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

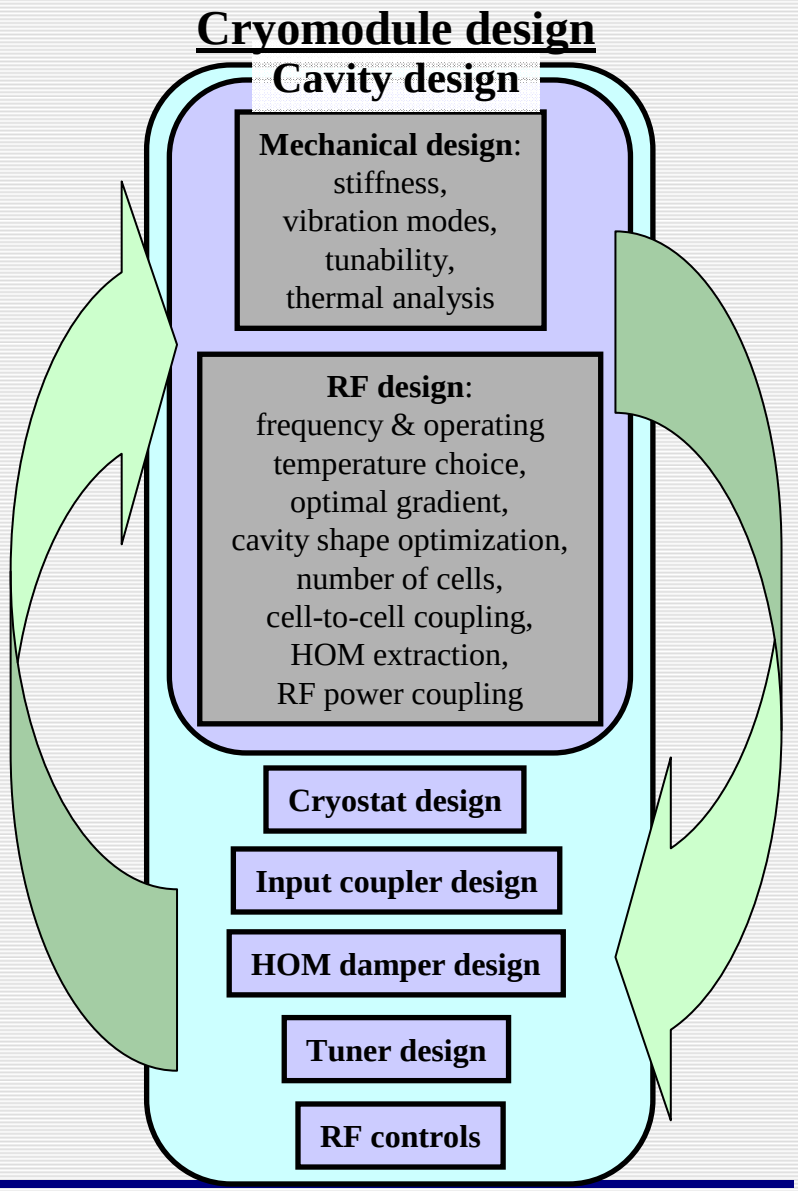
- **Lecture 8** ***Cavity design and optimization***

Cavity design parameters

What shall we consider while designing a cavity?

- **Choice of material (impacts losses and operating gradient)**
- **Frequency (impacts size of cavity, cost, surface resistance, assembly technique …)**
- **Number of cells (impacts field flatness, tunability, HOM extraction, pulsed vs CW operation, linac fill factor, mechanical resonances …)**
- **Aperture size (impacts beam stability, peak fields, HOM damping …)**
- **Cavity shape (impacts peak surface fields, power dissipation, multipacting, tunability, …)**
- **…**

The cavity design is intimately coupled with that of other cryomodule components.

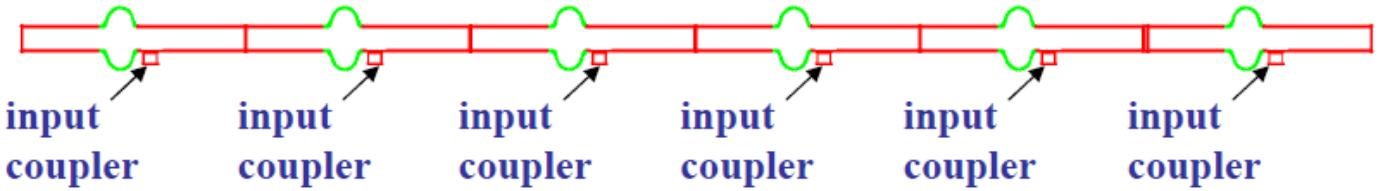


Cavity design (RF)

The cavity performance is optimized, BUT the criteria/requirements differ depending on application:

SRF accelerator type	Requirements	RF parameters	Cavity design
Pulsed linacs	High-gradient operation	E_{pk}/E_{acc} H_{pk}/E_{acc}	Iris and equator shape, smaller aperture
CW linacs and ERLs	Low cryogenic loss (dynamic), good fill factor	$G\cdot(R/Q)$ # of cells	Cell shape, smaller aperture, larger number of cells per cavity
Storage rings, ERLs	High beam current	$(R/Q)Q_L$ of HOMs	Larger aperture, fewer number of cells per cavity, cavity shape
Storage rings, ERL injectors	High beam power	P_{couper}	Larger aperture, fewer number of cells per cavity (single-cell cavities for SR)

Why multi-cell cavities?



F≈ 25 %

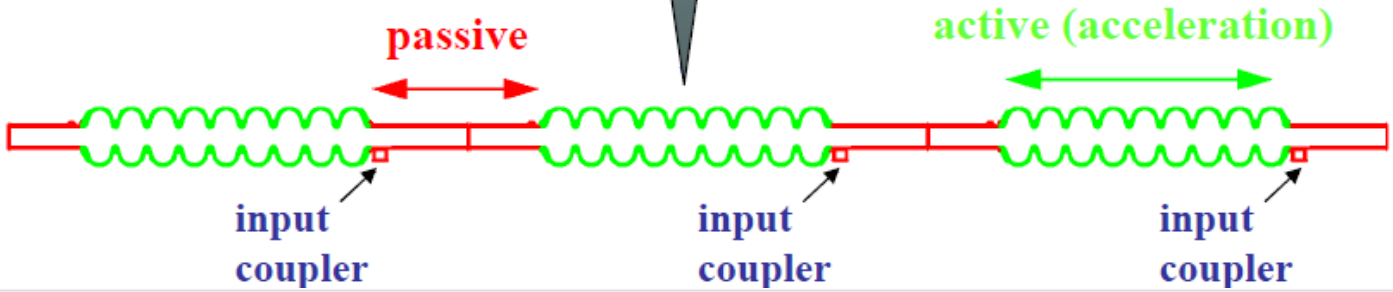
higher fill-factor:

$$F = \frac{\text{active length}}{\text{total length}}$$

$\Rightarrow$ *lower costs*

fewer

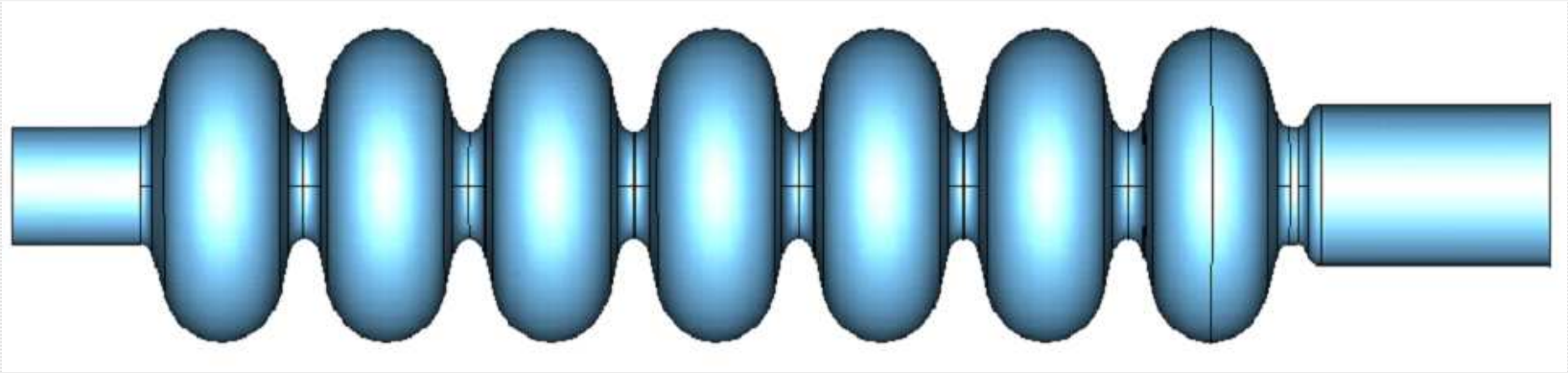
- **input couplers**
- **waveguide elements**
- **RF control systems**
- **…**



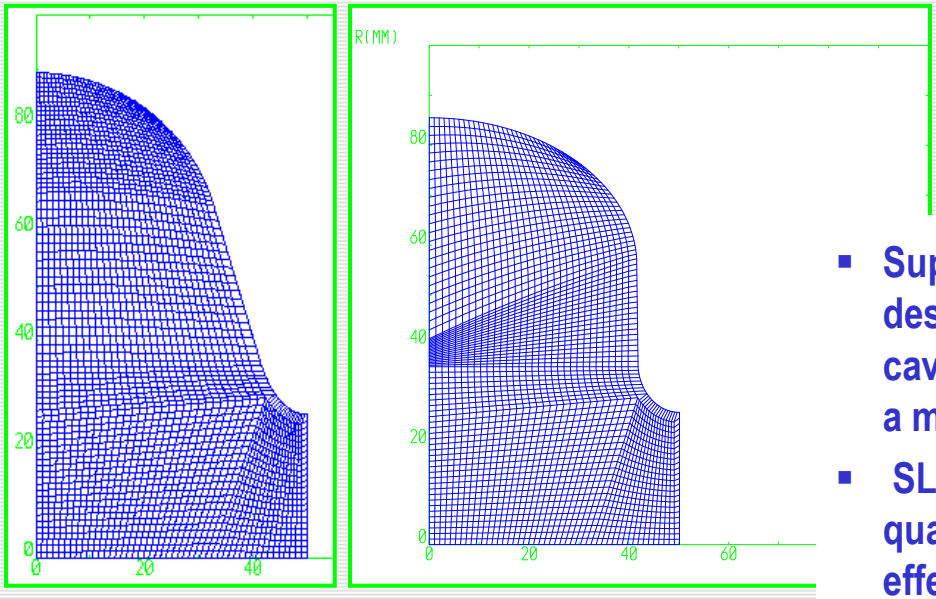
F≈ 75 %

RF design tools

- As the real cavity cannot be modeled analytically, numerical codes are used.
- Usually design of elliptical cavities is performed in two steps: 2D and 3D.
- 2D codes (Superfish, SLANS/CLANS, …) are faster and allow to design geometry of the cylindrically-symmetric body of the cavity.
- 3D codes (MAFIA, Microwave Studio, HFSS, Omega-3P, GdfidL, …) are necessary to complete the design by modeling the cavity equipped with fundamental power couplers, HOM loop couplers, calculating coupling strength, etc.



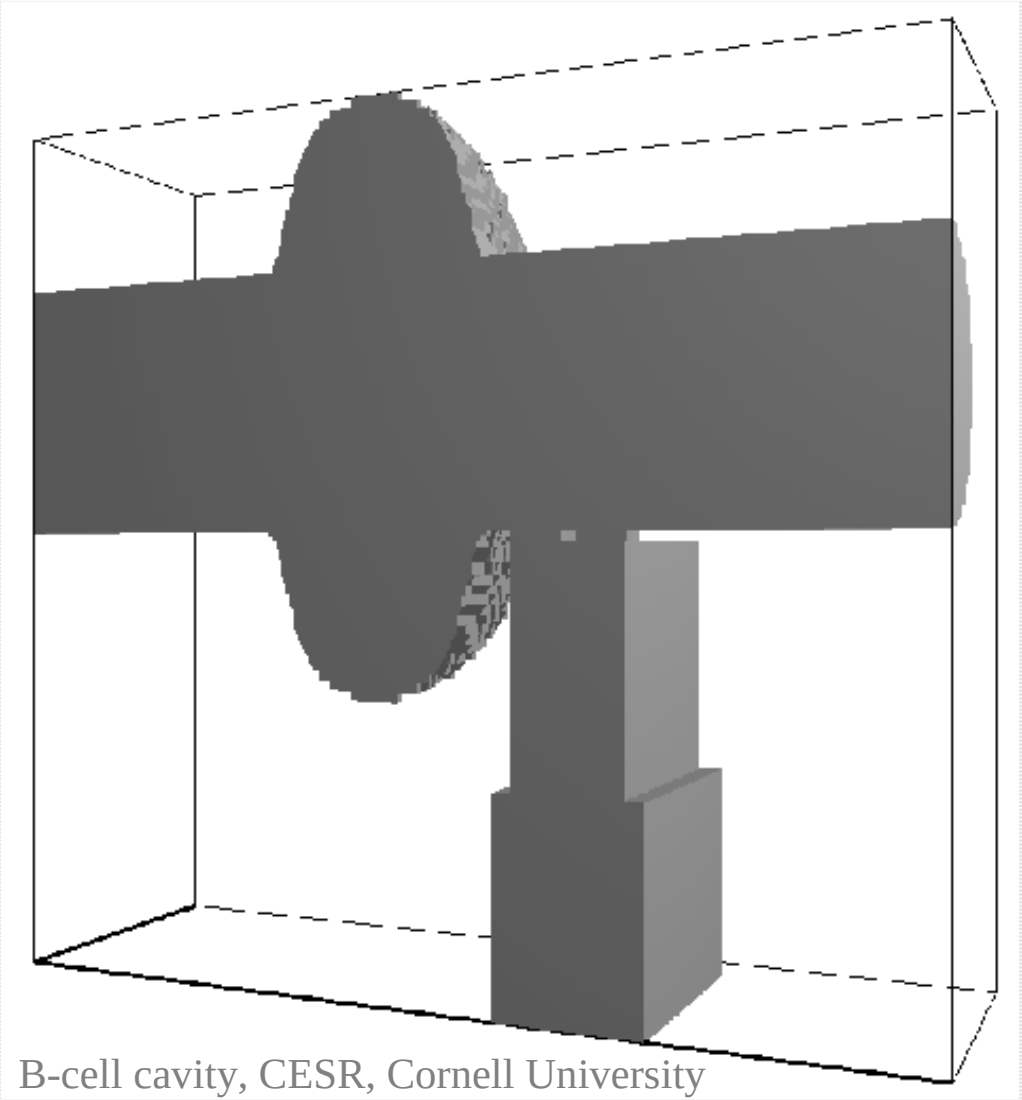
2D code example: SLANS/CLANS



- SuperLANS (or SLANS) is a computer program designed to calculate the monopole modes of RF cavities using a finite element method of calculation and a mesh with quadrilateral biquadratic elements.
- SLANS has the ability to calculate the mode frequency, quality factor, stored energy, transit time factor, effective impedance, max electric and magnetic field, acceleration, acceleration rate, average field on the axis, force lines for a given mode, and surface fields.
- Later versions, SLANS2 and CLANS2, calculate azimuthally asymmetric modes, and CLANS and CLANS2 can include into geometry lossy materials.

3D code example #1: MAFIA

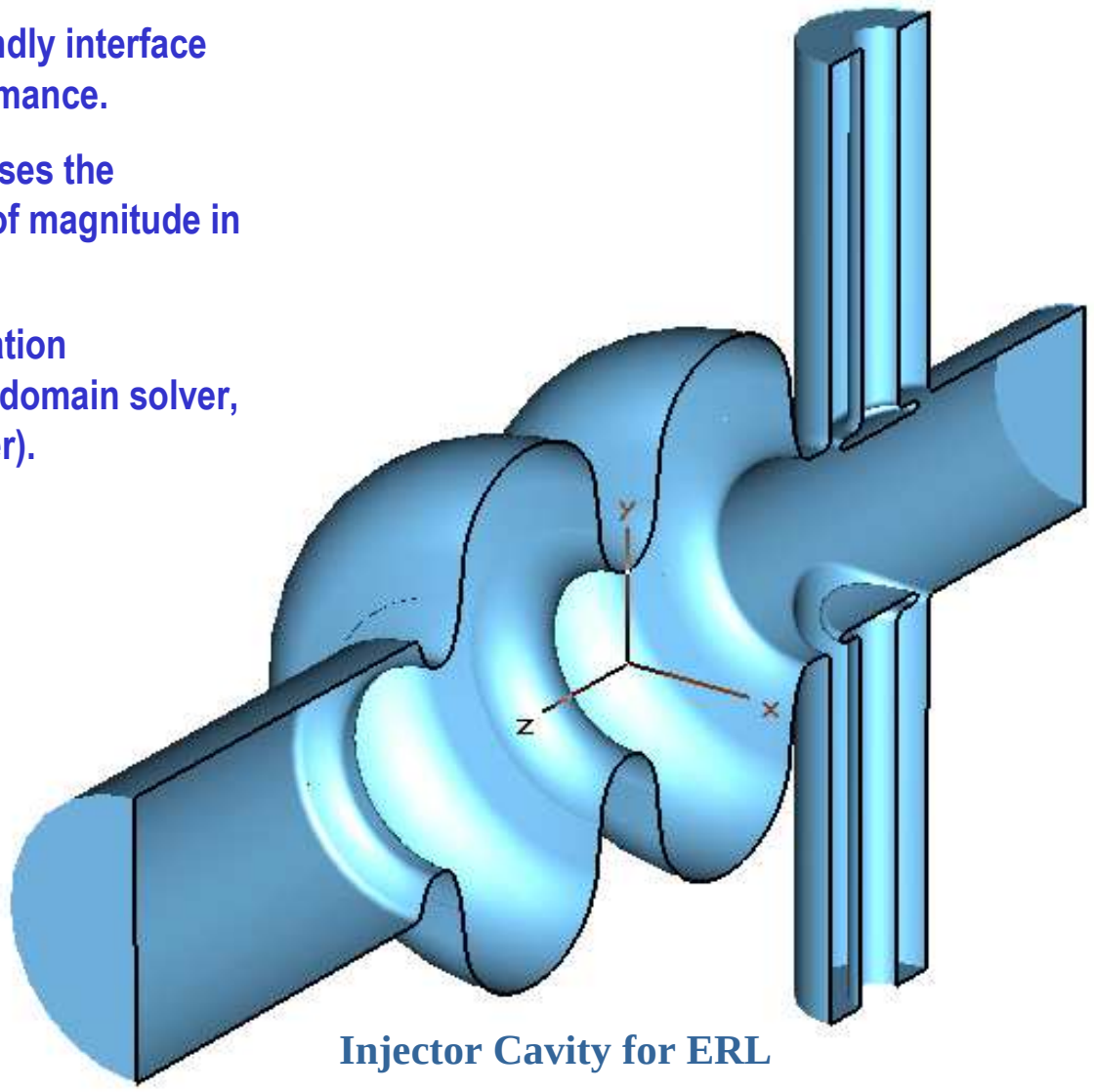
- MAFIA is a 3D simulation code used for the design of RF cavities and other electromagnetic structures, including electrostatic and magnetostatic devices.
- It is an acronym for the solution of MAxwell's equations using the Finite Integration Algorithm.
- MAFIA uses a rectangular mesh generation routine which is flexible enough to model even the most complex geometries.
- The routine allows the user to specify the "coarseness" of the mesh in a particular area of interest.
- Only few users still use this code.



B-cell cavity, CESR, Cornell University

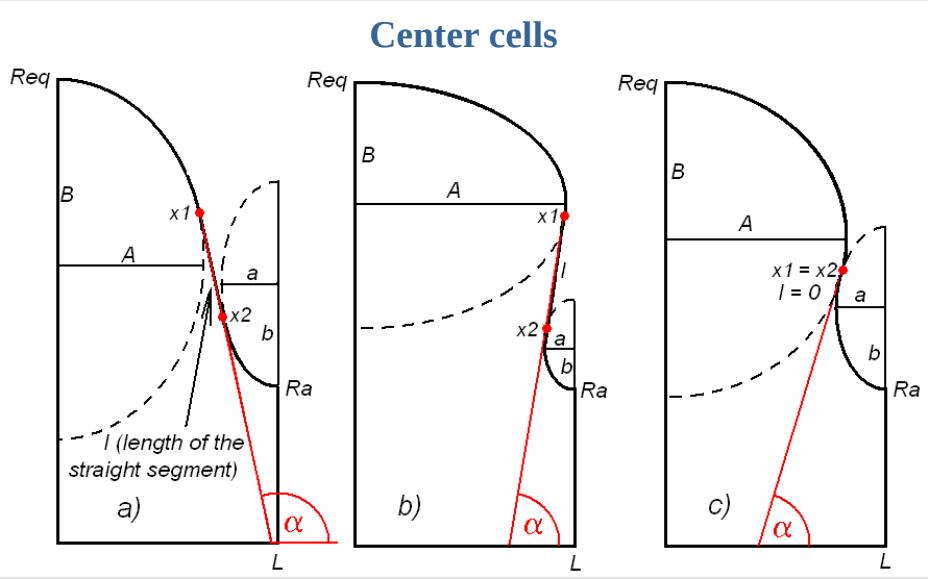
3D code example #2: Microwave Studio

- The program combines both a user friendly interface (Windows based) and simulation performance.
- Perfect Boundary Approximation increases the accuracy of the simulation by an order of magnitude in comparison to conventional simulators.
- The software contains 4 different simulation techniques (transient solver, frequency domain solver, eigenmode solver, modal analysis solver).



Injector Cavity for ERL

Elliptical geometry



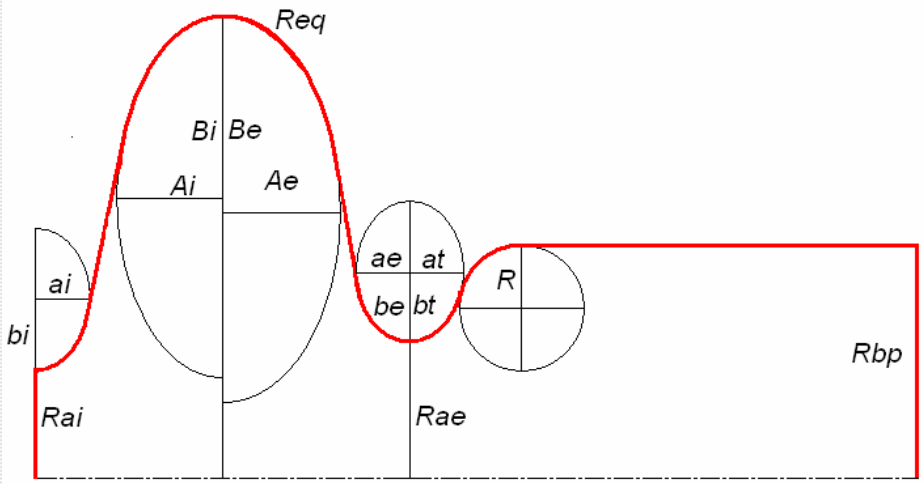
An elliptical cell geometry consists of two elliptical arcs connected by a straight line. Thus we have 7 independent parameters, some of which are pre-determined.

Center cells are symmetric:

- **The half-cell length *L* determines the cavity geometrical beta value and usually is $\beta\lambda/4$;**
- **The cell aperture radius R_a is determined by the cell-to-cell coupling requirements and cavity impedance limitations;**
- **The cell radius at the equator R_{eq} is used for frequency tuning;**
- **Then one can use any combination of 4 parameters from *A, B, a, b,* and α;**
- **The aperture ellipse ratio *b/a* is be used for optimization of the peak electric field;**
- **The side wall inclination angle α and equatorial ellipse half-axes *A* and *B* are used to optimize the peak magnetic field.**

End cell shape & Design goals

End cell



End cells are not symmetric:

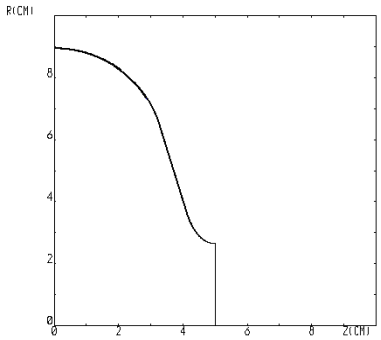
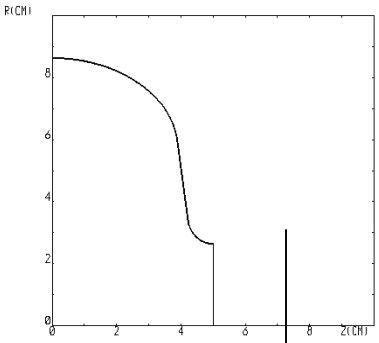
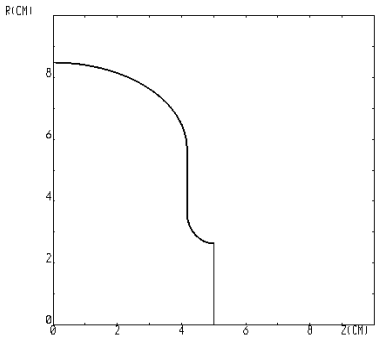
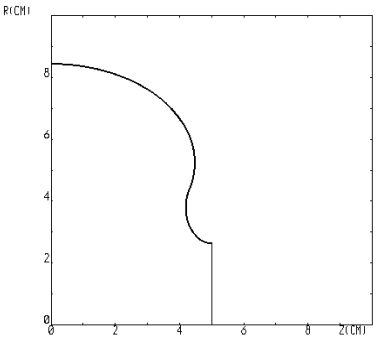
- **The inner half-cell is identical to the center half-cells;**
- **The end half-cell has to be frequency tuned by either *L* or α as R_{eq} is fixed;**
- **The end half-cell aperture radius R_{ae} can be used for HOM damping optimization in conjunction with the adjacent beam pipe parameters.**

The design goal is determined by the machine requirements and could be for example:

Maximize G*R/Q and minimize peak magnetic surface field with limits set for the wall inclination angle, maximum peak electric field and minimum iris radius.

One usually starts with a known shape (for example, TESLA cavity or original Cornell/CEBAF shape) and runs an optimization scripts until either an optimum or a limit is reached. If further optimization is restricted by one of the limits, one may want to re-consider reasoning used to set the limit.

Optimization example

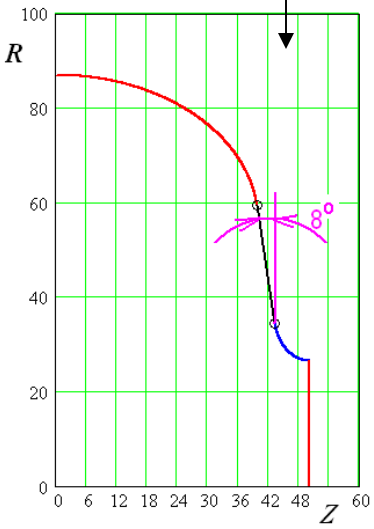





***G*R/Q*, relative units:**

0.90 (105°) **1.00 (98°)** **1.02 (90°)** **1.042 (75°)**

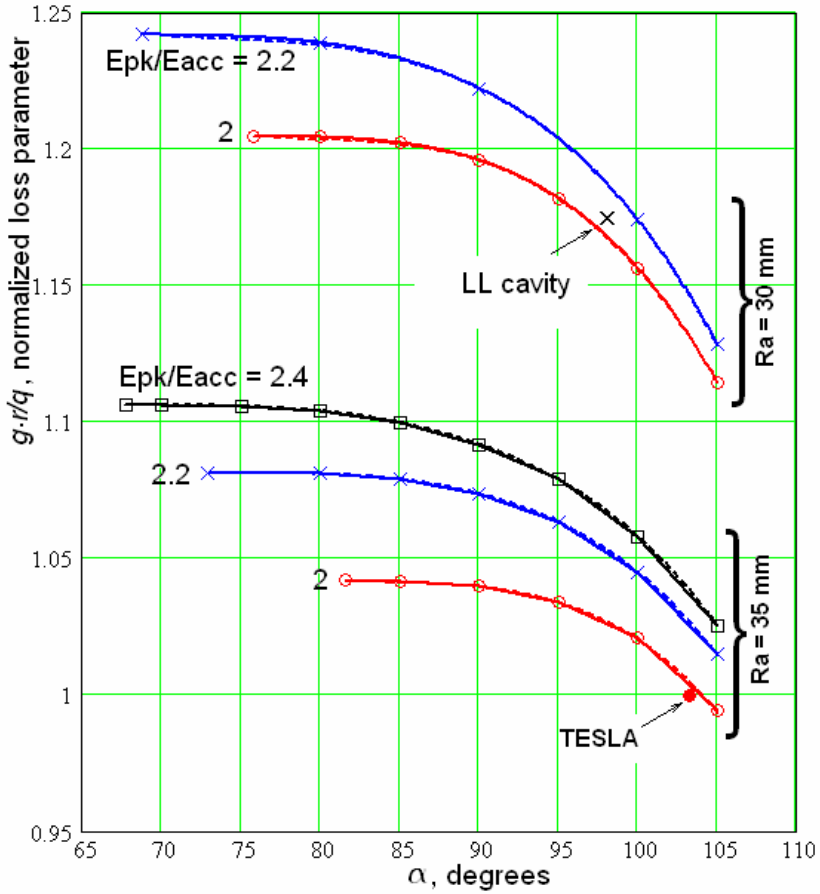
If one rejects the limitation of the angle we can further improve the value of *G*R/Q*

JLab LL Cell

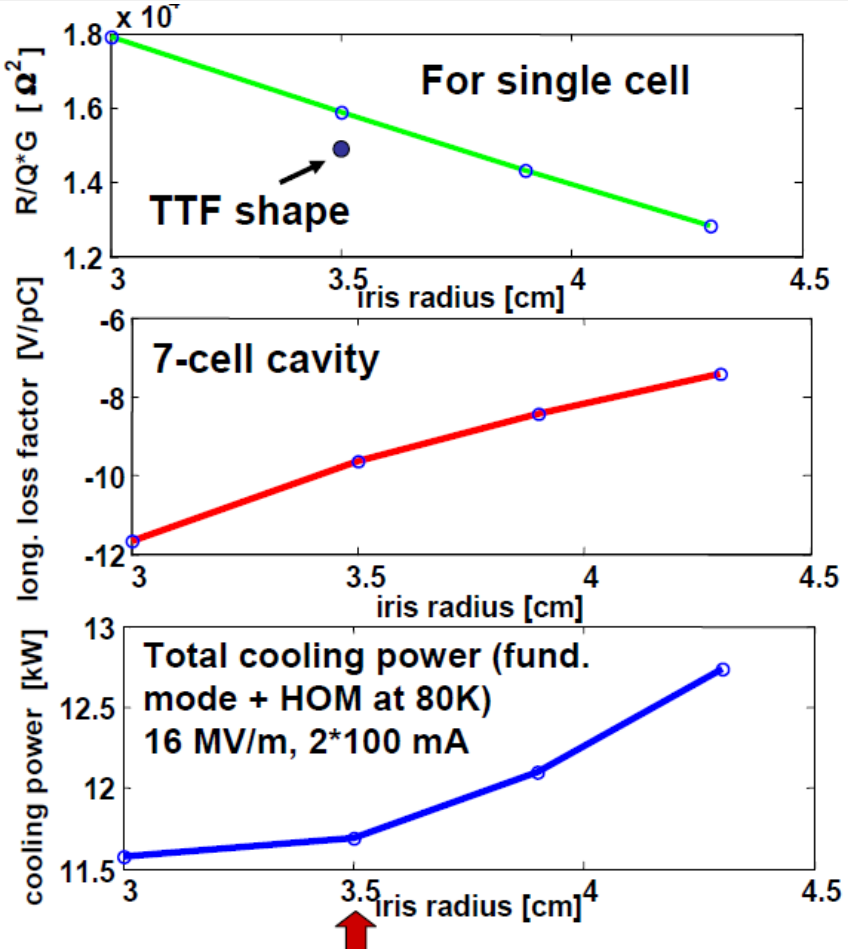


- **JLab's optimized shape was designed under restriction that the angle of the wall slope is not less than 8 deg. This angle is useful to let liquid easily flow from the surface when chemical treatment or rinsing are performed.**

What else one can get from the optimization?



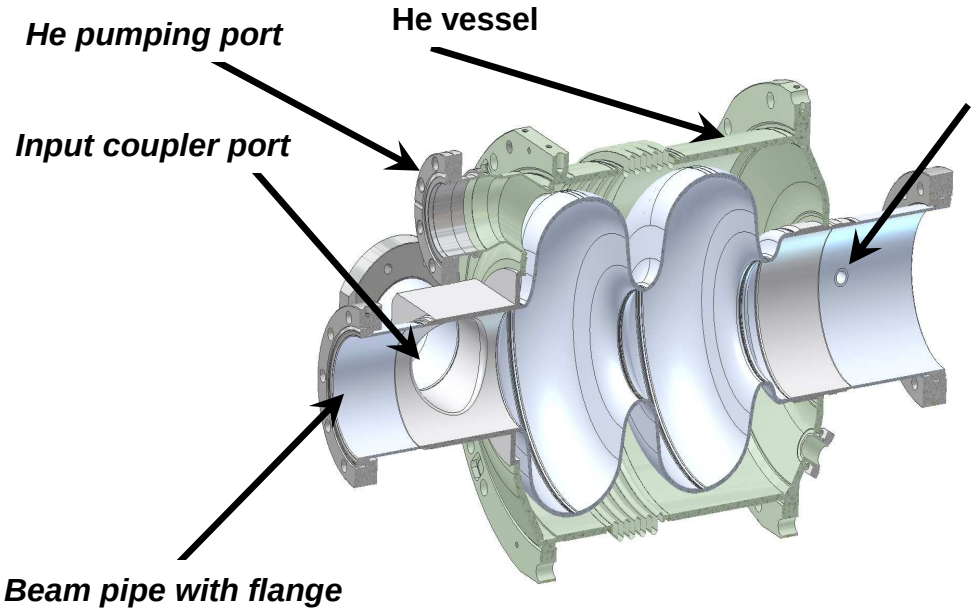
*G*R/Q* vs wall angle for different peak fields and apertures.

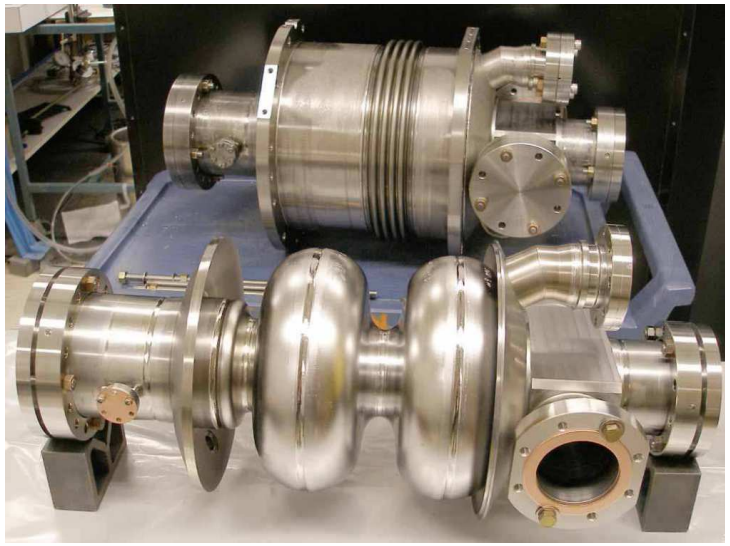


Cells optimized for fixed side wall angle (98 deg) and electric peak field (E/Eacc=2.2)

Cavity design (mechanical)

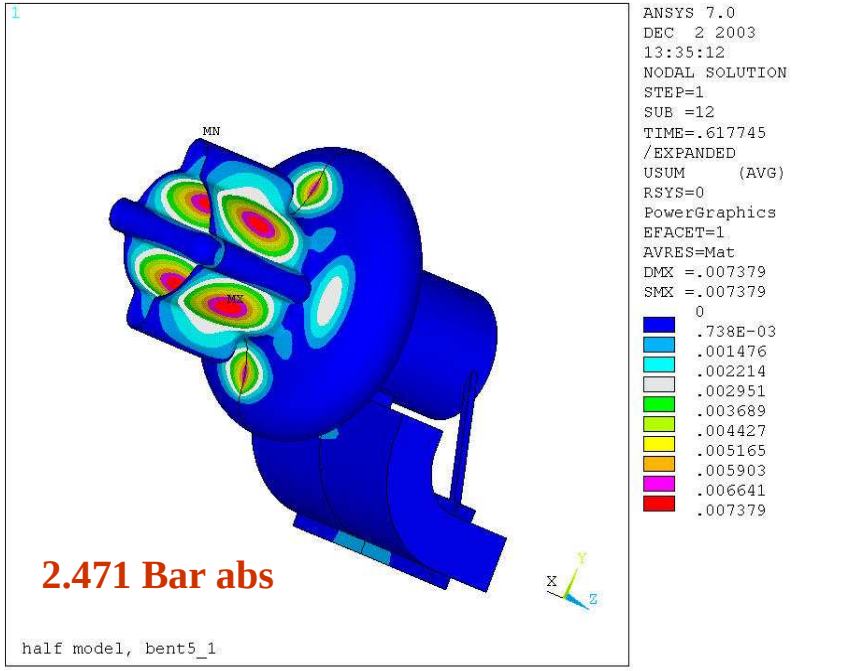
- Cavities have to accommodate RF input coupler ports & field probes.
- All interfaces (to liquid helium vessel, beam pipe flanges,…) should be defined.
- Mechanical design includes computer simulations of mechanical stresses due to cooldown, pressure differentials, tuning of the cavity frequency, etc., simulations of the heat transfer, and determining most dangerous vibrations modes.
- At this point all fabrication techniques are specified, and a package of drawings is produced.





Mechanical aspects

- Strength (ability to withstand atmospheric pressure).
- Mechanical stresses due to cool-down from room temperature to cryogenic temperature, frequency change.
- Thermal analysis using material properties at appropriate temparatures.
- Codes like ANSYS are used.

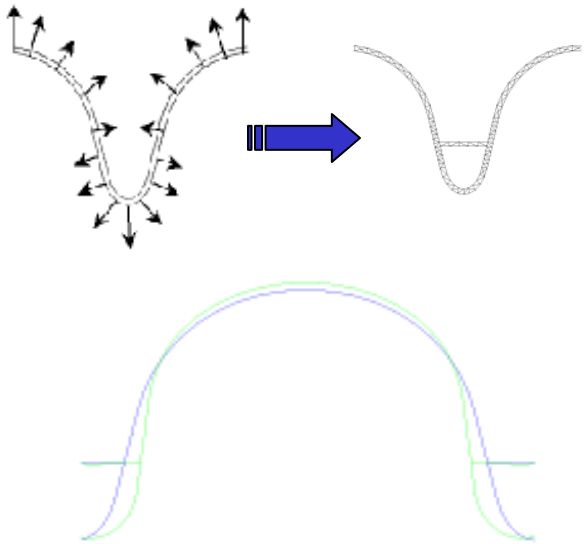


Mechanical aspects (2)

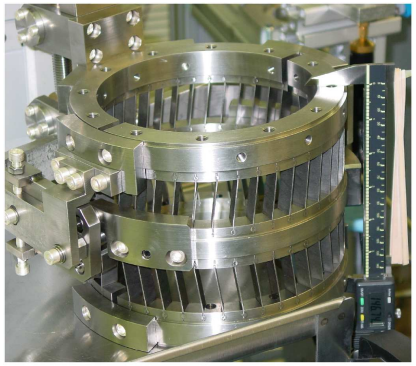
- **Stiffness: a compromise between Lorentz-force detuning and tunability.**

$$P = \frac{\mu_0 H_s^2 - \varepsilon_0 E_s^2}{4}$$

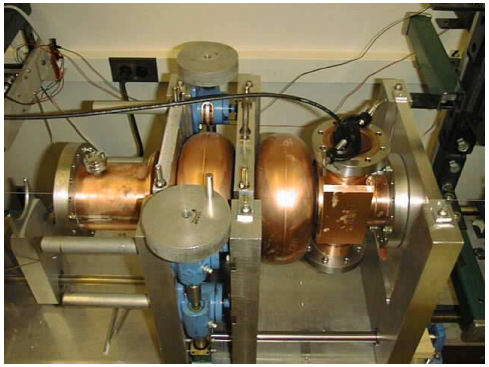
$$\frac{\Delta f}{f_0} = -\frac{1}{4U}\iiint\left(\mu_0 H^2 - \varepsilon_0 E^2\right)dV$$



- **Tunability: tuning for field flatness (multi-cell cavities) and for correct frequency.**

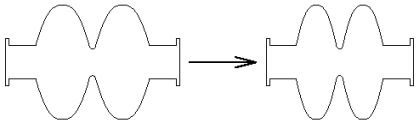


Blade tuner

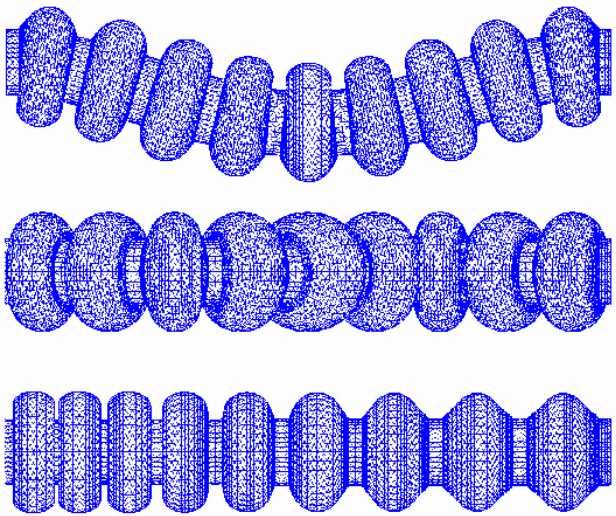


Cavity tuning set-up

Mechanical aspects (3)



- **Vibration mode frequencies and Qs: sensitivity to microphonic noise.**

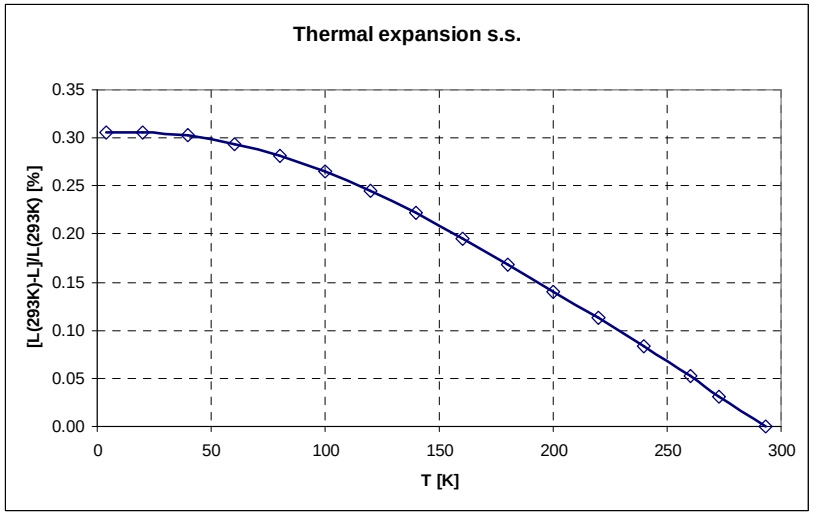


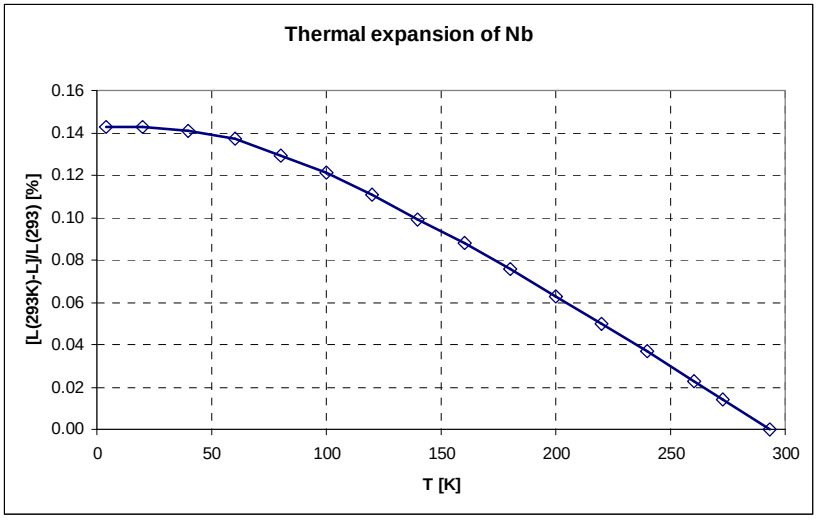
One more step

- RF and mechanical optimizations are complete, but we are not ready yet to proceed with the production drawings: cavity shape was optimized for low temperature, vacuum and certain tension or compression due to frequency tuner force, but fabrication will be at room temperature, in air and with no tuner forces!
- All these factors must be taken into account to determine the cavity shape for fabrication and its frequency at room temperature.

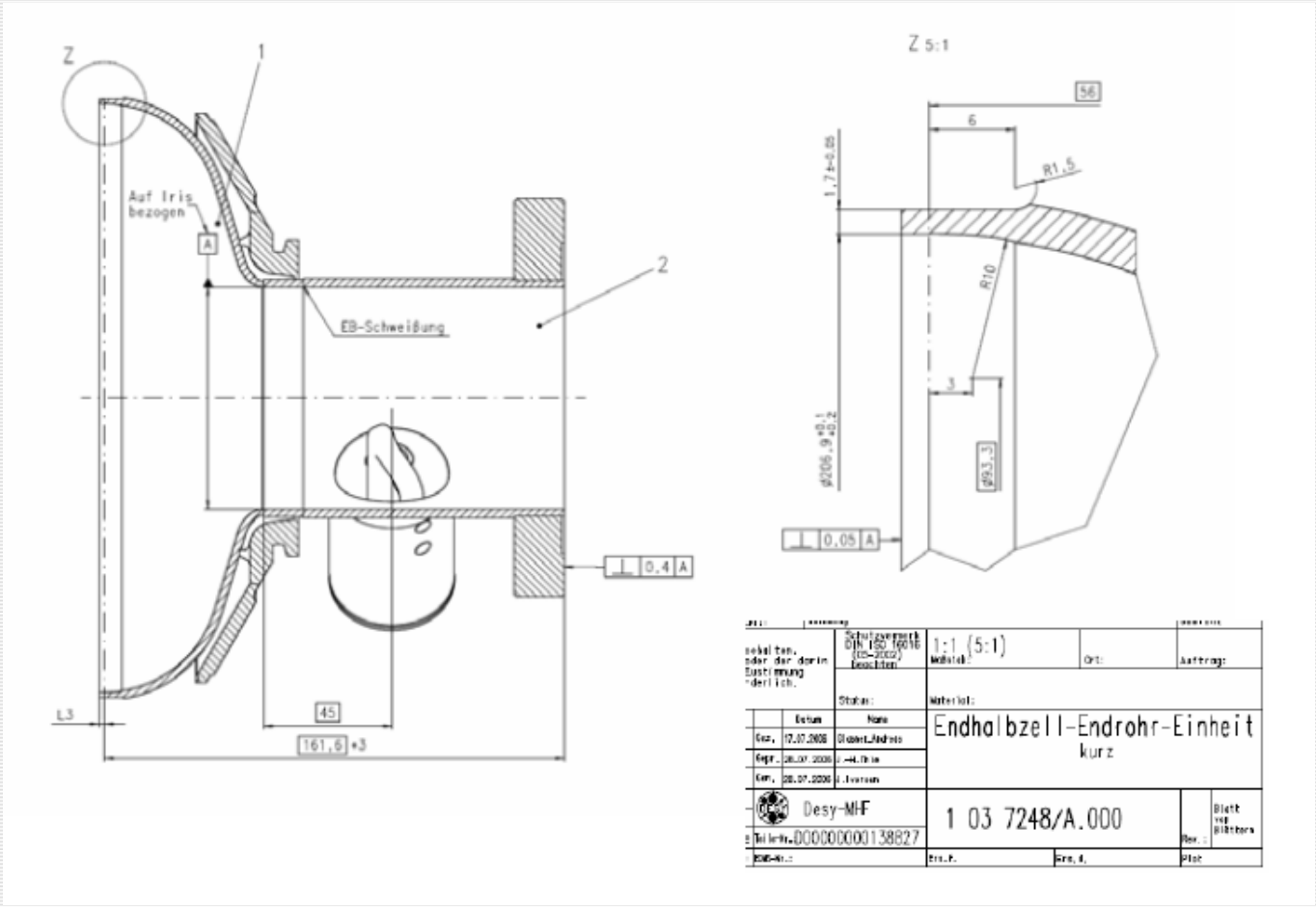
$$\varepsilon_r^{air} = 1 + \frac{210}{T}\left(P + 48\frac{P_s}{T}H\right)\cdot 10^{-6},$$

where P is the pressure in Torr, T is the temperature in K, P_s is the saturated pressure of water, H is relative humidity in percent.



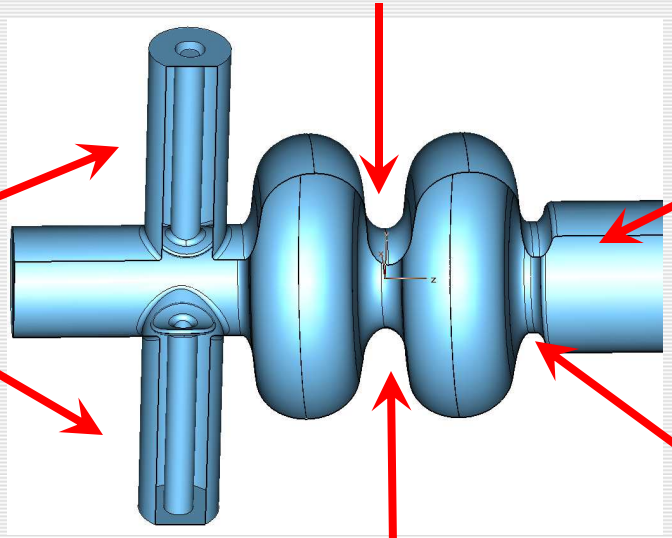


An example of production drawing



Cavity design example: Cornell ERL injector

2 cells:
Upper limit set by 100 kW coupler power (max. energy gain per cavity)
Lower limit: Maximum field gradient < 20 MV/m



Symmetric twin input coupler: to avoid transverse kick

Large 106 mm diameter tube to propagate all TM monopole HOMs and all dipole modes

Reduced iris to maximize R/Q of accelerating mode: to reduce cryogenic load

f_{acc} = 1.3 GHz (TESLA)
Optimum: 1 GHz – 1.5 GHz
Lower f: Larger cavity surface, higher material cost,…
Higher f: Higher BCS surface resistance, stronger wakes, …

What have we learned?

- Choices in cavity design strongly depend on a particular accelerator requirements.
- RF codes and fast computers not only assist in the design process, but allow to use multi-variable optimization algorithms .
- Careful attention should be paid to cavity interfaces with other components of a cryomodule.
- Mechanical aspects of cavities are very important and should be carefully modeled using appropriate codes.

✪ Next lecture: cryomodule design.