



***S. Belomestnykh***

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

- **Lecture 1** *Introduction: advantages and limitations of SRF technology*





- ❑ Dr. Dave Meidlinger is a teaching assistant for this class. He will help me and you in the course of this week during the review sessions, Computer Lab project and Study Room time. He will also be grading some of your homework and final exams.
- ❑ We will have three classes in the morning: two lectures, from 9:00 am to 11:00 am, and a computer lab session from 11:00 am to noon.
- ❑ During the computer lab sessions you will learn how to use **ABCI** and **CLANS** to create cavity shapes and calculate wake potentials and cavity eigenmodes. Also, you will use software like **Matlab**, **MathCAD** and **Excel** to write scripts for homework problems and create and modify input files for **ABCI** and **CLANS**.
- ❑ The afternoon classes will begin at 2:00 pm and will consist of one lecture and one review session and will end between by 5:00 pm.
- ❑ The Study Room is open for you from 7:00 pm to midnight. Dave and I will spend some time there every evening so you can get help. During this time you can also use the Computer Lab if you didn't bring a laptop with you.
- ❑ We will post lectures, homework assignments and solutions on the course web site <http://www.lns.cornell.edu/~sab/uspas09> as we are making progress through the course.
- ❑ The homework is due by 9:00 am next day. You can submit it via email (preferred) or hand in paperwork before the first lecture.
- ❑ The results of the Computer Lab project are due by 9:00 am on Friday.



## Logistics (2)

- ❑ A textbook *RF Superconductivity for Accelerators* by H. Padamsee, J. Knobloch and T. Hays will be used extensively.
- ❑ In lectures, I also will use materials from the new book by H. Padamsee, *RF Superconductivity: Science, Technology, and Applications*, which is recommended for further reading on the subject.



## Monday – Thursday

- 09:00 – 09:50      Lecture 1
- 10:00 – 10:50      Lecture 2
- 11:00 – noon        Computer Lab session
- noon – 14:00        Lunch break
- 14:00 – 15:20      Lecture 3
- 15:30 – 17:00      Review session, homework assignment
- 19:00 – ...         Study room

**on Friday the classes will end at noon**



## Monday

- ❑ *Introduction: advantages and limitations of the SRF technology*
- ❑ *Basics of microwave engineering: cavity fields and modes, figures of merits, coupling to transmission lines, computer codes*
- ❑ *Introduction to ABCI and CLANS, practice in creating cavity shapes and meshes with the codes*
- ❑ *Basic concepts of RF superconductivity: RF losses and related figures of merits,  $Q$  vs  $E$ ,  $Q$ -slope*

Relevant chapters from the textbook: 1, 2, 3, 4, 5, 9 & 11



## Tuesday

- Related phenomena: field emission, multipacting, ponderomotive effects*
- Brief overview of storage rings, ERLs and linac-based FELs: SRF systems requirements and challenges*
- Computer Lab project*
- Beam-cavity interaction: fundamental mode beam loading, wake fields and higher-order modes, instabilities and cures, bunch length manipulation*

Relevant chapters from the textbook: 10, 12, 13, 15, 17 & 20



## Wednesday

- Systems engineering approach to superconducting RF system design: interconnectedness, cost optimization*
- Computer Lab project*
- Cavity design and optimization*
- Cryomodule design*

Relevant chapters from the textbook: 2



## Thursday

- Input couplers*
- HOM dampers*
- Computer Lab project*
- Frequency tuners*

Relevant chapters from the textbook: 16, 18 & 19

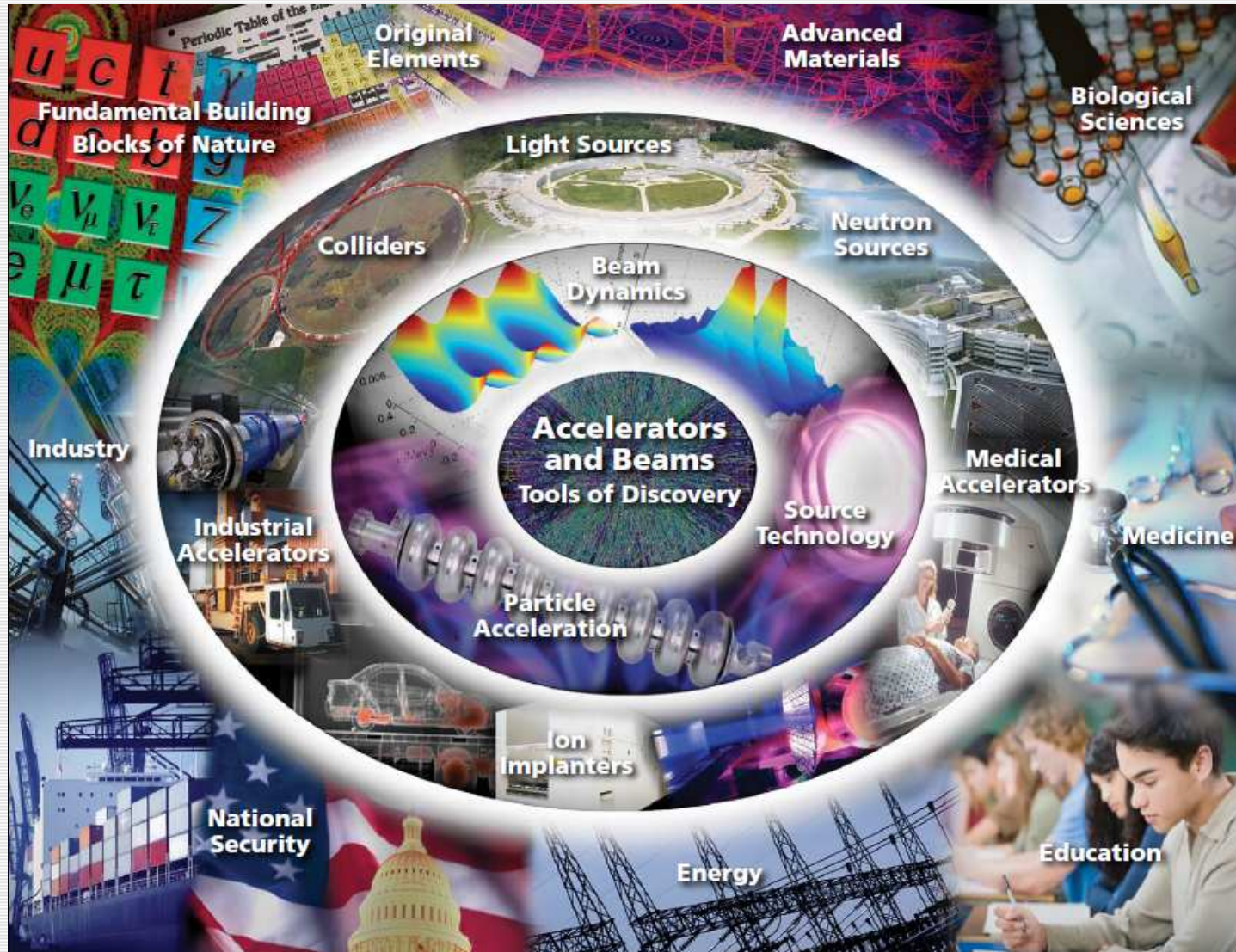




## Friday

- Cavity fabrication techniques, preparation & testing*
- Other systems: refrigeration and cryogen distribution; high-power RF; low-level RF controls*
- Overview of remaining challenges, new materials, existing and future SRF accelerators*
- Review of the take-home final exam; **deadline: June 30th***

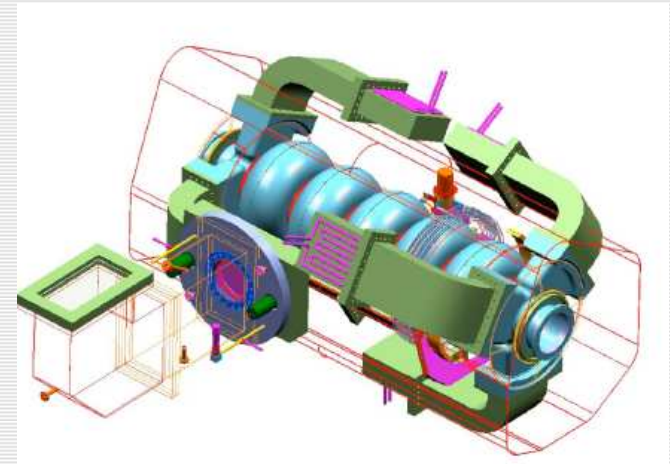
**Relevant chapters from the textbook: 6, 7, 8, 13, 14, 20 & 21**





# Accelerating RF systems

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

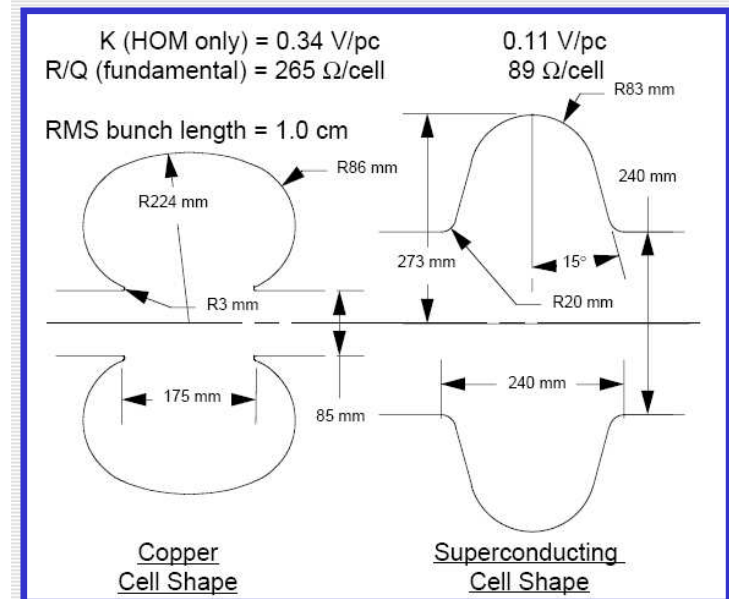






# Benefits of RF superconductivity

- The development of superconducting (SC) cavities for accelerators has enabled new applications not previously possible with normal conducting (NC) structures.
- SC cavities excel in applications requiring continuous wave (CW) or long-pulse accelerating fields above a few MV/m.
- For NC cavities (usually made of copper) power dissipation in cavity walls is a huge constrain in these cases → cavity design is driven by this fact, optimized for lowest possible wall dissipation → small beam aperture.
- The surface resistance of SC cavities is many orders of magnitude less than that of copper → SC accelerating system is more economical: less wall plug power, fewer cavities required, etc.
- Additional benefit: the cavity design decouples from the dynamic losses (wall losses associated with RF fields) → free to adapt design to a specific application.
- The presence of accelerating structures has a disruptive effect on the beam and may cause various instabilities, dilute beam emittance and produce other undesirable effects. Fewer SC cavities → less disruption. SC cavities can trade off some of wall losses to a larger beam pipe → reduce disruption more.





Refrigerator's Coefficients of Performance (COP) for different temperatures.

$$COP_{real} = 1 / (K * \eta_{CARNOT})$$

$$\eta_{CARNOT} = T / (300 - T)$$

Refrigeration Temperature	Carnot 1/ $\eta$ IDEAL WORLD	XFEL-Spec REAL WORLD	% Carnot
2 K	149	870	17
5 K	79	220	36
40 K	7	20	33

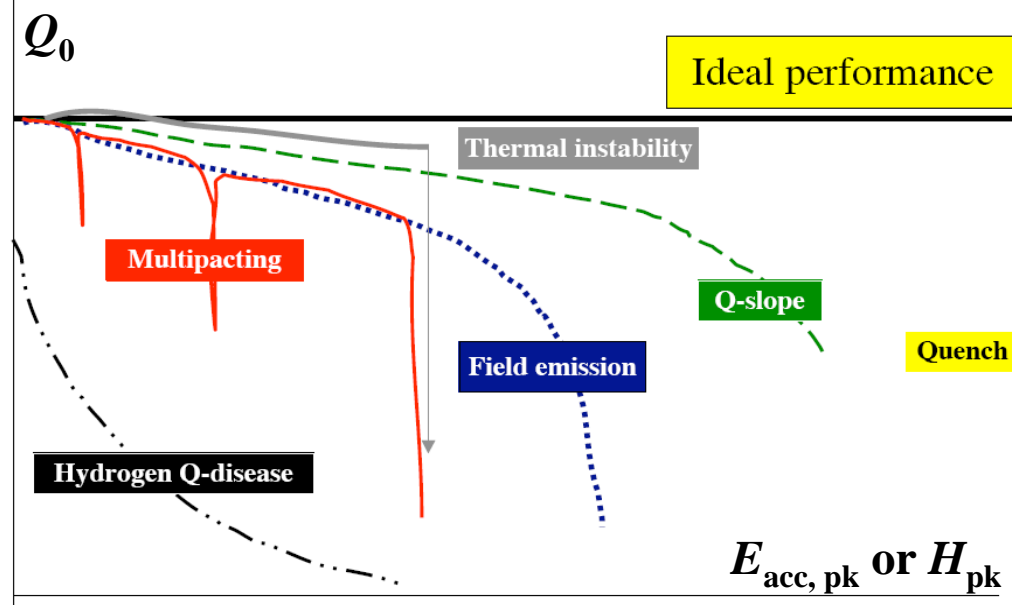
$$P_{AC} = COP \times (P_{dynamic} + P_{static})$$

Still more efficient than normal conducting RF!



# SC cavity performance limitations

- Maximal surface magnetic field → fundamental limitation, ~60 MV/m for elliptical cavity shapes.
- Maximal surface electric field → field emission → can be cured by applying proper preparation techniques: clean room (dust-free) assembly, high-pressure DI water rinsing (HPR).
- Thermal quench → use of high-purity material (RRR) to improve thermal conductivity, material quality control to avoid mechanically damaged surfaces, particulate free assembly.
- Multipacting → use of elliptical cell shapes.
- Q-diseases due to lossy niobium hydride → perform acid etch at  $T < 15^\circ\text{C}$ , rapid cooldown, degassing at 600 – 800°C.
- Medium- and high-field Q-slope → still under investigation.
- Long-pulse operation tends to favor the highest reliably achievable gradient (23.6 MV/m for XFEL, 31.5 MV/m for ILC).
- CW operation → cryogenics vs linac cost optimization determines operating gradient (15 – 20 MV/m).





## SRF science & technology for particle accelerators

Beam physics

Superconductivity

Vacuum science

Materials science

Surface science

RF/microwave engineering

Cryogenics

Surface treatment techniques

Cleaning technology

Cavity test methods

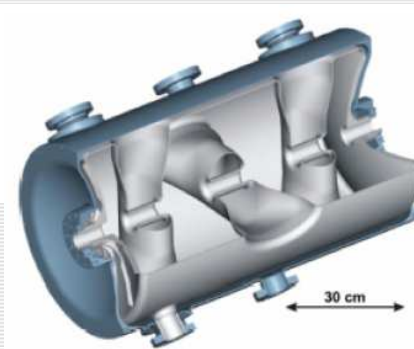
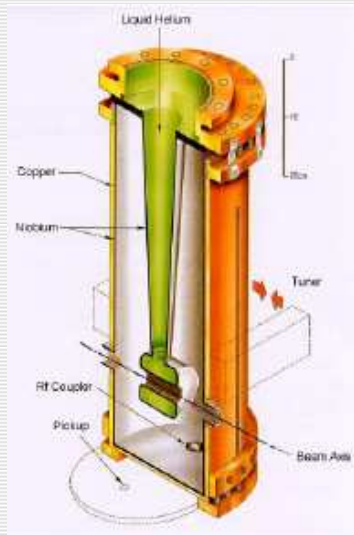
Mechanical engineering



# A sample of SRF cavity shapes

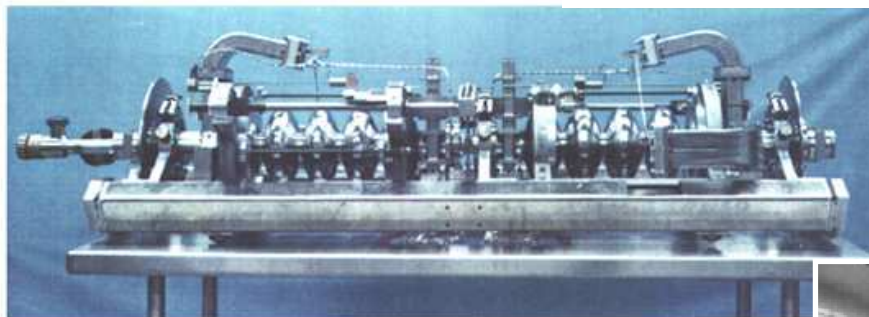
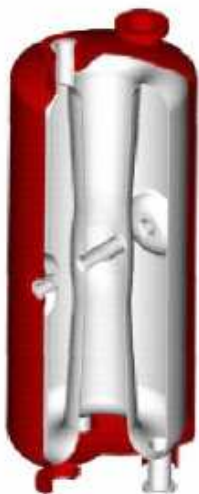
## Low $\beta$ :

- a zoo of structures (QWR, split-ring, RFQ, HWR, spoke, H-type,...)

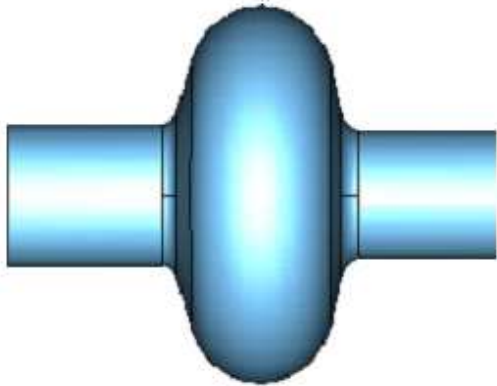


## High $\beta$ :

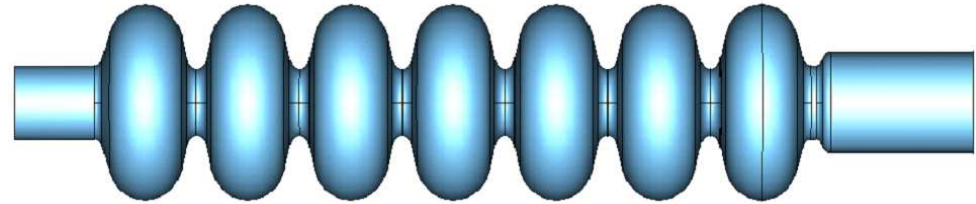
- mostly various elliptical shape structures







Single-cell elliptical cavity



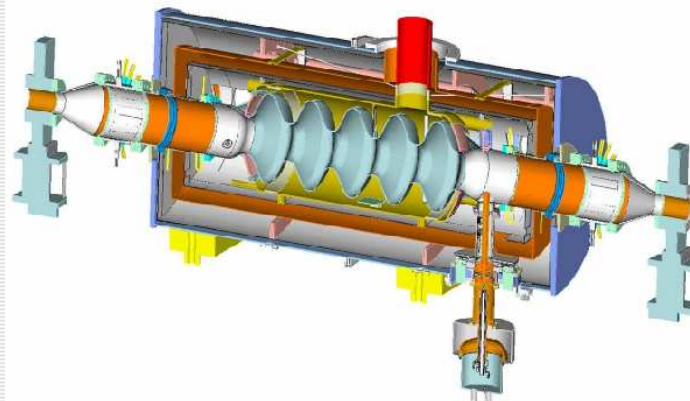
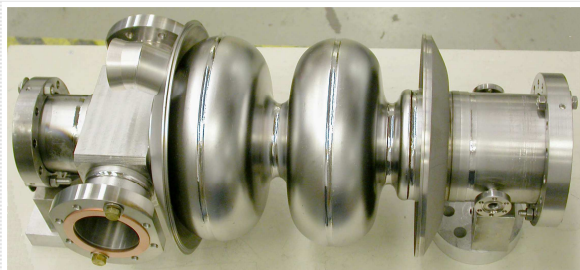
Multicell elliptical cavity

- Predominantly cavities with elliptical cells are used to accelerate particles with  $\beta \sim 0.6 \dots 1$ .
- For standing wave cavities with  $\pi$ -mode the length of the cavity cells is  $L = \beta \lambda / 2$ .
- Other cavity shapes are better suited for lower  $\beta$ : half-wave and quarter-wave coaxial resonators, spoke cavities and others.
- High- $\beta$  cavities operate at higher frequencies: 200... 3000 MHz. Low- $\beta$  cavities tend to operate at lower frequencies though there is an overlap.



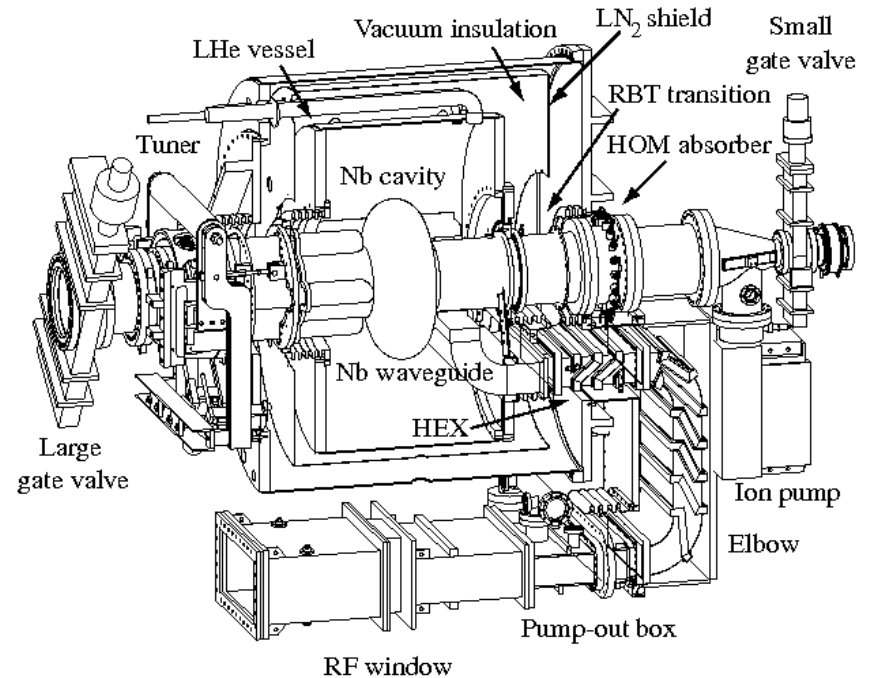
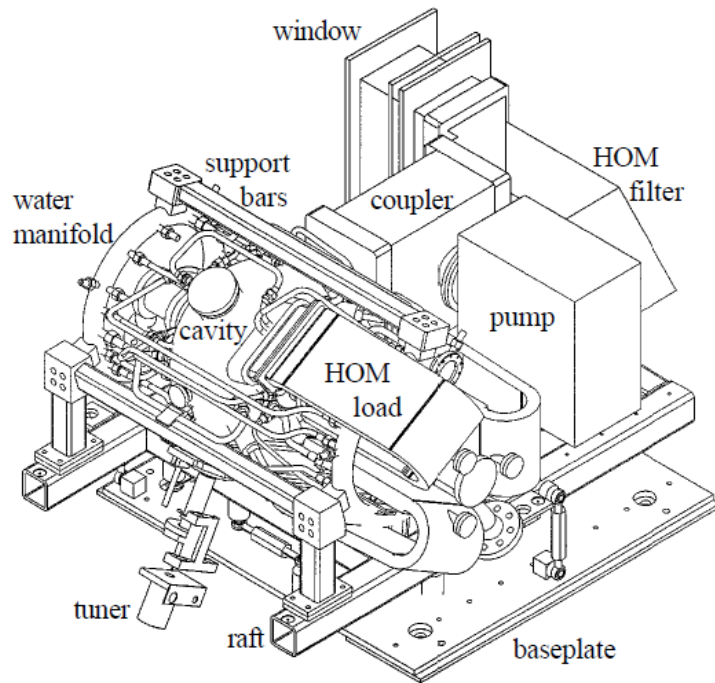
# Examples of high- $\beta$ systems

	Examples	Accelerating gradient	RF power	HOM damping
<b>Pulsed linacs</b>	XFEL, FLASH	High ( $> 20$ MV/m)	High peak ( $> 250$ kW), low average ( $\sim 5$ kW)	Moderate ( $Q = 10^4 \dots 10^6$ )
<b>Low-current CW linacs</b>	JLab FEL, ELBE, CEBAF	Moderate to low ( $8 \dots 20$ MV/m)	Low ( $5 \dots 15$ kW)	Relaxed
<b>High-current ERLs</b>	Cornell ERL, Electron cooler for RHIC	Moderate ( $15 \dots 20$ MV/m)	Low (few kW)	Strong ( $Q = 10^2 \dots 10^4$ )
<b>High-current ERL injectors</b>	Cornell ERL injector, JLab FEL 100 mA injector	Moderate to low ( $5 \dots 15$ MV/m)	High ( $50 \dots 500$ kW)	Strong ( $Q = 10^2 \dots 10^4$ )
<b>High-current storage rings</b>	CESR, KEKB, LHC, CLS, TLS, BEPC-II, SOLEIL, DIAMOND, SRRF	Low ( $5 \dots 10$ MV/m)	High (up to 400 kW)	Strong ( $Q \sim 10^2$ )





## Which cavity to choose?





## SLAC B-factory normal conducting cavities

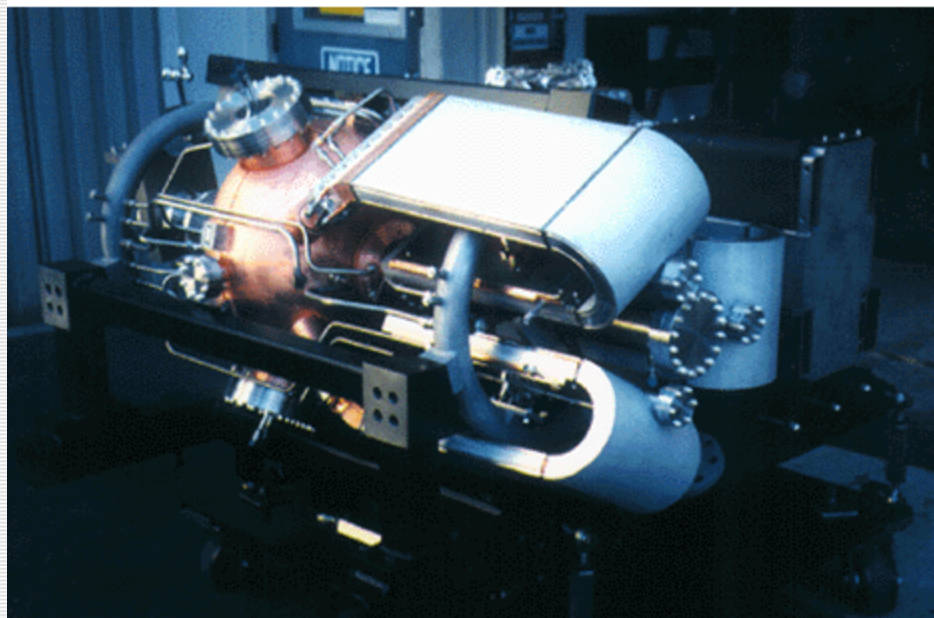


Figure 4. Twenty-six high-power radio-frequency cavities in groups of two and four will be attached to 1-megawatt microwave generators to maintain the electron and positron beams at their proper energy levels in the high- and low-energy rings. One of the spherical cavities, machined at Livermore, is shown here at the Stanford Linear Accelerator Center, where it has been attached to a host of other parts.

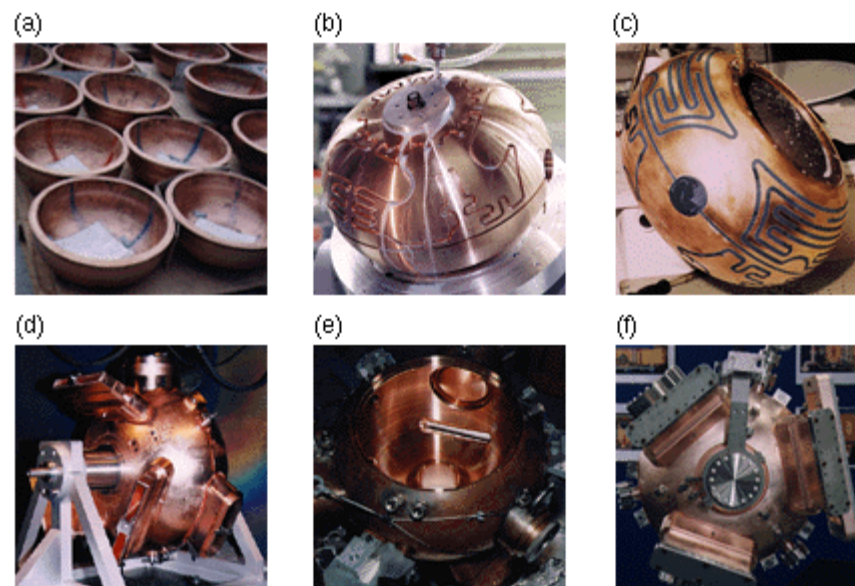


Figure 5. Six of the many steps in the radio-frequency cavity manufacturing process. (a) The radio-frequency cavities are formed from 2.54-centimeter- (1-inch-) thick copper plates. (b) The machined bowls are electron-beam welded to form a cavity; then water channels are cut into the outer contour. (c) Wax is placed into the water channels before the cavity is plated with ultrapure copper approximately 1 centimeter (three-eighths inch) thick. (d) Several ports are attached to each cavity by electron-beam welding. (e) The cavity's surface is finished using a Livermore diamond-turning machine. (f) The final product is cleaned for ultrahigh-vacuum use and made ready for shipment to the Stanford Linear Accelerator Center for integration with other components.





## CESR-type superconducting cavities

