temperature: 1.8K
- Average 1.8K Static Heat Load/Cavity: 0.5 W
- Average 1.8K Dyn. Heat Load/Cavity: 10 W
- Max. 1.8K Load in some Cavities: 32 W
- Total 5 K static load : 2.3 kW
- Total 5 K dynamic load: (3.4 kW)
  Total 80 K static load: 5 kW
- Total 80K dynamic load: (70 kW)
- Ave RF Power/Cavity: 2 kW
- Peak RF Power/Cavity: 5 kW
- Number of Cavities/RF Unit: 1
- Bunch to bunch energy fluct.: $2{\cdot}10^{-4}$
- Field Ampl. Stab. uncorrelated. (rms): $5{\cdot}10^{-4}$
- Field Ampl. Stab. correlated. (rms): $<1{\cdot}10^{-4}$
- Field phase stab. uncorrelated (rms): 0.15 deg
- Field phase stab. correlated (rms): 0.02 deg
- Coupling range (Q_ext): $2{\cdot}10^{7}$- $2{\cdot}10^{8}$
- Number of Cavities per Module: 5
- Number of BPMs per module: 1
- Number of gate valves per module: 2
- Number of quads per module: 1
- Number of kickers per module: 1
- Number of modules: 78
- Length per module: 9.1 m

Cryomodule components: (1) Cavity

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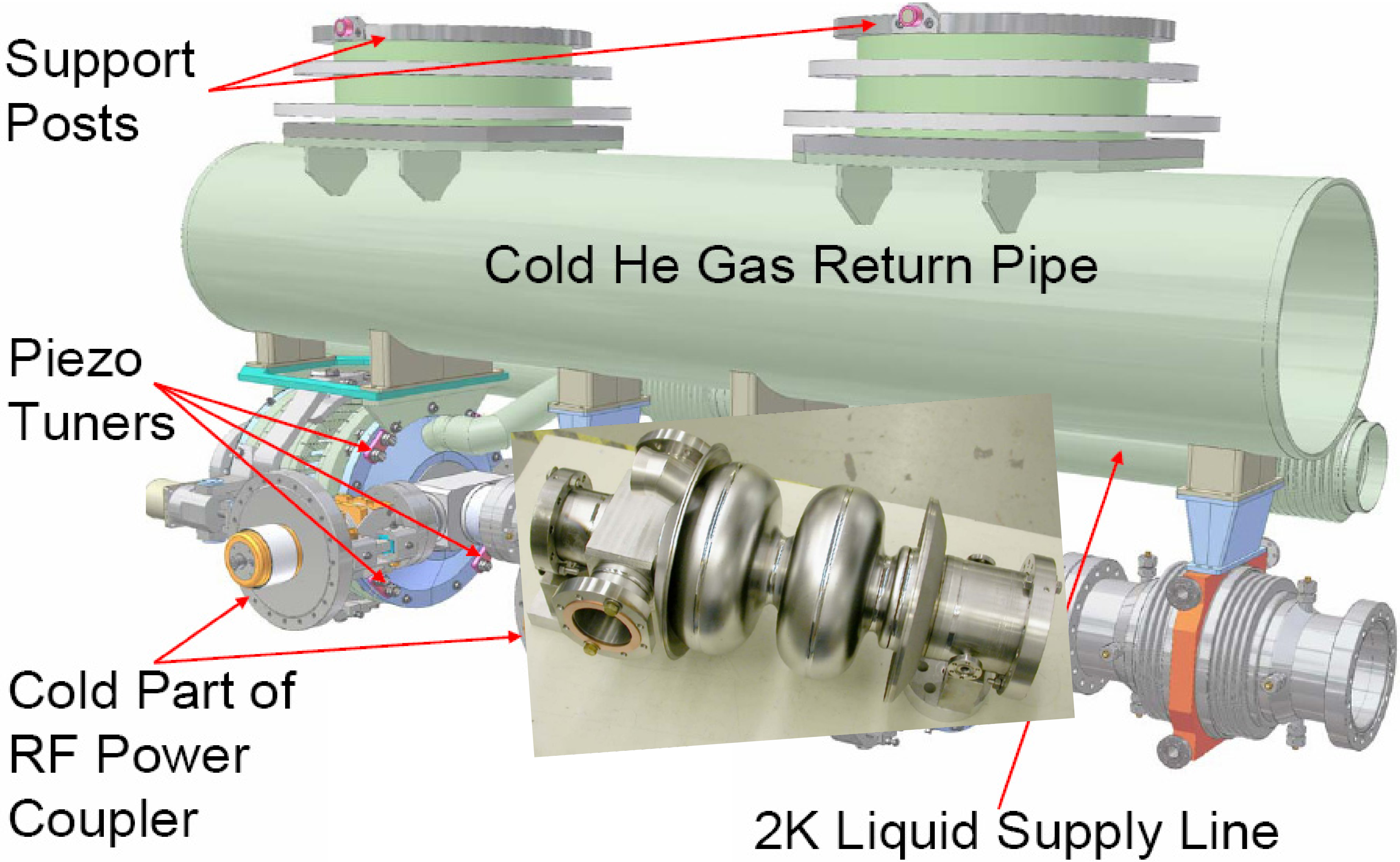
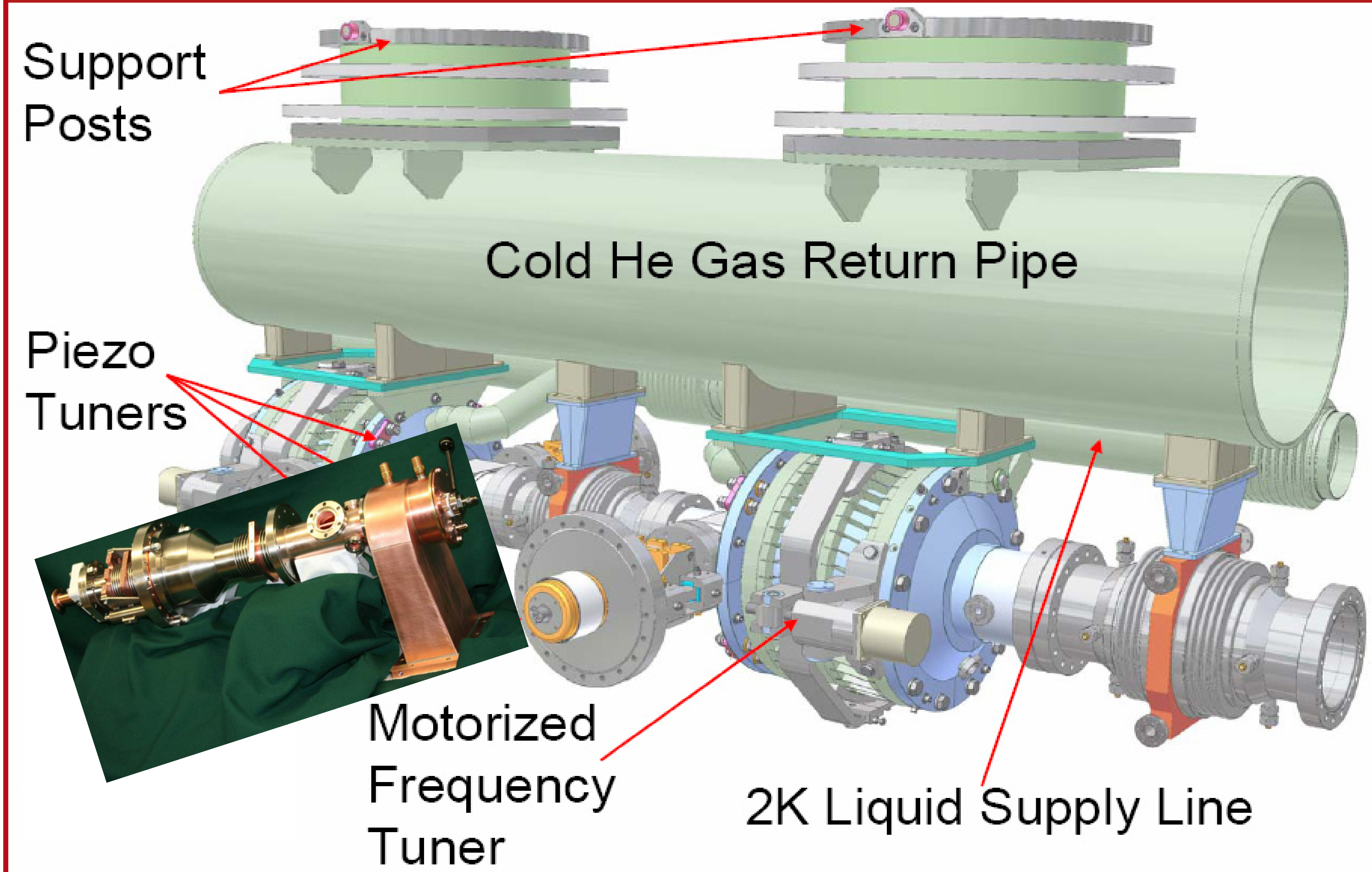
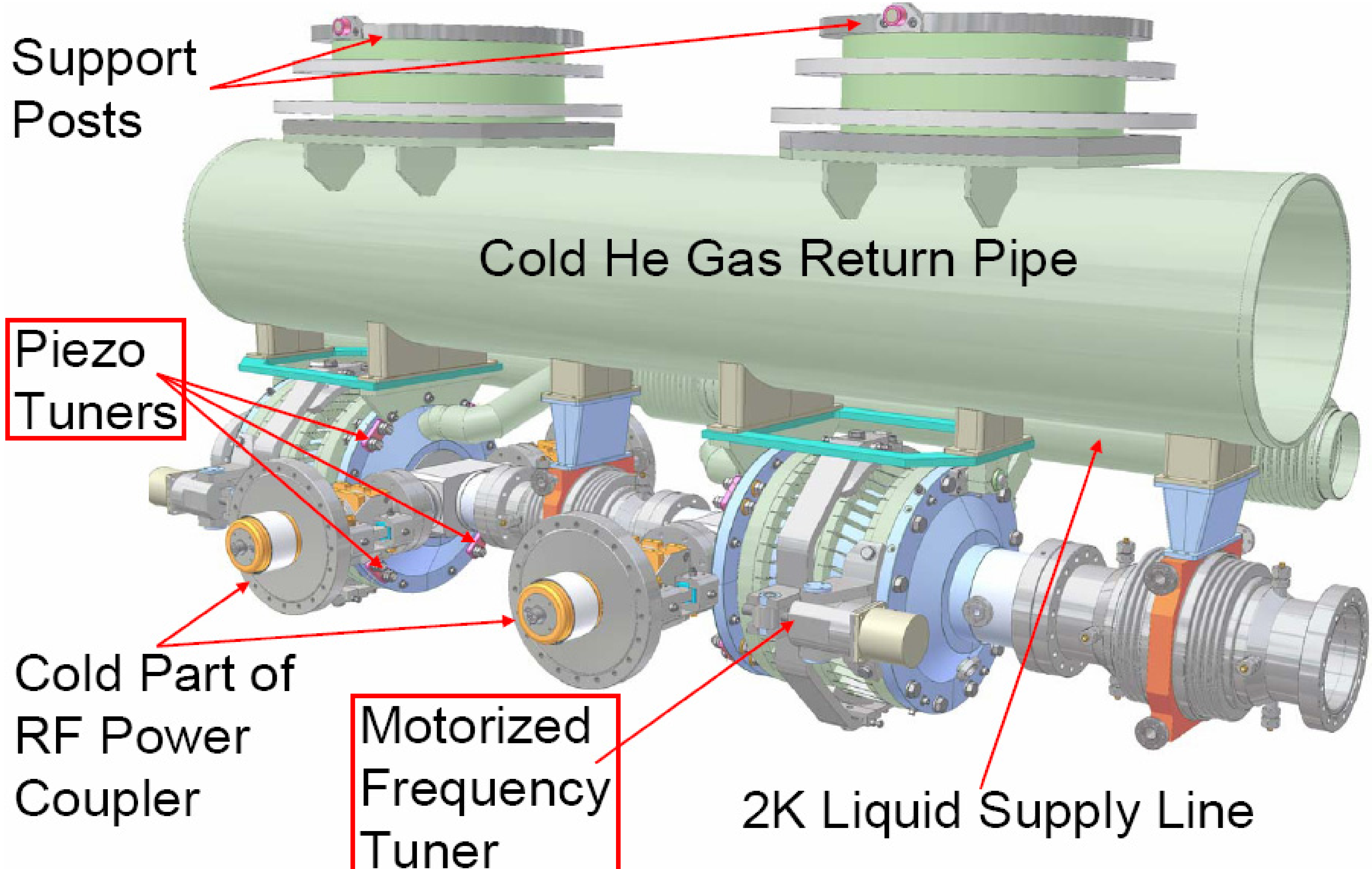


Cryomodule components: (2) Coupler



Cryomodule components: (3) Tuners



Cryomodule components: (4) HOM absorbers

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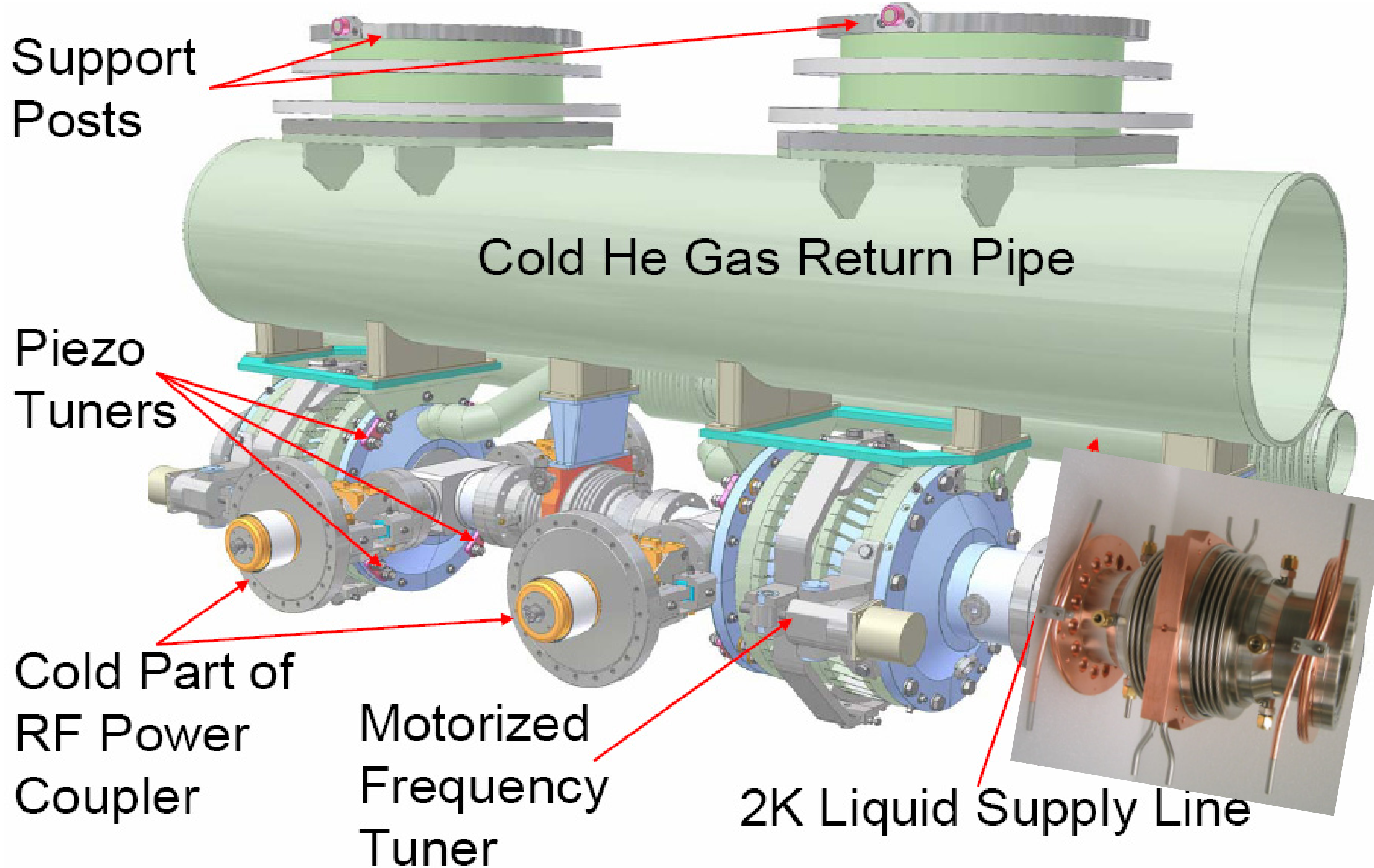
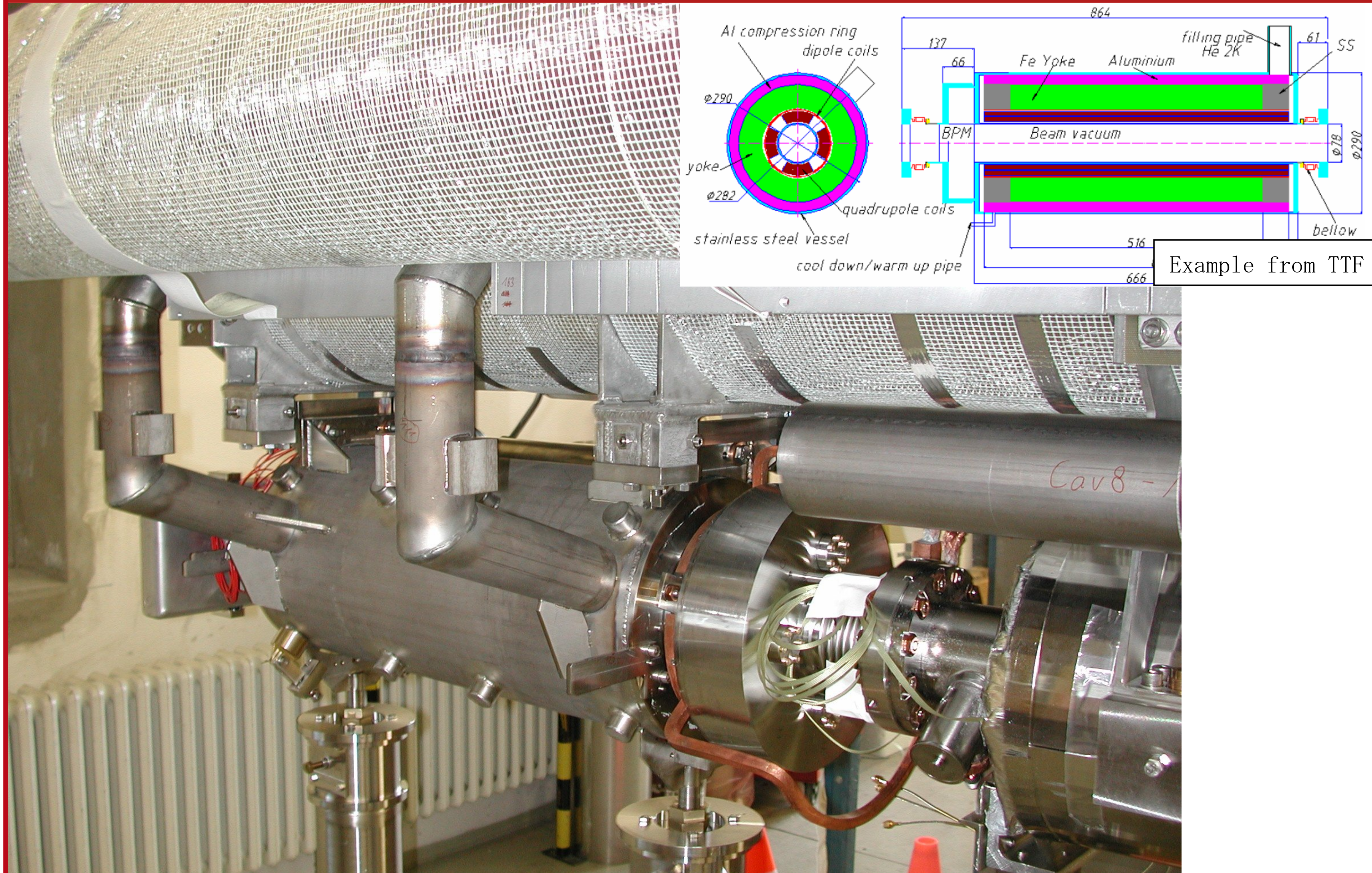


Cryomodule components: (5) Quadrupoles



Example from TTF

Cavities

Parameters:

1) Challenge of low dynamic loss leads to
   a) Optimized cavity shape
   b) large $Q_0 = 2\text{x}10^{10}$ / operating temperature = 1.8K

2) Challenge of low total cost and high operational stability leads to
   a) Operating voltage = 16MV/m

3) Challenge of high current leads to
   a) Number of cells = 7
   b) Beam pipe diameter to HOM absorber = 53 / 39mm

4) Challenge of low emittance growth leads to
   a) Summarizing input coupler region by a stub to limit coupler kick
   b) Cavity alignment tolerance = 1mm (needs more detailed study)

Cavity Cell Shape and R/Q*G

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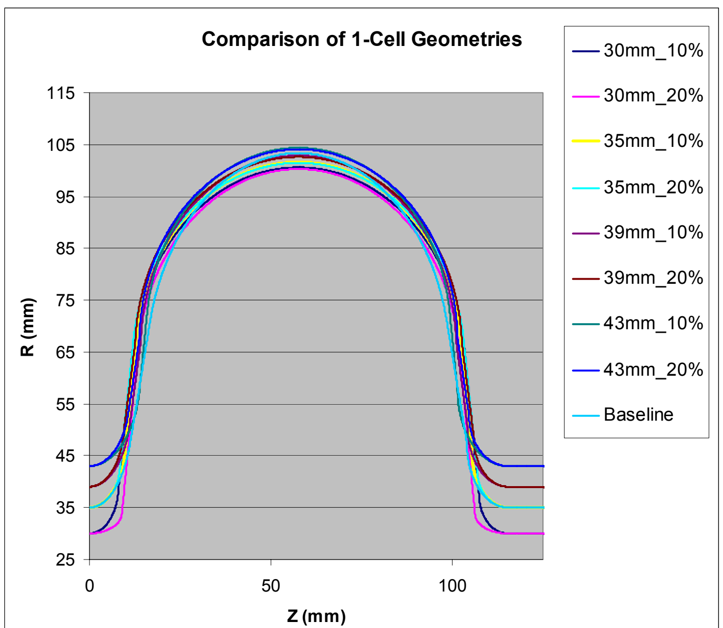
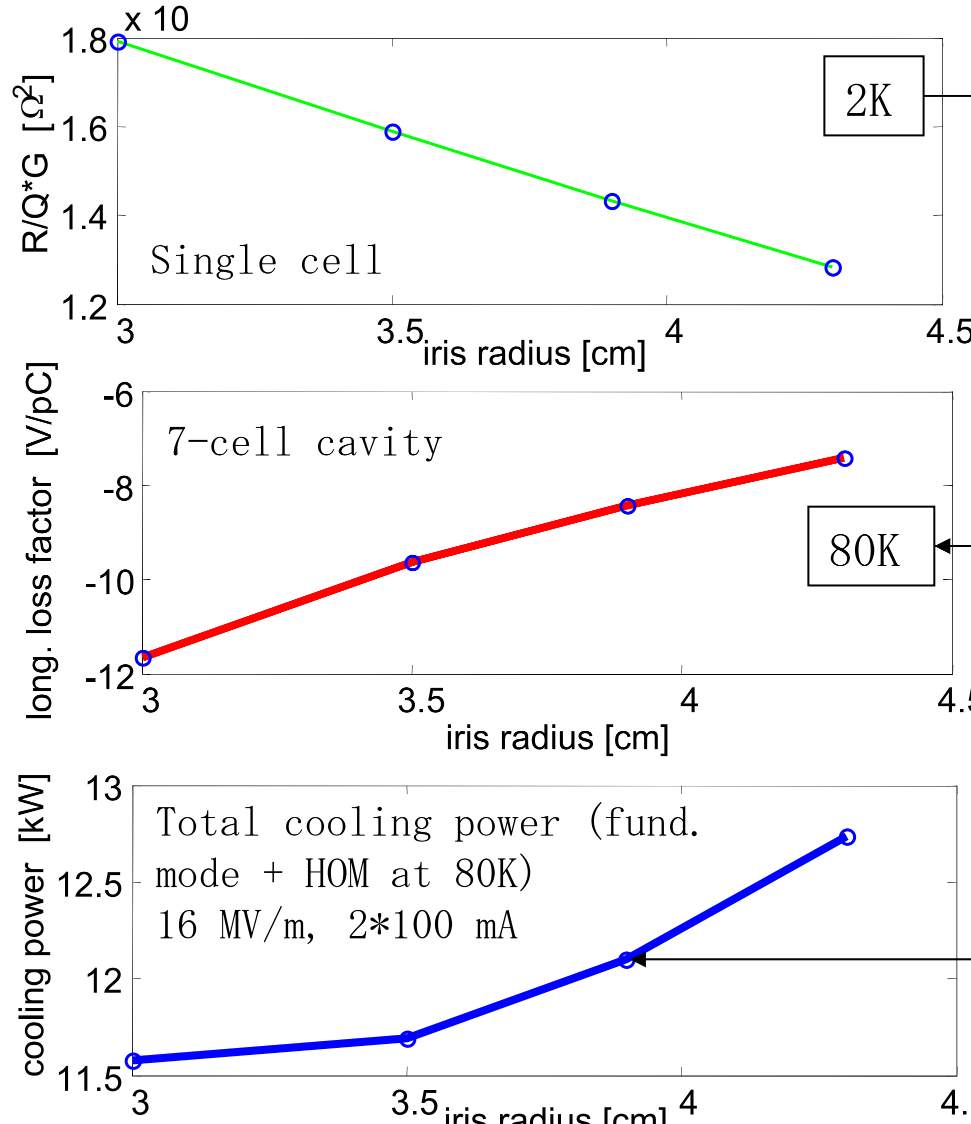
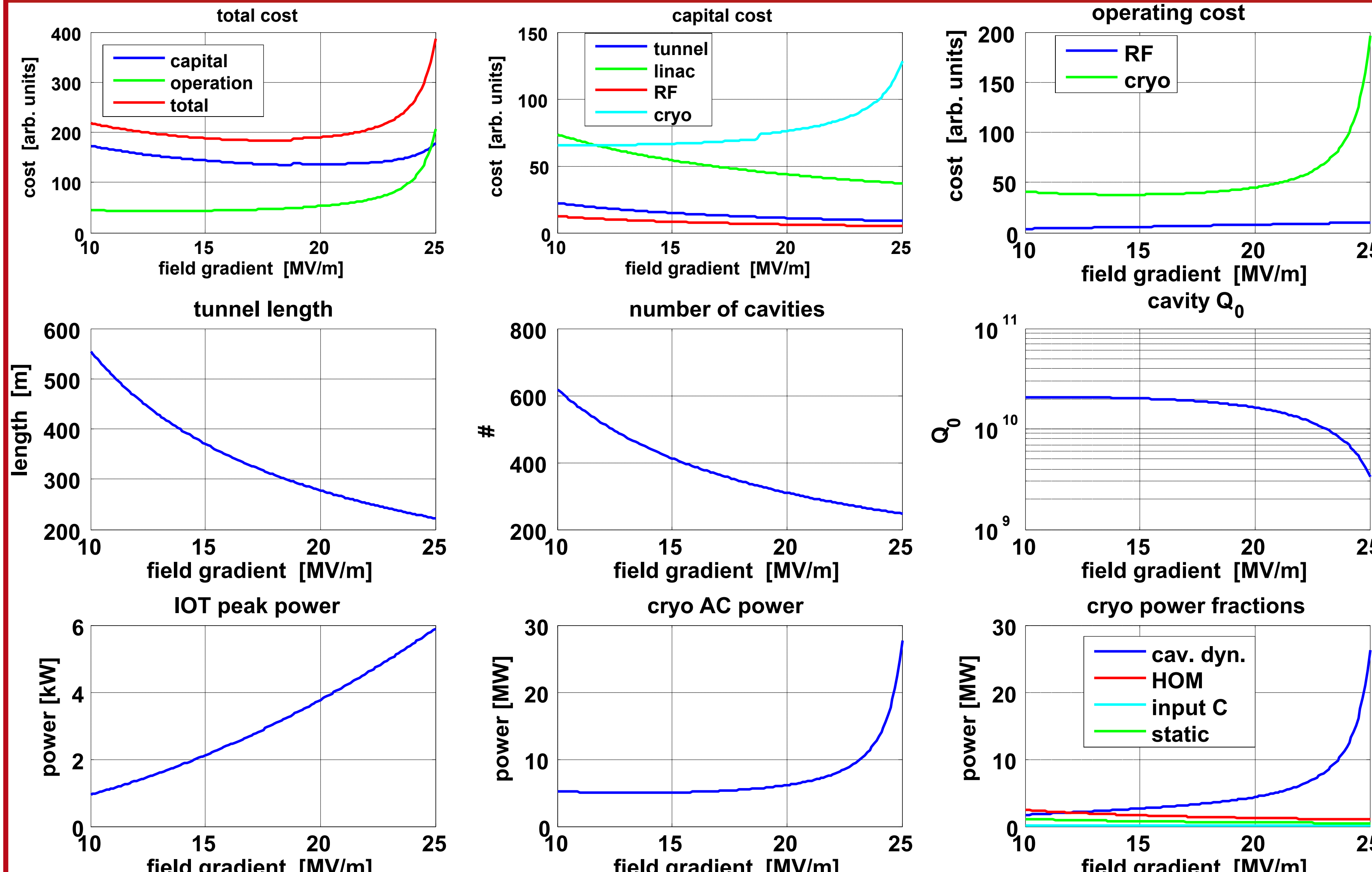
1.3 GHz center-cell:

- Cells optimized for fixed side wall angle (<= 82 deg) and electric peak field (E/E_{acc}<= 2.2), maximizing Rs.



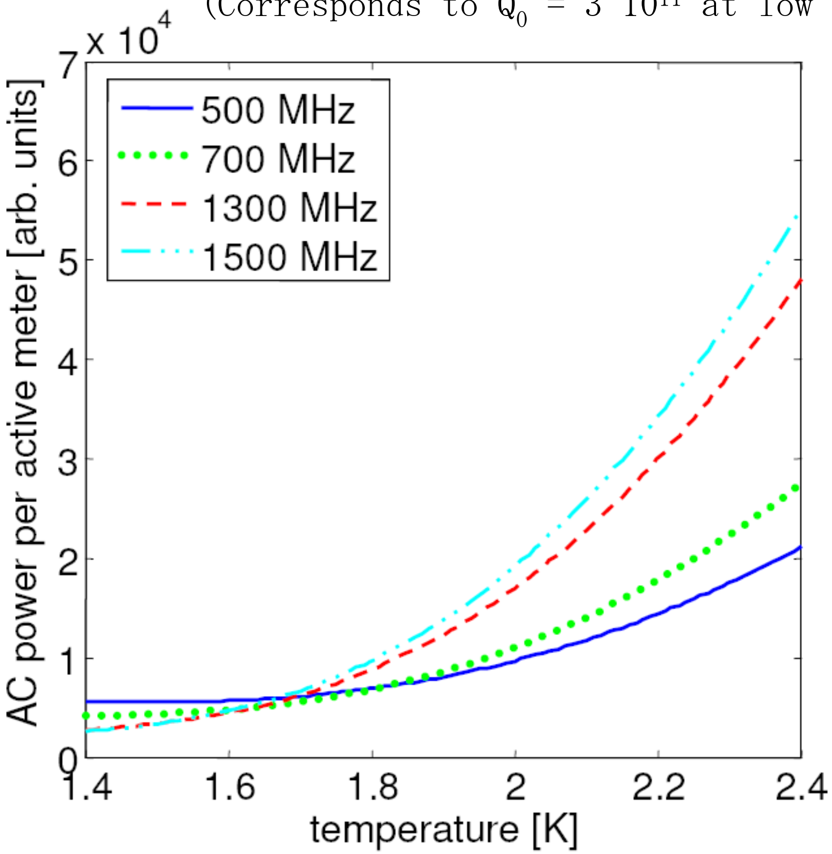



total cost
capital
operation
total
cost [arb. units]
field gradient [MV/m]
capital cost
tunnel
linac
RF
cryo
cost [arb. units]
field gradient [MV/m]
operating cost
RF
cryo
cost [arb. units]
field gradient [MV/m]
tunnel length
length [m]
field gradient [MV/m]
number of cavities
#
field gradient [MV/m]
cavity Q_0
Q_0
field gradient [MV/m]
IOT peak power
power [kW]
field gradient [MV/m]
cryo AC power
power [MW]
field gradient [MV/m]
cryo power fractions
cav. dyn.
HOM
input C
static
power [MW]
field gradient [MV/m]

Optimal temperature

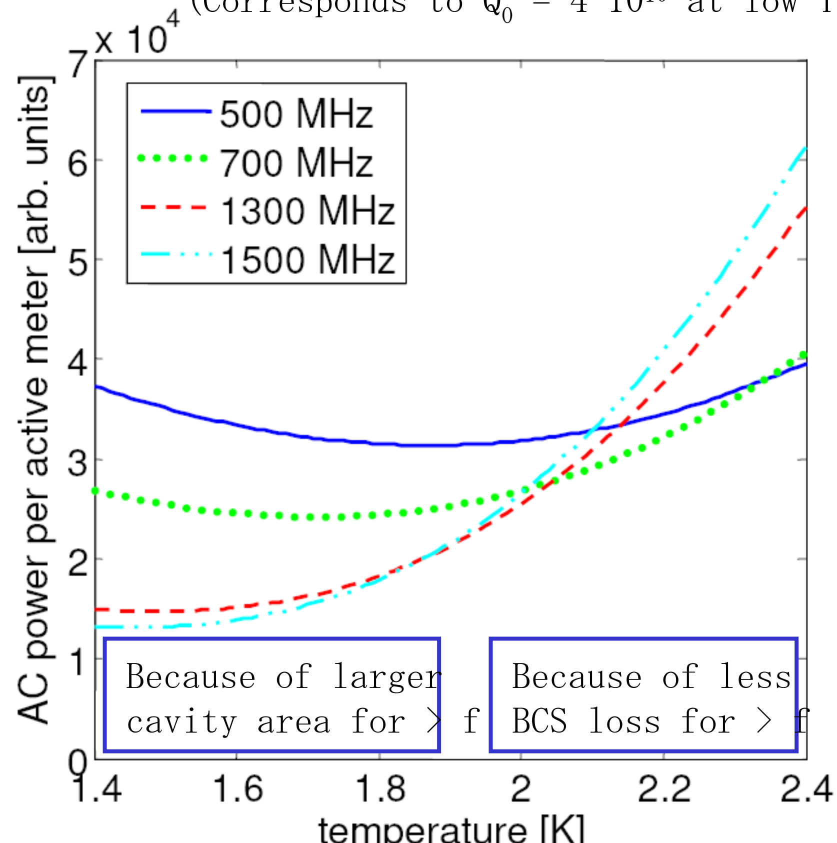
1 nΩ residual resistance

(Corresponds to Q_0 = 3 10^{11} at low T)



7 nΩ residual resistance

(Corresponds to Q_0 = 4 10^{10} at low T)



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

Optimal field gradient

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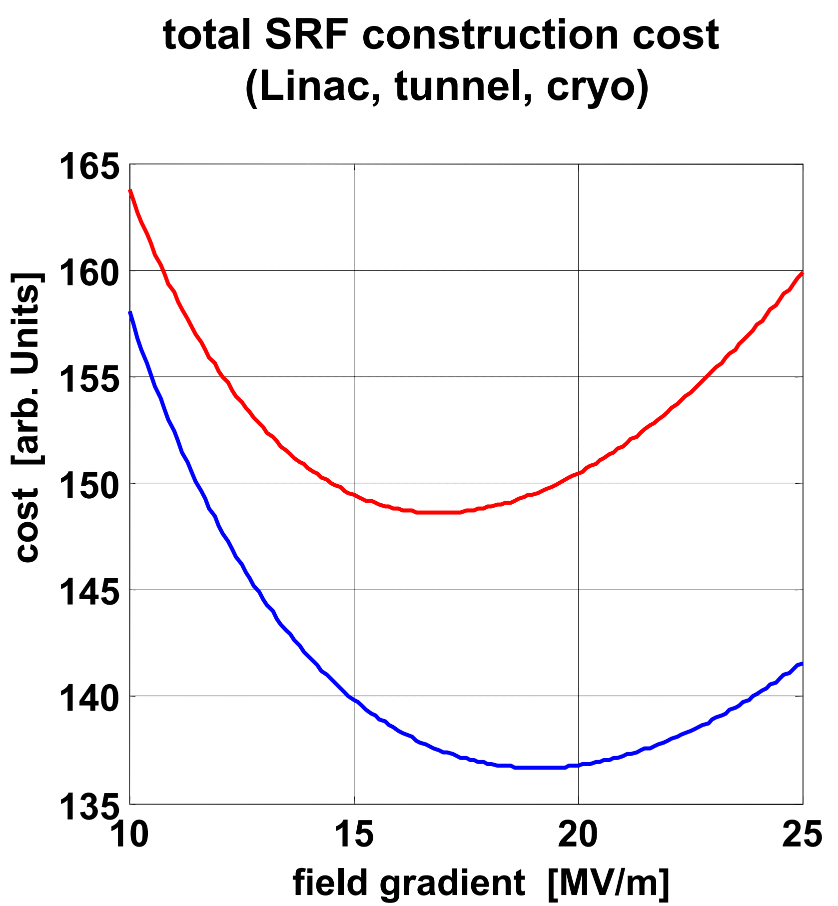

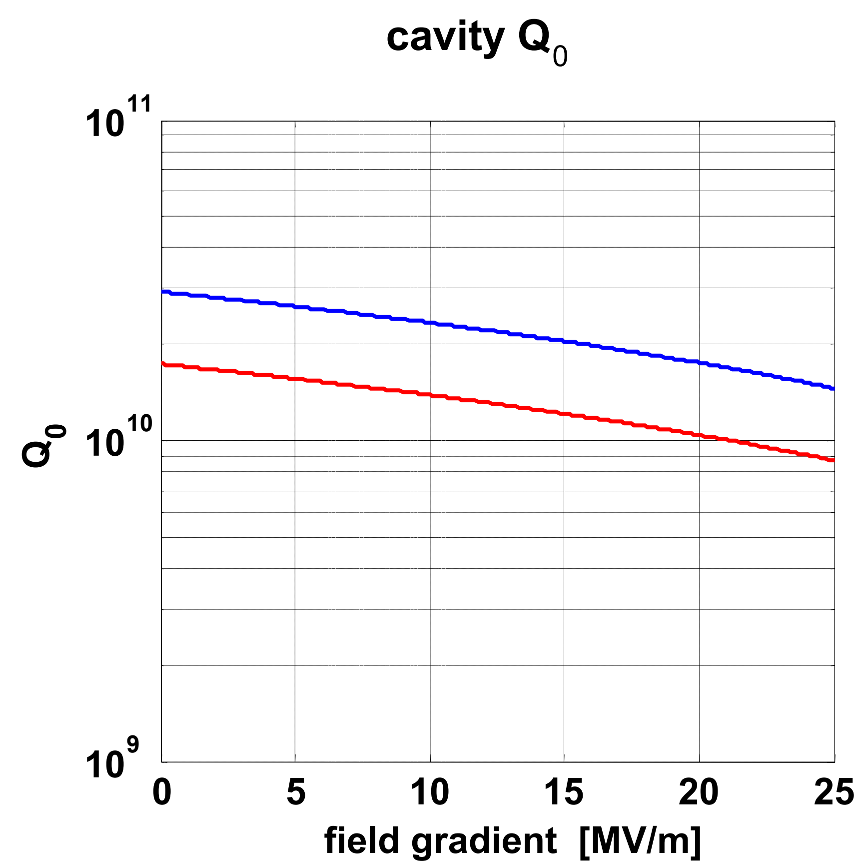

Additionally the operational stability improves with lower voltage!

⇒ Average operation at 16 MV/m

ERL cavity performance

Operation spec: 16 MV/m

But to have sufficient safety margin we design the Cryomodule for:

- **max. supported gradient by cryo module: 20 MV/m at $Q = 1{\cdot}10^{10}$**
- **RF power installed for 20 MV/m, 20 Hz peak detuning = 5kW / cavity**
- **Min. (guaranteed) cavity performance in linac: 16 MV/m at $Q = 2{\cdot}10^{10}$**
- **Average cavity performance in linac: 18 MV/m at $Q = 2{\cdot}10^{10}$ with $\pm$2 MV/m spread to allow loosing 4 cryomodules.**
- **5GeV requires 390 seven-cell cavities !**
- **$\Rightarrow$ Can use BCP cavities (Q-lope starts at $\approx$ 20 MV/m)**

- **This provides more than 10% safety margin**

Trapped dipole HOMs in 9 cell cavities

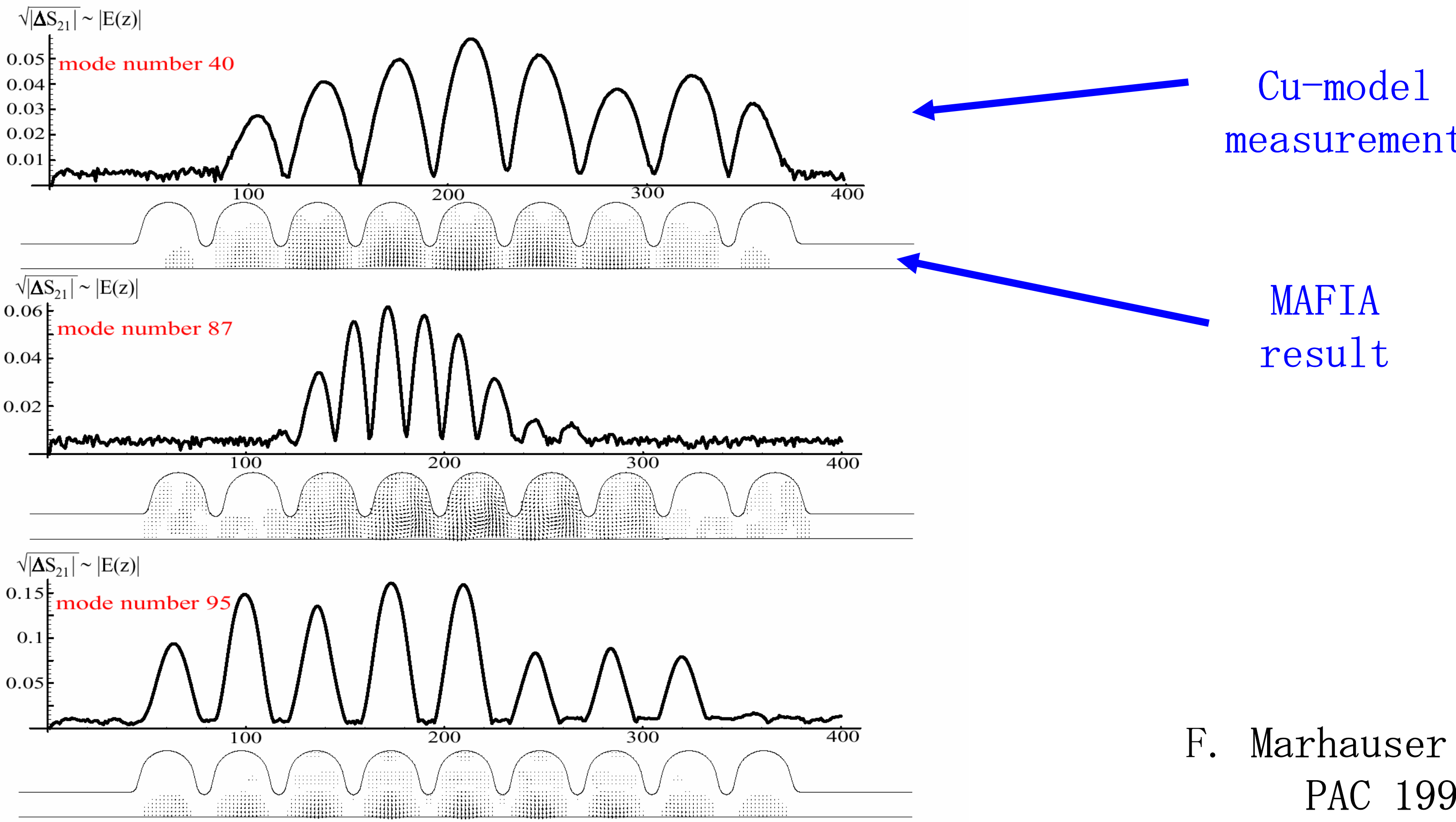

Figure 5: Trapped dipole mode (comp. Figure 4) no. 40 (f = 3.084 GHz MAFIA; 3.078 GHz meas.), mode no. 87 (f = 4.323 GHz MAFIA; 4.314 GHz meas.) and mode no. 95 (f = 4.426 GHz MAFIA; 4.421 GHz meas.).

F. Marhauser at al.
PAC 1999

Trapped dipole HOMs in 9 cell cavities

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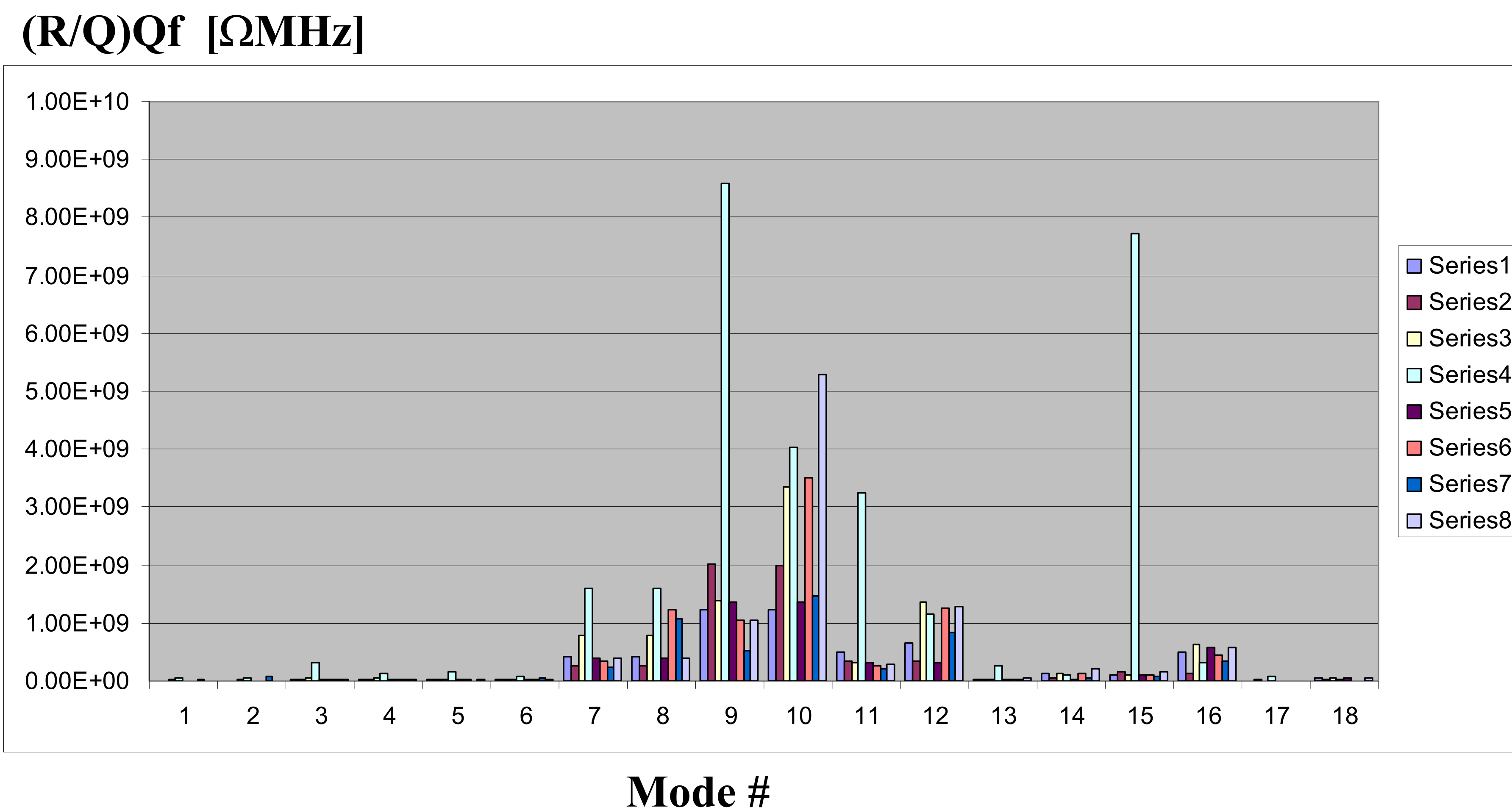

HOM minimization for 7 cell design

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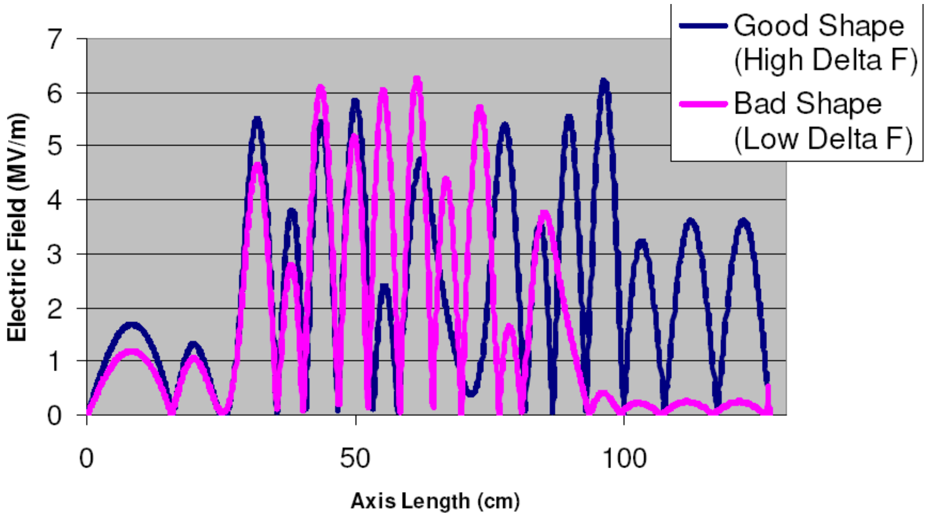
Dimensions are optimized to reduce Q*(R/Q) of worst HOM until as many HOMs as possible are about equal.

Example: End cell shape has significant impact

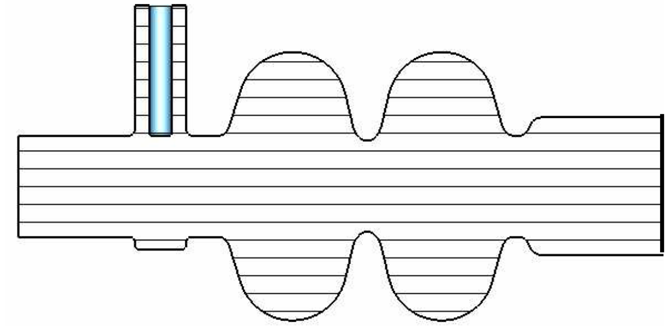


Limitations of these optimizations:

- **HOMs couple through large beam tubes:**
  - **Some modes will have high R/Q**
  - **Difficult to simulate. Actual R/Q strongly impacted by fluctuation in cavity shapes**
- **Still to be analyzed: Coupling of main input coupler to HOMs.**

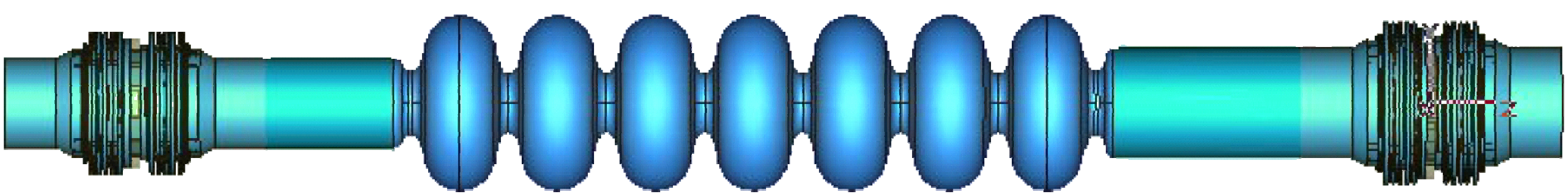
7 cell design philosophy

- **Design approach:**
  - Optimize center and iris radius cell for power loss (started).
  - Optimize end cells for HOM damping
  - Optimize mechanical layout for low microphonics in final design
  - Input coupler region design (coupling, kicks, …)



- **Still needs significant work for Cornell ERL!**

- **Polarized cavities have been analyzed to suppress BBU but have been ruled out for now**



Reliability study for 7cell cavities

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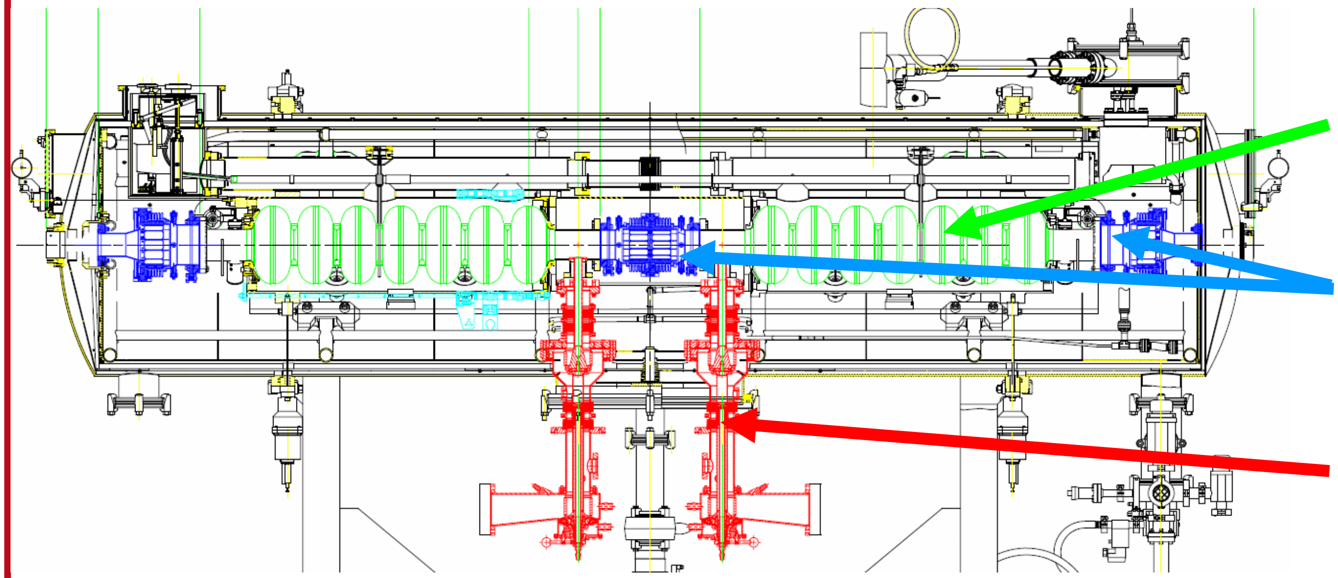

Two 1.3 GHz 7 cell cavities

Cornell-style cold HOM load

Cornell-style input coupler

- Collaborative development (Daresbury, Cornell, LBNL) for an advanced high-Q_0 cavity and cryomodule system for ERLs (I=100 mA)
- Housed in a modified Stanford/Rossendorf cryomodule
- Beam test on ERL-P in 2008 / possibly at Cornell with 100mA ?

Microphonics and the optimal Q

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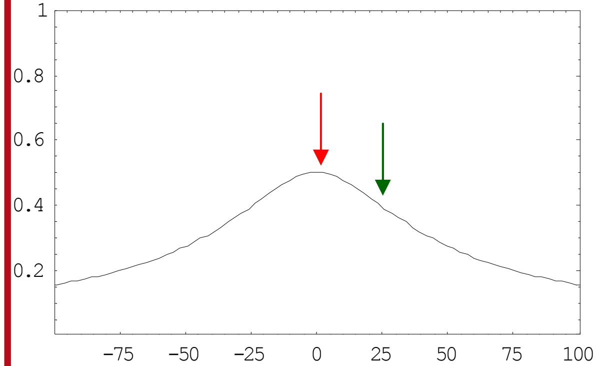
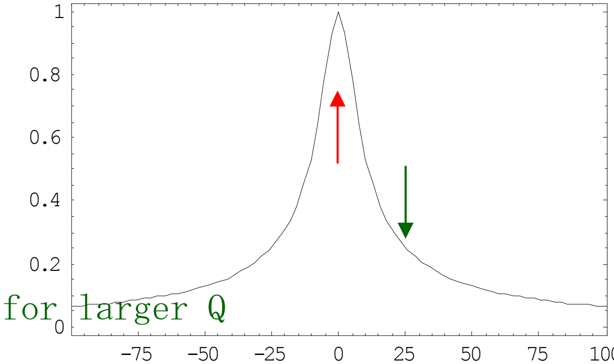
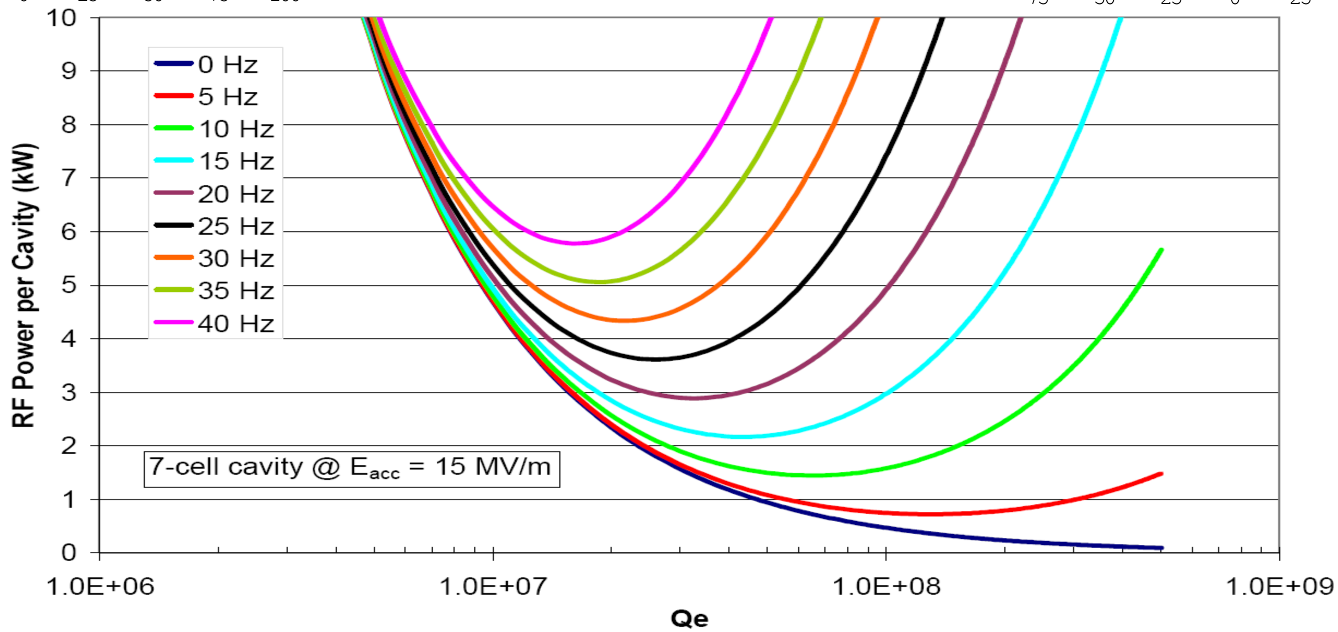


Higher Q → less power needed

Detuning → more power needed
especially for larger Q





- **Cavity and cryostat design for low microphonics**
- **Active frequency control (fast frequency tuner)**
- **Lacking detailed knowledge, we work with 20Hz peak detuning.**

Measured microphonics levels

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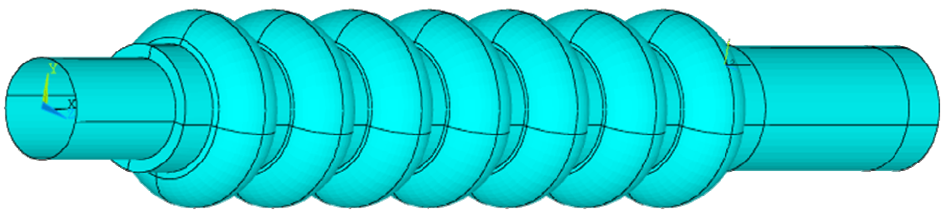
Machine	σ [Hz]	6σ [Hz]	Comments
CEBAF	2.5 (average)	15 (average)	significant fluctuation between cavities
ELBE	1 (average)	6 (average)	
SNS	1 to 6	6 to 36	significant fluctuation between cavities
TJNAF FEL	0.6 to 1.3	3.6 to 7.8	center cavities more quiet
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)	significant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

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

- **Assume optimistic 10 Hz as typical detuning (< 20 Hz peak).**
- ⇨ QL=6. 5·107
- This minimizes the typical (average) power need, not the maximum power that has to be available.

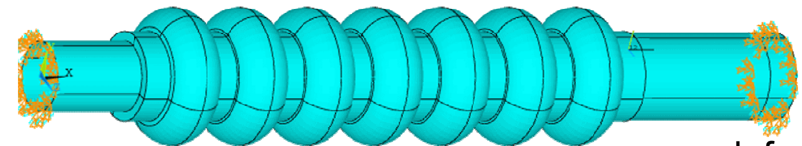
Mechanical frequencies

Rring = 0.65 X equator radius (Req)

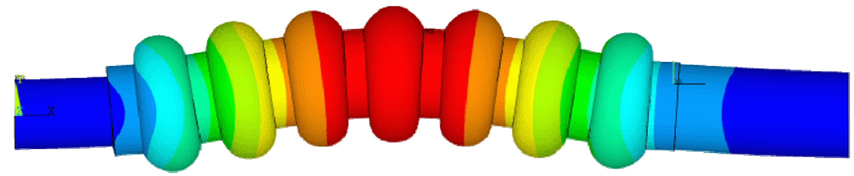


ring	0.7*req	0.4*req	0.65*req	no ring
ring-left	0.65*req	0.65*req	0.65*req	no ring
ring-right	0.75*req	0.75*req	0.65*req	no ring
mode	**freq / Hz**	**freq / Hz**	**freq / Hz**	**freq / Hz**
1	131.03	85.34	115.15	54.62
2	131.04	85.33	115.15	54.62
3	315.52	191.3	268.39	133.34
4	315.52	191.3	268.39	133.34
5	409.83	250.67	344.89	195.90
6	459.51	294.12	456.26	226.60
7	549.51	294.13	456.27	226.60
8	549.51	394.77	456.85	319.34

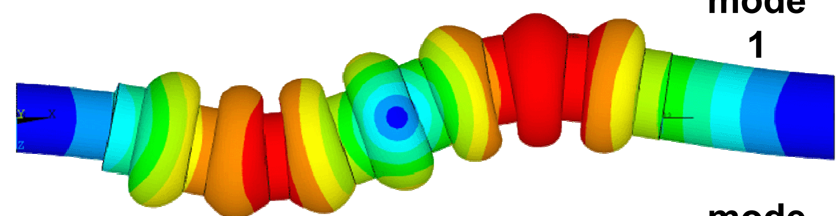
Courtesy E. Zaplatin



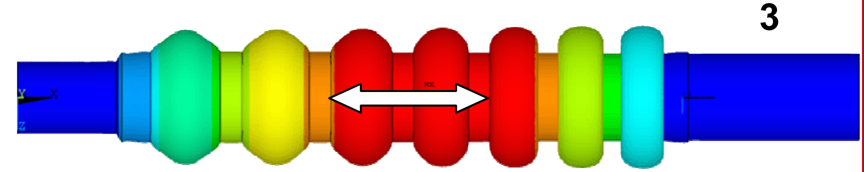
dof



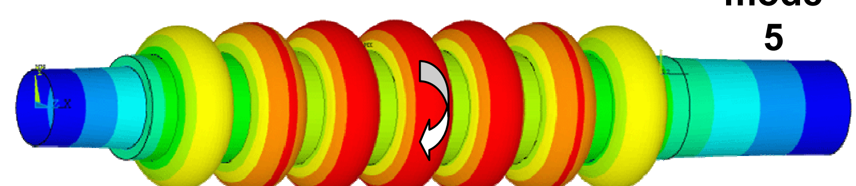
mode 1



mode 3



mode 5



mode 8

Low microphonics cavity design

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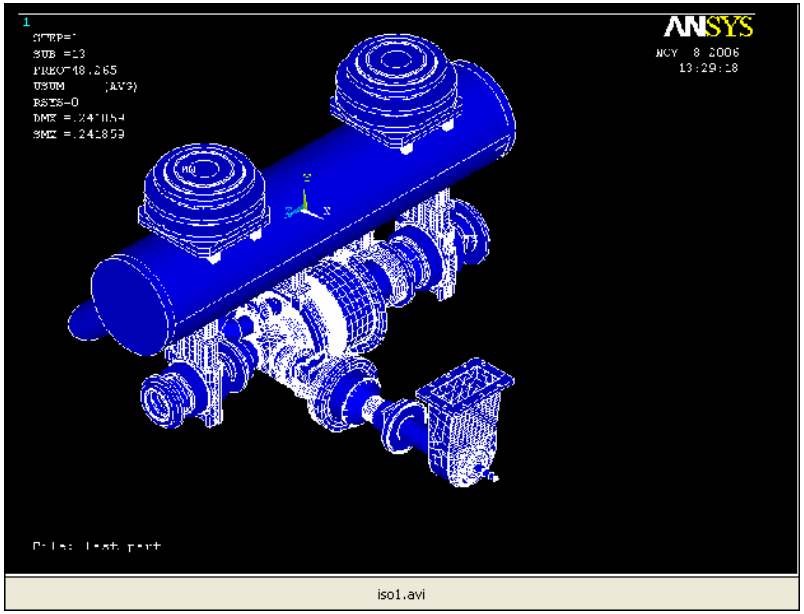
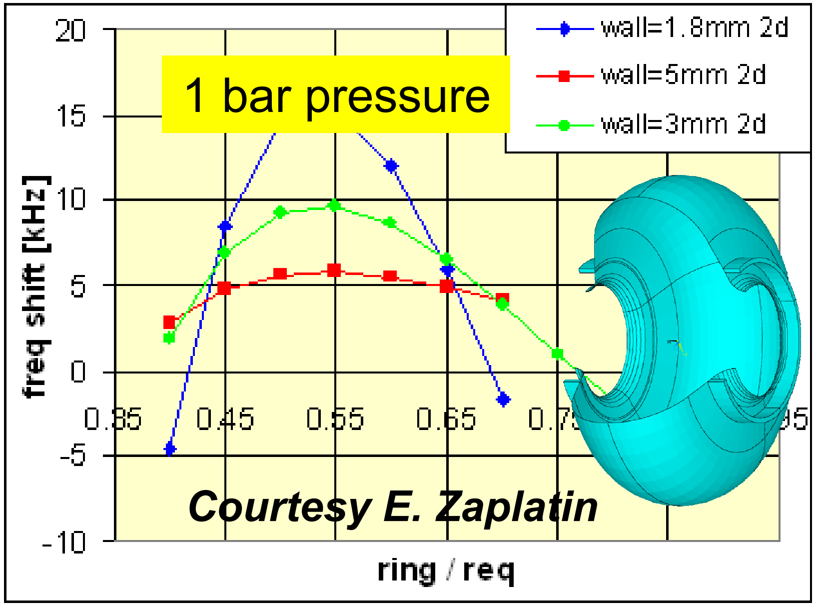
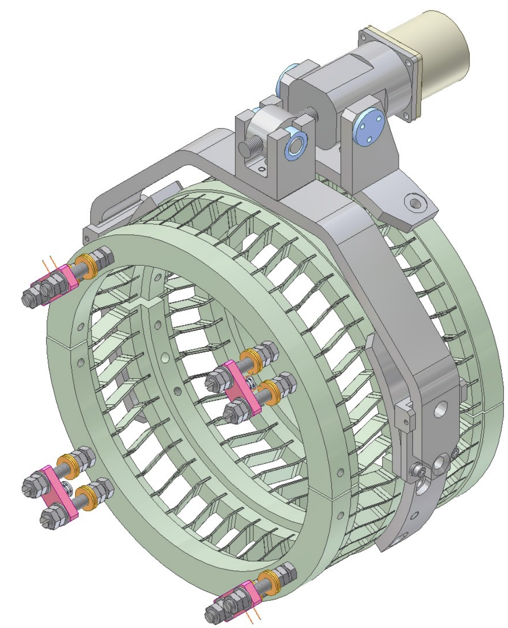
- **Cavity design:**
  - **Low sensitivity to He-pressure changes (of 0.1-1mbar)**
  - **High mechanical vibration frequencies**
- **Module design:**
  - **High mechanical vibration frequencies**
  - **Decouple module from vibration sources**
  - **This vibration analysis has been done for the ERL injector, but not for the main linac yet.**





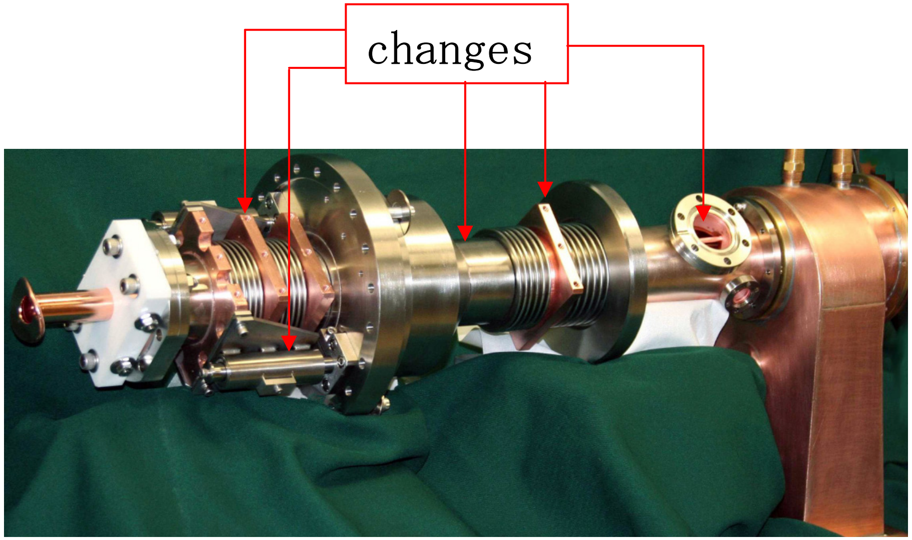
Frequency tuners

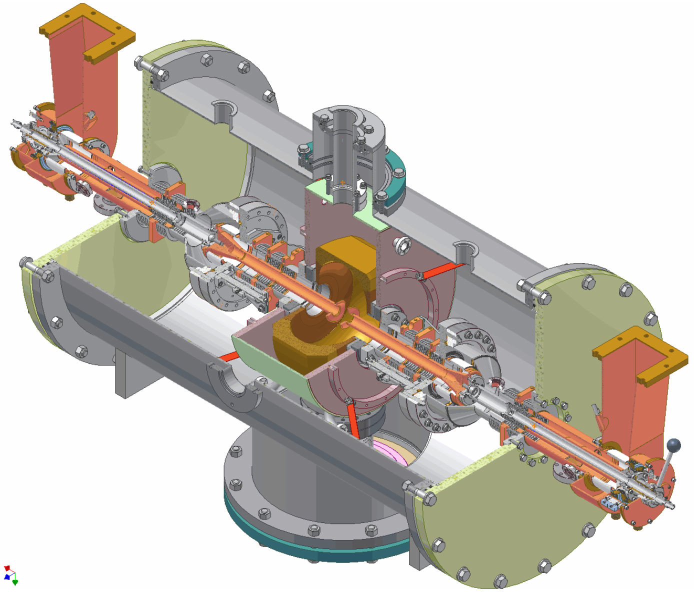
- **Fast frequency tuning (piezo tuner) essential for realistic microphonics and $Q_L > 3\ 10^7$.**
- **Injector frequency tuner (modified INFN type) is a prototype for main linac tuner (Although $QL=10^4$, it is equipped with piezos for R&D).**
- **Future work:**
  - **Detailed studies of mechanical behavior (cavity + He-vessel + tuner)**
  - **Design modifications to lower cost**



Couplers

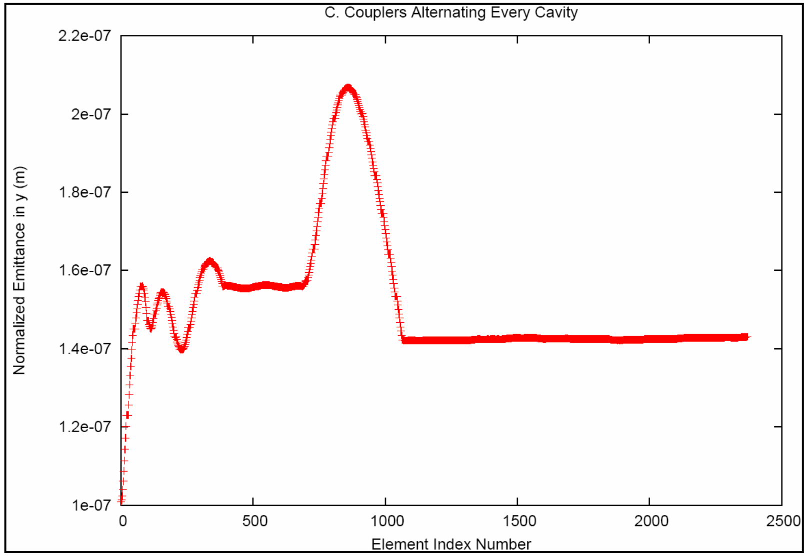
- **Peak power: 5 kW**
  - **Modified TTF coupler (3 kW average).**
  - **Modified injector coupler (reduced cooling, design modified for lower static loads)**
  - **Some modifications are similar to the changes needed for the 50kW ERL injector coupler.**

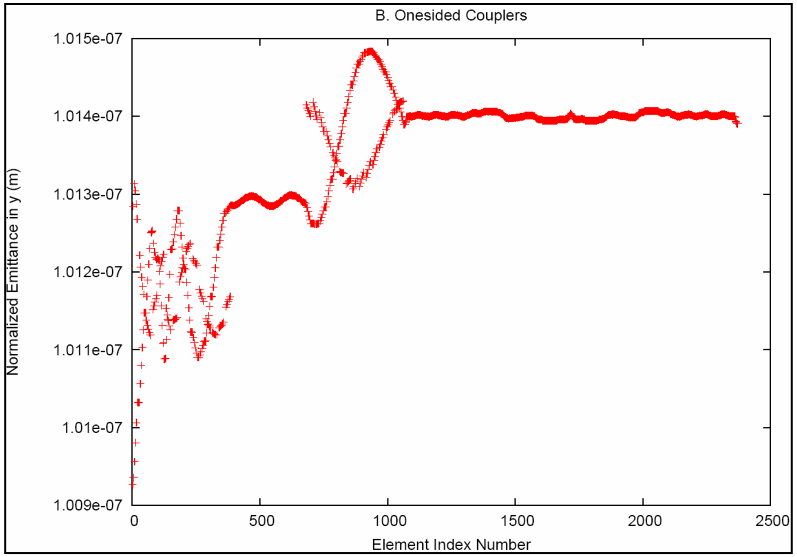


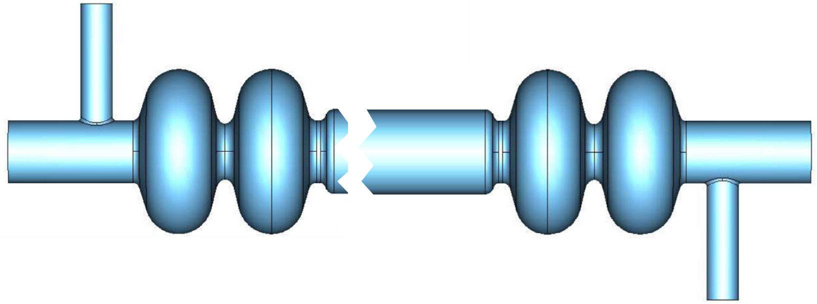


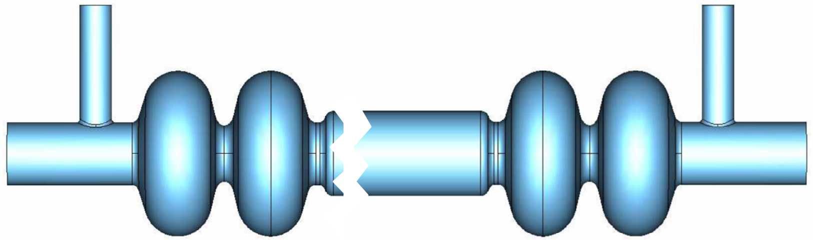
Coupler Kicks

(1) Kick cancellation by symmetry

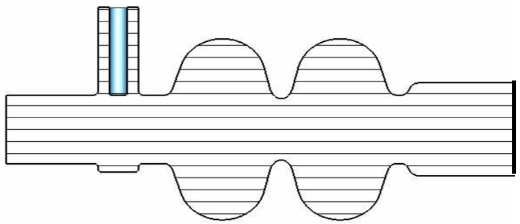






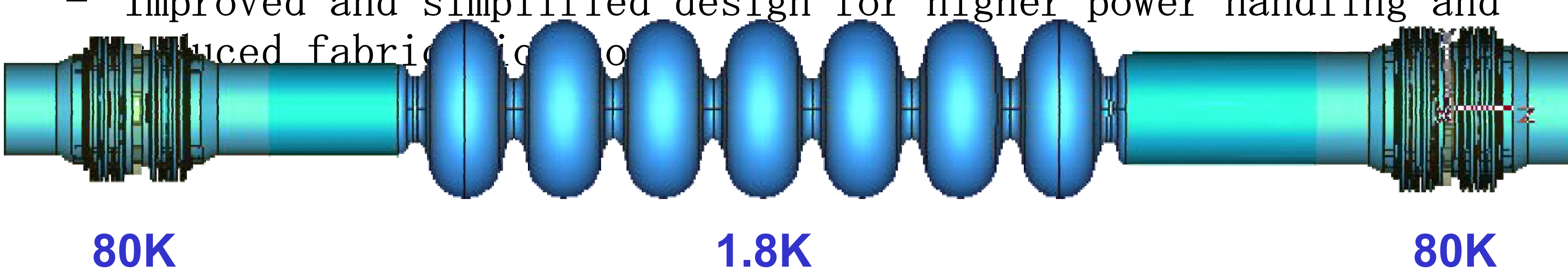


(2) Kick cancellation by a more symmetric coupler region



Higher order mode absorbers

- Cold beamline HOM absorbers between cavities
  - Adopted from the SRF ERL injector prototype (larger beam tubes for BBU):
  - End cells and tubes optimized for good HOM power extraction
  - All higher-order monopole, dipole and quadrupole modes propagate in beam tube
  - But: Higher current (200 vs 100mA) and longer cavities (7 vs 2 cells)
    - ⇨ More power needs to be absorbed (170 vs 30W)
  - Resonant HOM excitation can result in a few 10W for a few cavities and the design therefore needs to work for > 200W.
- Future work:
  - Material studies
  - Improved and simplified design for higher power handling and



Quadrupoles and the Optics

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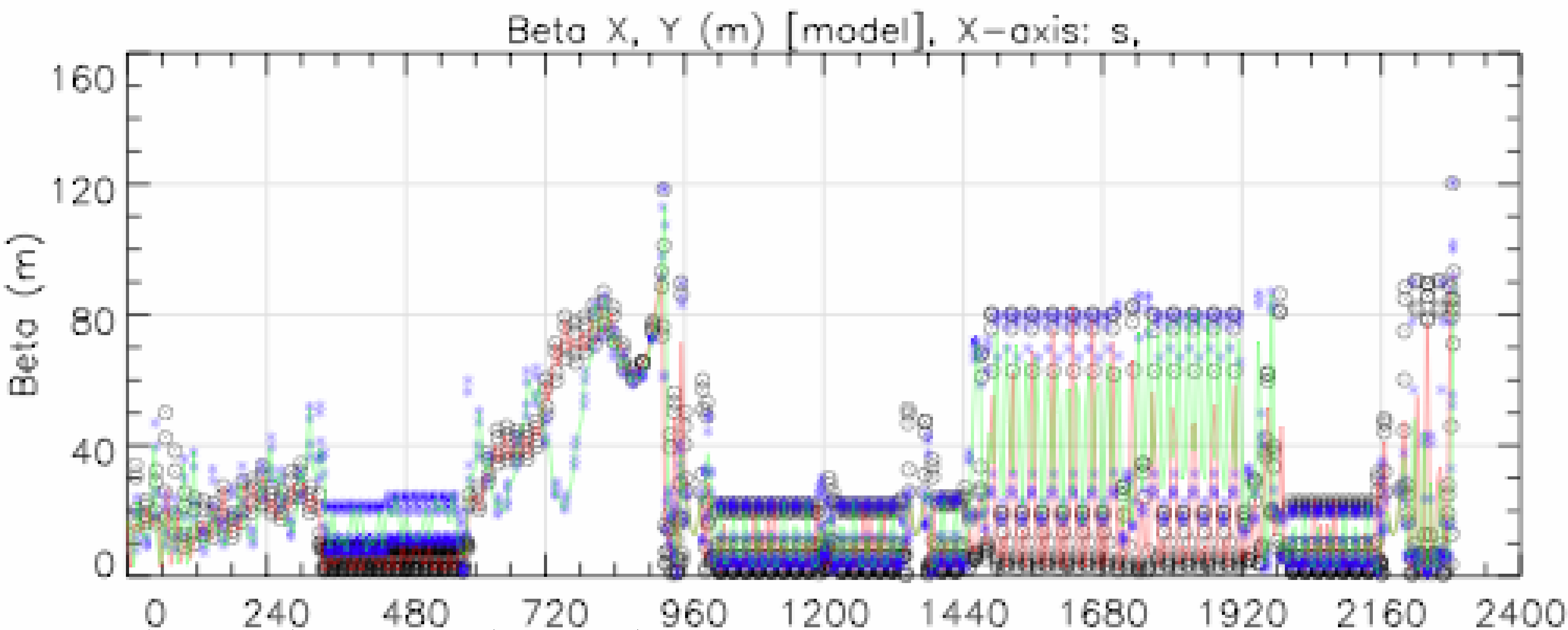

Linac A　　Linac B

- An optics for 10MeV to 5GeV and simultaneously 5GeV to 10 MeV Can easily be found by letting the 5GeV beam drift through the first week quadrupoles.
- The decelerating optics is very close to the mirror image of the accelerating optics.
- The optics uses two quadrupoles after 10 cavities, each …cm long and … and … apart

Cryomodule needs

- **Cryomodule needs to**
  - **Provide good cavity alignment (<1mm)**
  - **Minimize cavity vibration and coupling of external sources to cavities**
  - **Provide good magnetic shielding**
  - **Support cw cavity operation with high loads**
- **Injector cryomodule severs also as main-linac module prototype**
  - **Same cross section**
  - **All cryo-pipes designed for main linac loads**
  - **No Nitrogen cooling, but He gas for 80K**
  - **Piezo tuners provided as needed for much larger loaded Q**

Cryomodule needs

- **Differences to ILC**
  - No 5K shield for ERL because dynamic load >> static load
  - Narrow He-gas pipes to HOM loads
  - 3 magnetic shields (vs 1) for larger Q0
  - Ti - He return pipe to support cavities, no sliding support
  - Modified to easily exchange tuner motor
  - Piezo
  - Gate valve drives outside the module
  - Larger pipes for cw operation
  - Connect both ends of 2-phase line with He-return pipe to limit gas velocity.

Module design for high cryo power

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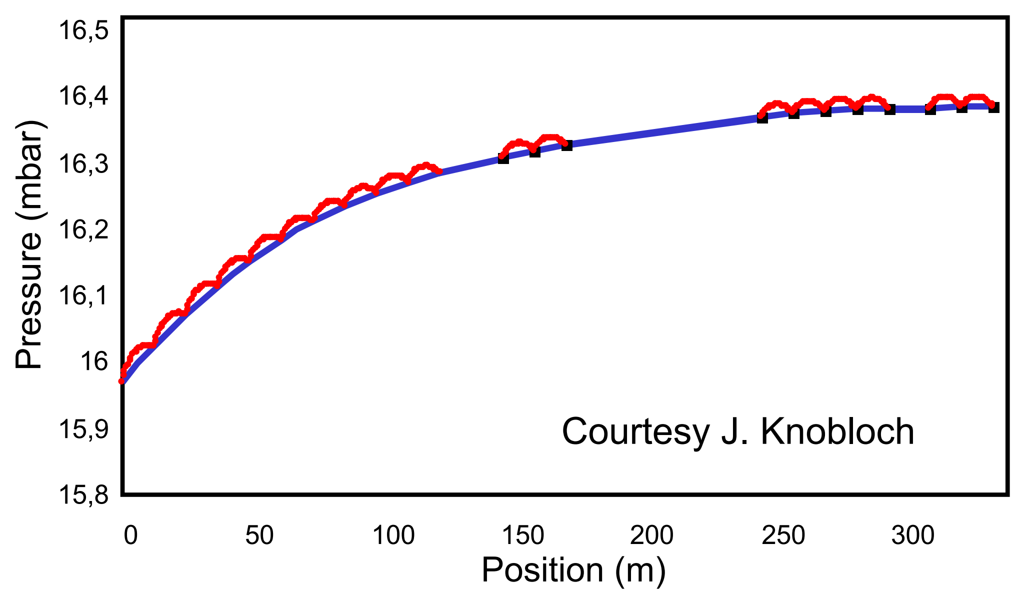
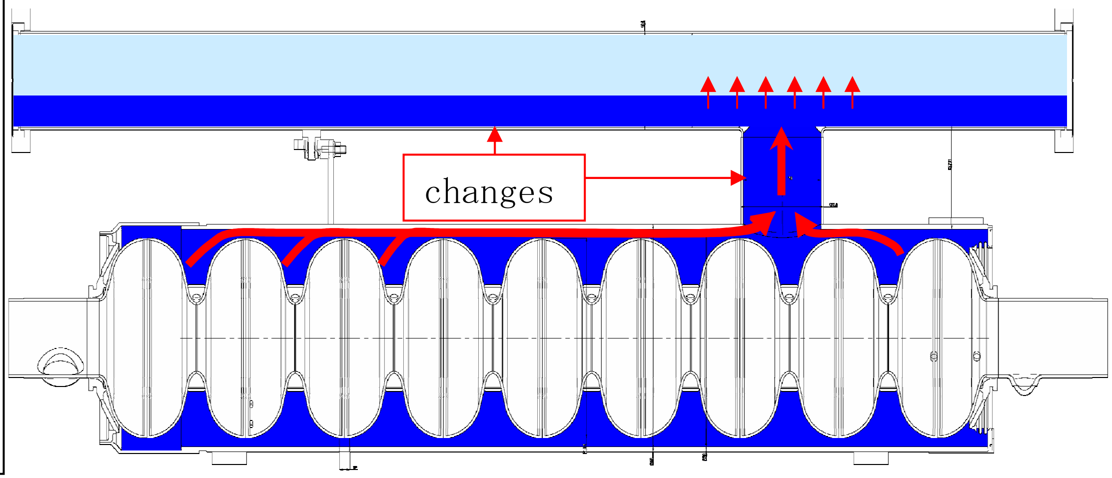
Pipe sizes limit maximum heat load:

- Heat transfer in He-II (< 1 W/cm^2)
- Vapor velocity in 2-phase lines
  (stratified flow ⇨ < 4 m/s)
- Pressure drop in pump lines

⇨Careful module design essential !

⇨Simulation has been done to specify pipe dimensions. There are used for the Cornell ERL injector prototype





Module length

- **Most up to date Module:**

  (Shortened for transportability, not the module for which optics and layout was designed)
  - Five 7-cell cavities
  - 6 HOM loads
  - 1 quad
  - 1 kicker (v. or h.)
  - 1 BPM
  - 2 gate valves

- **Length = 9 m**

- **Active length = 4 m**

Element	Element Length/m	Total Length/m
valve	0.1	0.1
HOM load	0.2	0.3
beam tube large	0.24	0.54
cavity active	0.8	1.34
beam tube small	0.17	1.51
HOM load	0.31	1.82
beam tube small	0.17	1.99
cavity active	0.8	2.79
beam tube large	0.24	3.03
HOM load	0.31	3.34
beam tube large	0.24	3.58
cavity active	0.8	4.38
beam tube small	0.17	4.55
HOM load	0.31	4.86
beam tube small	0.17	5.03
cavity active	0.8	5.83
beam tube large	0.24	6.07
HOM load	0.31	6.38
beam tube large	0.24	6.62
cavity active	0.8	7.42
beam tube small	0.17	7.59
HOM load	0.2	7.79
to quad	0.1	7.89
quad	0.5	8.39
drift last quad to kicker	0.15	8.54
kicker	0.2	8.74
valve	0.1	8.84
intra-module	0.2	9.04

Next steps

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- **Full main linac module design based on injector module design.**
- **Open issues:**
  - Verification of HOM load operation
  - Verification of magnetic shielding for highest Q_0
  - Design optimization for low microphonics
  - Study best way to regulate cooling of HOM loads individually
  - Synchrotron radiation shielding of cavities
  - Beam collimation. Beam loss, radiation, and heating (especially for cavities at linac end)

Conclusion

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- The parameters for the Cornell ERL main linac are challenging,
  but well motivated.
- High Q_0=2 10^{10} at 1.8K seems not unachievable, but needs verification
- Amplitude and phase control for Q_L= 10^8 has been tested satisfactorily
- Cavity shape has been optimized
- HOM absorbers have been optimized but need cost reduction
- Tuners are designed and will be tested
- Low microphonics design needs modeling and model/reality checks will be done in the Cornell ERL injector

⇒ Lots of work remains to be done !
Cornell is looking for preconstruction funding to verify the