
Photo:
Reidar Hahn

Non-elliptical cavities

Special thanks to R. Laxdal (TRIUMF) and A. Facco (INFN & FRIB)


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Outline

- Why non-elliptical cavities?
- Applications and trends
- Cavity concepts
- Examples of TEM cavities
- Basic principles of acceleration – figures of merit, beam dynamics for low beta
- Cavity beta/frequency choice
- Other cavity types
- Design issues
- Fabrication
- Cryomodule
- On-going developments


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Useful relations

Protons/H- ($A = 1, Q = 1$)

$$p = \gamma\beta m_0 c = \frac{\gamma\beta E_0}{c}$$

$$E = W + E_0 = \gamma E_0$$

$$W = (\gamma - 1)E_0$$

$$F_\xi = |e|\xi$$

$$W = |e| V_{\text{eff}} \cos\varphi$$

Heavy Ions (A, Q)

$$p = \gamma\beta A m_0 c = \frac{\gamma\beta A E_0}{c}$$

$$E = W + AE_0 = \gamma A E_0$$

$$W/A = (\gamma - 1)E_0$$

$$F_\xi = Qe\xi$$

$$W/A = (Q/A)\, V_{\text{eff}} \cos\varphi$$


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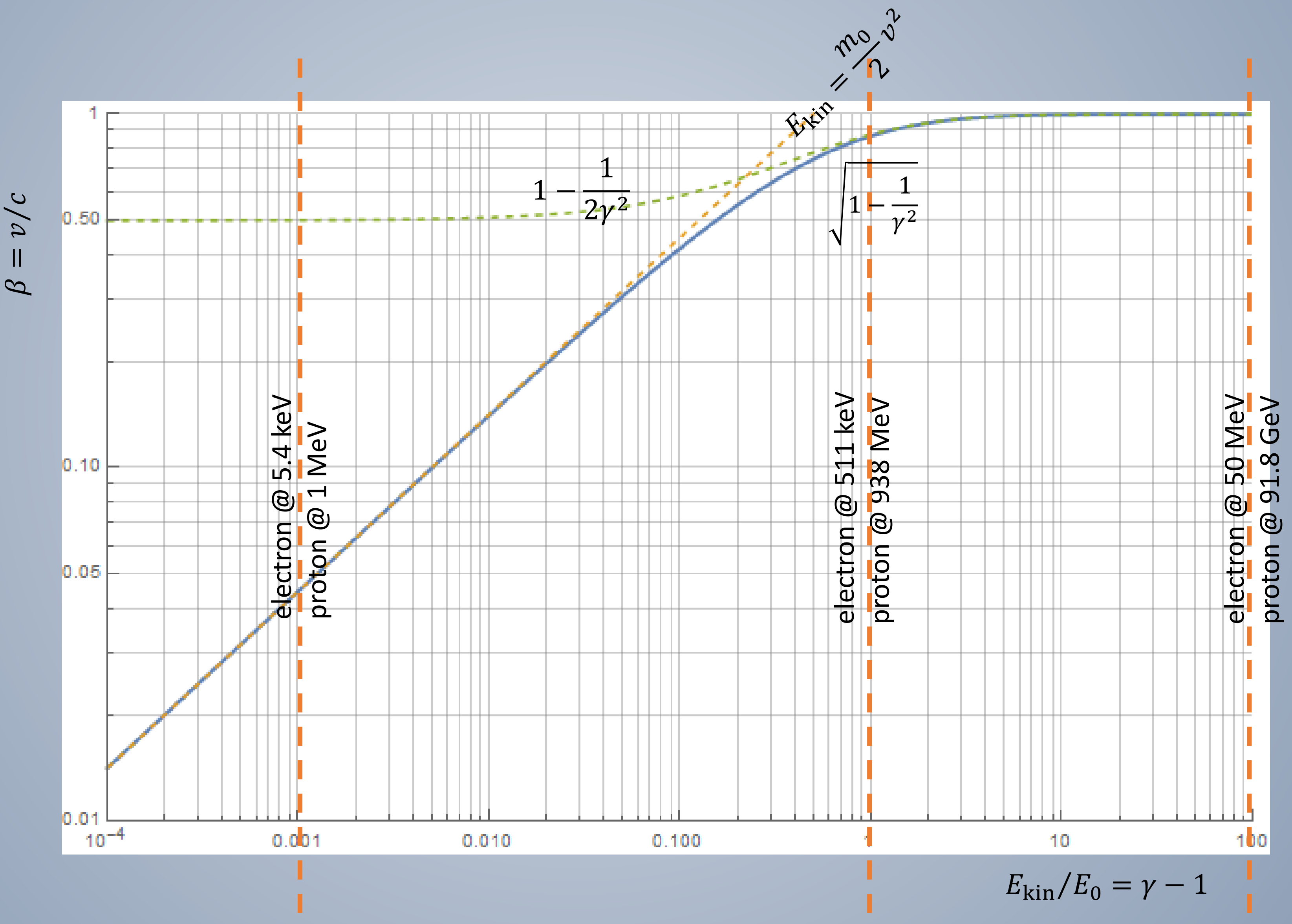
Particle velocity vs. kinetic energy

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Accelerating electrons vs. accelerating ions

Example: a 300kV DC bias is enough to get electrons going at a relativistic speed (ie E_o=511keV so γ=1.58, v/c=β=0.78) – for protons a 300kV bias only produces v/c=β=0.025 – for A=30 v/c=β=0.005

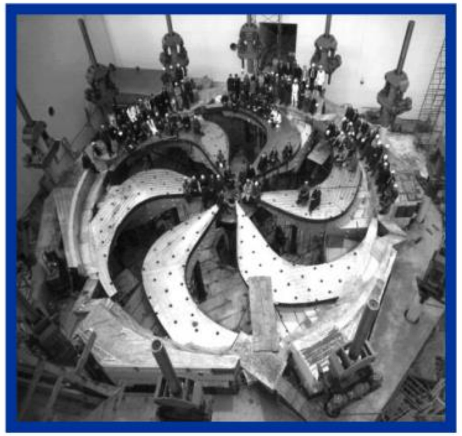
- Electron – 0.511MeV/c^2
  - 300kV - γ=1.58, v/c=β=0.78
  - 550MeV - γ=1011, v/c=β=1

8 gm

ARIEL 300kV e-gun

- Protons – 938 MeV/c^2
  - 300kV - γ=1.003, v/c=β=0.025
  - 550MeV - γ=1.58, v/c=β=0.78

160 kgm



TRIUMF 500MeV cyclotron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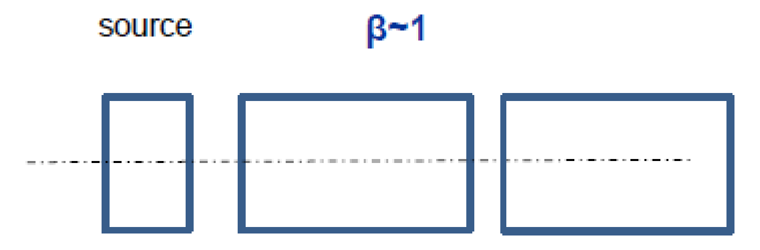
Accelerating electrons vs. accelerating ions

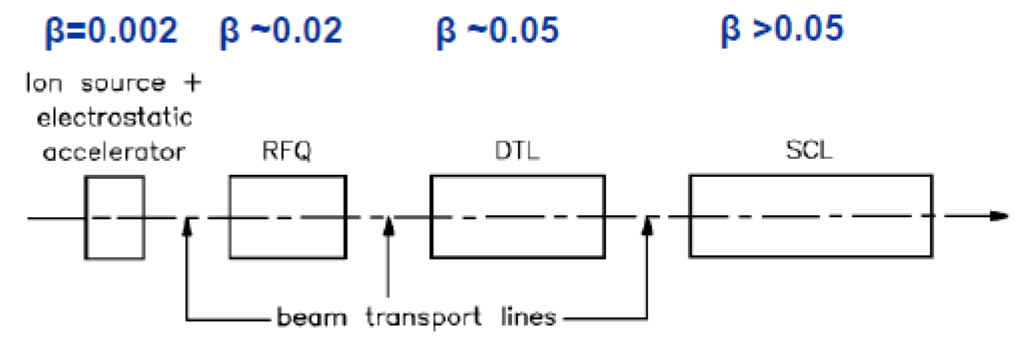
Electrons

Common building blocks – all designed for $\beta = 1$.



Ions

Various building blocks – different technologies, each optimized for a certain velocity range

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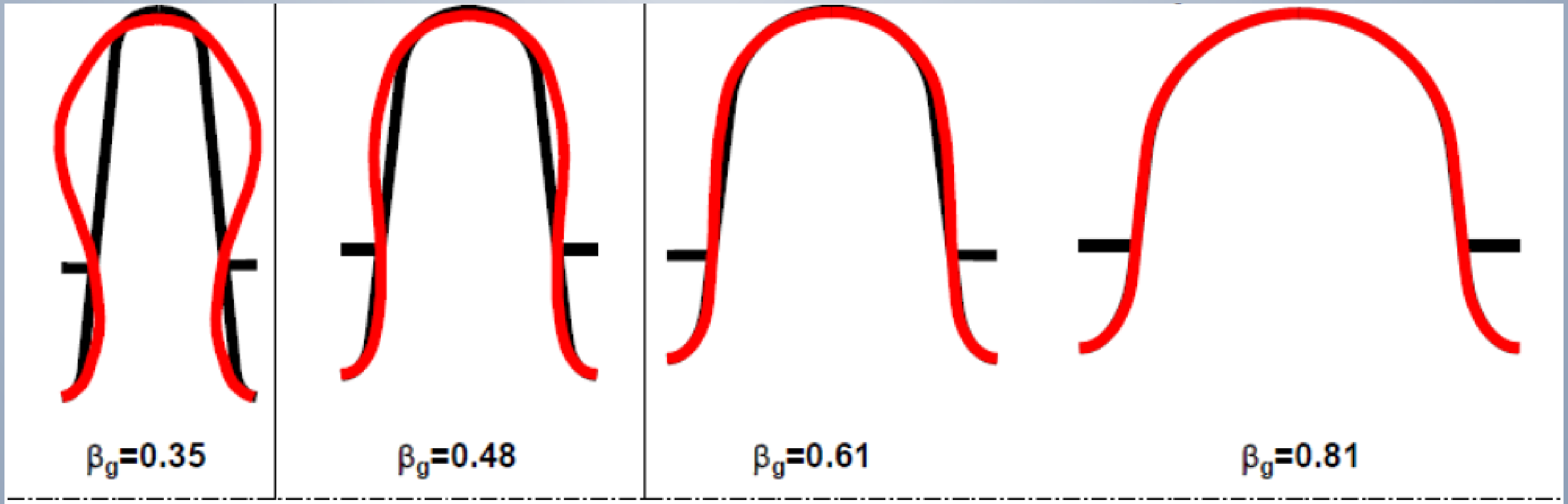
Limitations of elliptical cavities

- Elliptical cavities have been designed starting at $\beta \geq 0.5$ for CW applications, for $\beta \geq 0.6$ for pulsed (SNS, ESS).
- The π-mode requires cell-to-cell distance of $\beta\lambda/2$, but outer diameter $\approx 0.9\ \lambda$, i.e. at low β the cavity looks more like bellows, sensitive to LFD!

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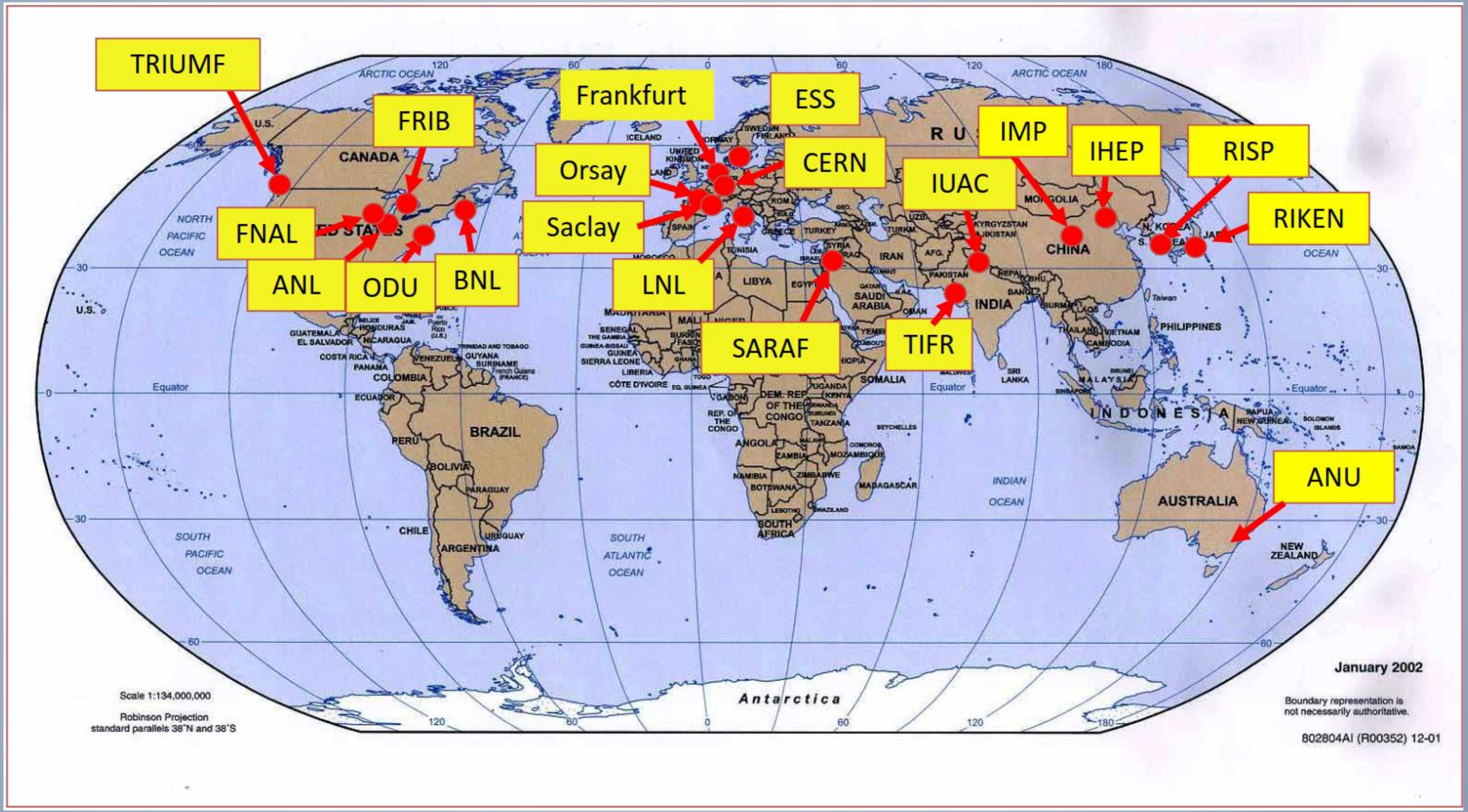
Non-elliptical SRF Community around the world



Scale 1:134,000,000
Robinson Projection
standard parallels 38°N and 38°S

January 2002

Boundary representation is not necessarily authoritative.

802804AI (R00352) 12-01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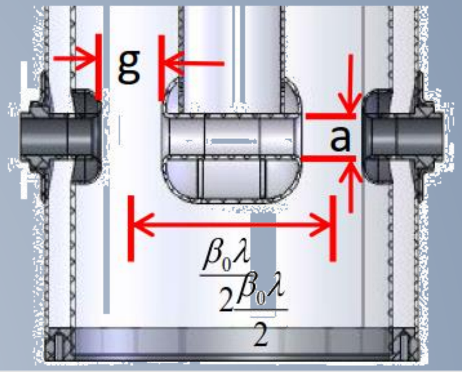
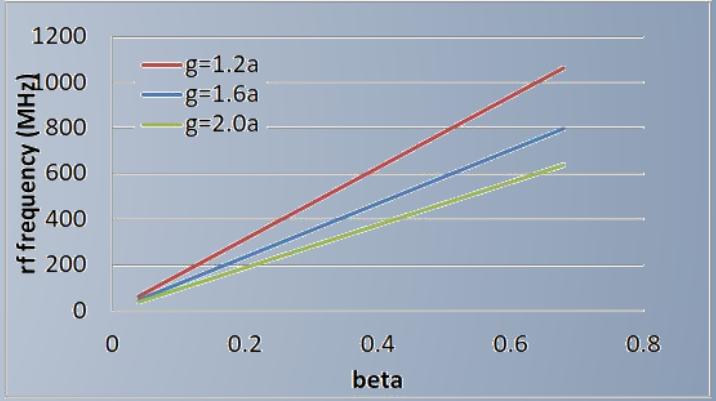
Resonator types for low beta acceleration

- Quarter wave resonator (QWR) $\beta \approx 0.04 \ \ldots 0.2$
- Half wave resonator (HWR) $\beta \approx 0.1 \ \ldots 0.5$
- Single spoke resonator (SSR) $\beta \approx 0.15 \ \ldots 0.7$
- Multi-spoke resonator (MSR) $\beta \approx 0.06 \ \ldots 1$
- For comparison: Elliptical cavities $\beta \approx 0.5 \ \ldots 1$



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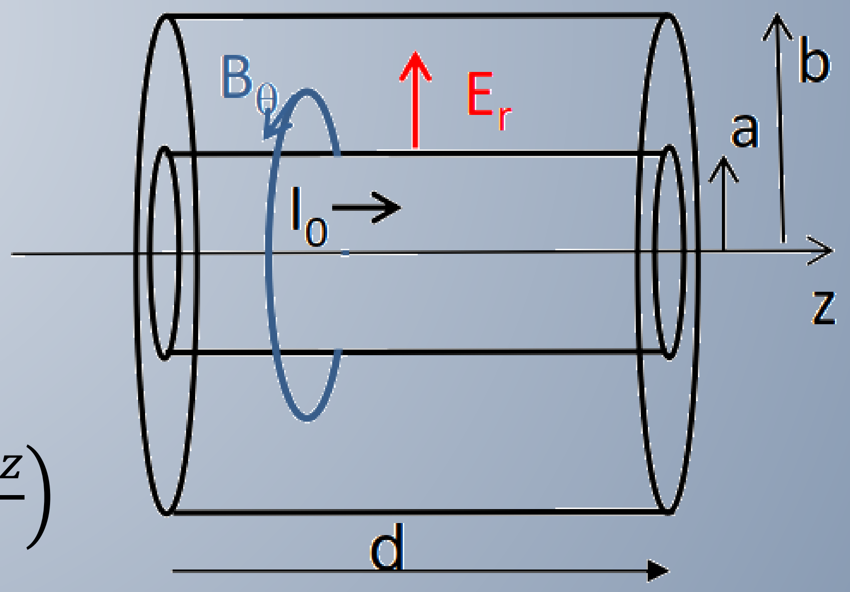
Coaxial resonator

- Consider a coaxial geometry with grounded end plates, an inner conductor with radius a and an outer conductor with radius b.
- A standing wave occurs with E_r vanishing on the end walls at $z = 0$ and $z = d$.
- The remaining non-zero field components are

$$B_\theta = \frac{\mu_0 I_0}{\pi r} \cos\left(\frac{p\pi z}{d}\right),$$

$$E_r = -j2\sqrt{\frac{\mu_0}{\varepsilon_0}} \frac{I_0}{2\pi r} \sin\left(\frac{p\pi z}{d}\right),$$

where $\omega = \frac{p\pi c}{d}$, $p = 1,2,3,\ldots$



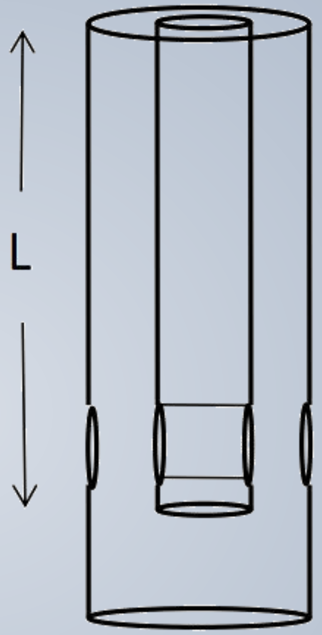
- Peak voltage:

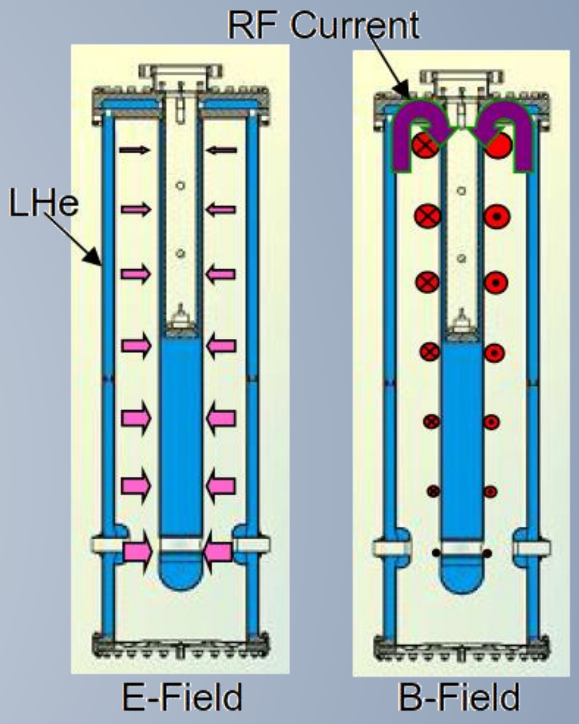
$$\hat{\mathrm{V}}(z) = \int_a^b E_r(z)\,dr = \sqrt{\frac{\mu_0}{\varepsilon_0}} \frac{I_0}{\pi} \ln\frac{b}{a} \sin\left(\frac{p\pi z}{d}\right)$$


Photo:
Reidar Hahn

Quarter-wave resonator (QWR)

- The most popular coaxial TEM mode cavity is the quarter wave resonator – capacitively loaded $\lambda/4$ transmission line
- The inner conductor is open at one end with a resonant length of $(1+2p)\,\lambda/4,\ p=0,1,2,\ldots$
- For acceleration, $p=0$ is chosen.
- The maximum voltage builds up on the open tip – the maximum current at the root.
- A beam tube is arranged near the end of the tip.



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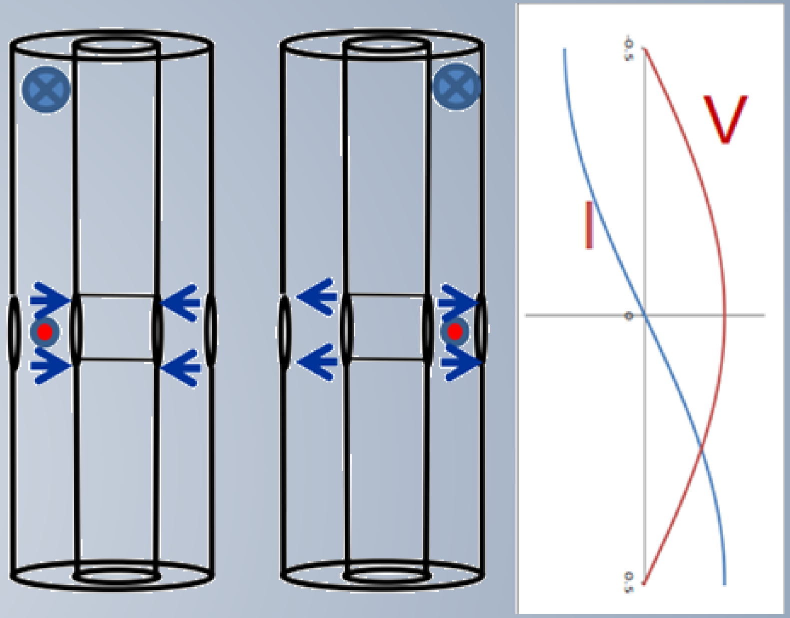
Half-wave resonator (HWR)

- In the HWR the beam port is at the centre of the inner conductor of a coaxial resonator, coincident with the maximum voltage for $p = 1$.
- Magnetic fields loop around the inner conductor with peak fields at the shorted ends.
- For acceleration, $p = 1$ is chosen.

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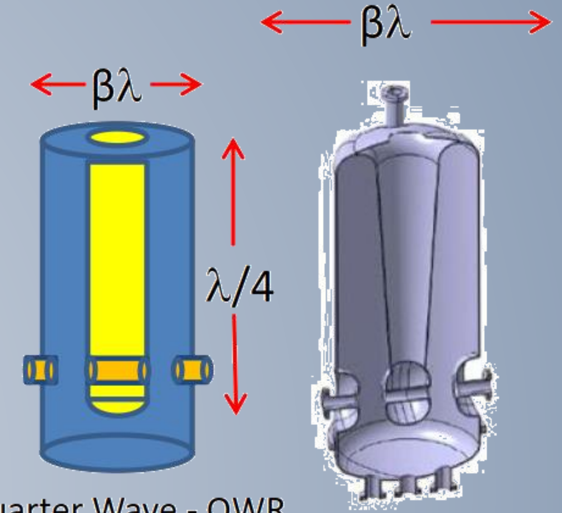
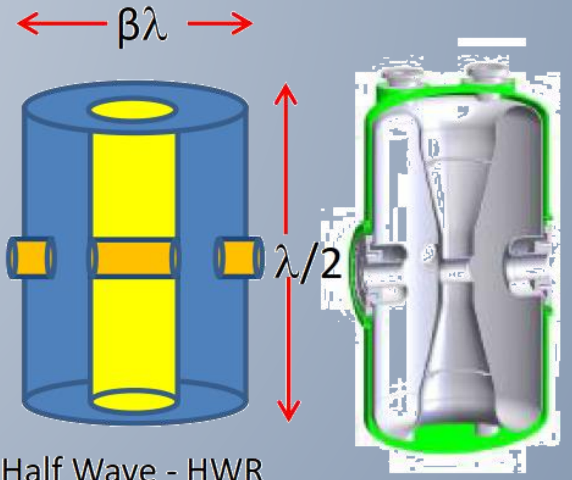
QWR vs. HWR

- QWR is the cavity of choice for low beta applications where a low frequency is needed
  - requires ~50% less structure compared to HWR for the same frequency – rf power loss is ~50% of HWR for same frequency and β_0.
  - allows low frequency choice giving larger longitudinal acceptance.
  - R/Q twice that of HWR.
  - Asymmetric field pattern introduces vertical steering especially for light ions that increases with velocity – avoid use for $\beta_0 > 0.2$.
  - Less mechanically stable than HWR due to unsupported end (microphonics).
- HWR is chosen in mid velocity range ($\beta_0 > 0.2$) or where steering must be eliminated (i.e. high intensity light ion applications)
  - produces twice rf losses for the same β_0 and λ.
  - is 2x longer for the same frequency.
  - Pluses are the symmetric field pattern and increased mechanical rigidity.



Quarter Wave - QWR



Half Wave - HWR


Photo:
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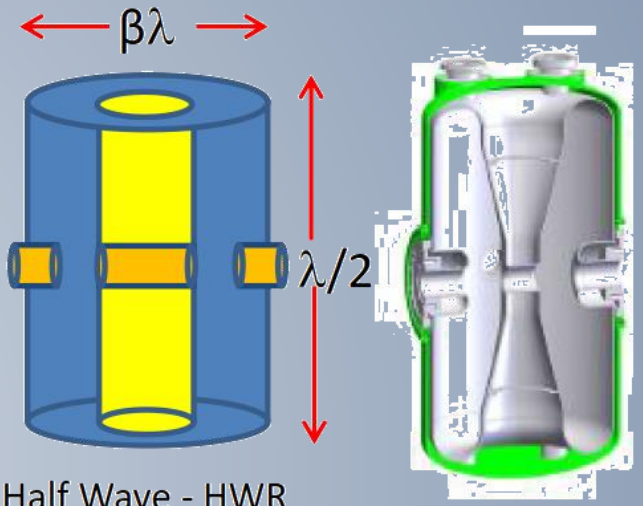
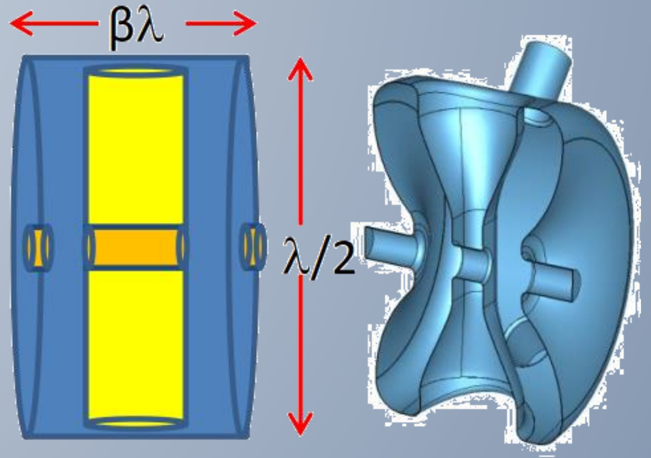
HWR vs. Single Spoke Resonator (SSR)

- A single spoke resonator (SSR) is another variant of the half-wave TEM mode cavity class.
- In HWR the outer conductor is coaxial with the inner conductor (with diameter $\beta_0\lambda$) while in the spoke cavities the outer cylinder is co-axial with the beam tube with diameter $\lambda/2$. It means that for $\beta_0 < 0.5$ the SSR has a larger overall physical envelop than the HWR for the same frequency.
- Thus for low beta applications $(0.1 < \beta < 0.25)$ HWRs are chosen at $\approx 160\ \mathrm{MHz}$, while SSRs are preferred at $\approx 320\ \mathrm{MHz}$.
- The spoke geometry allows an extension along the beam path to provide multiple spokes in a single resonator giving higher effective voltage, but with a narrower transit time acceptance.



Half Wave - HWR



Single spoke - SSR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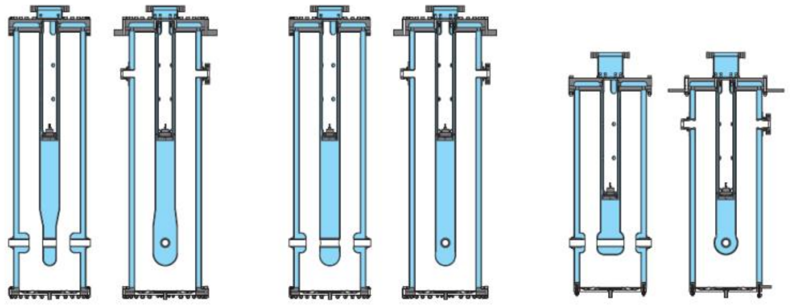
Cavity types – QWRs

TRIUMF ISAC-II Resonators

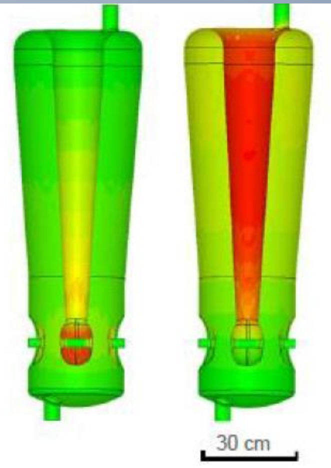


SCB low β (5.7%)
106.08 MHz

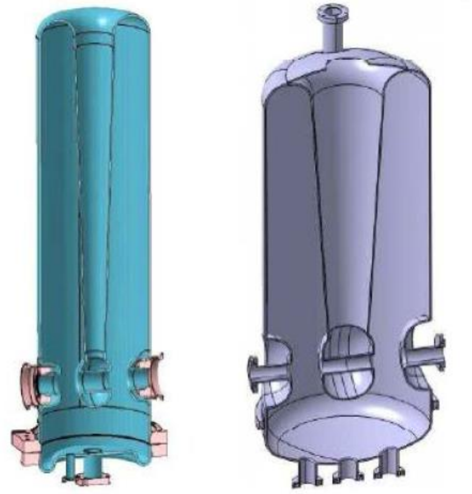
SCB medium β (7.1%)
106.08 MHz

SCC high β (11%)
141.44 MHz

FRIB β=0.041, 0.085 80.5MHz



ANL β=0.077, 0.085 72.5MHz



Spiral-2 β=0.007, 0.12 88.05MHz

RAON β=0.047, 81.25 MHz

Typical range:
$0.04 < \beta < 0.2$
$50\ \text{MHz} \le f \le 160\ \text{MHz}$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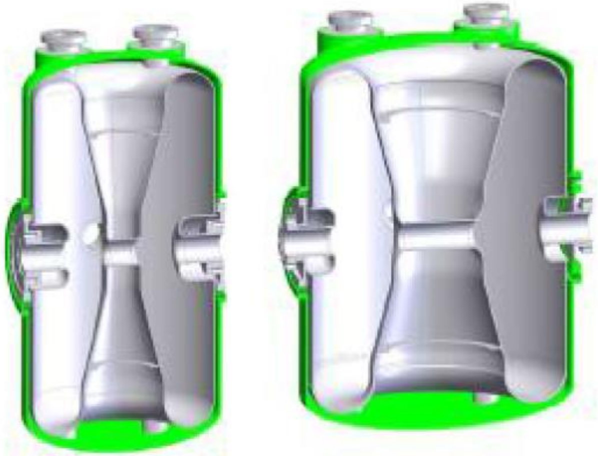
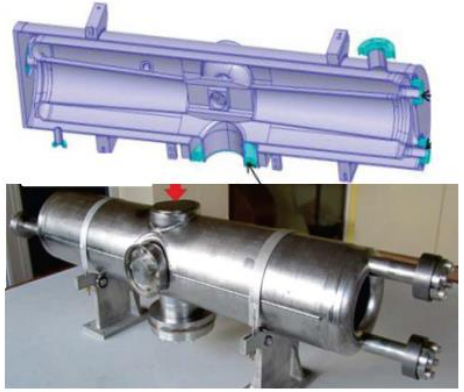
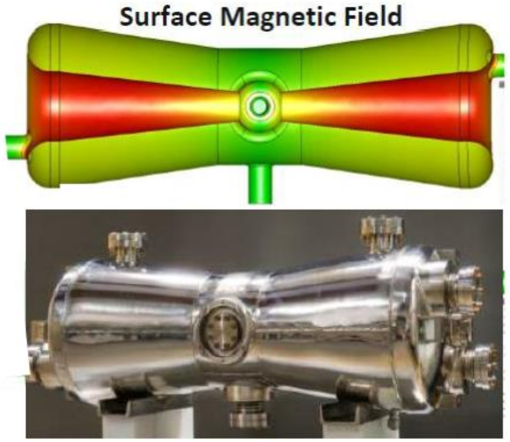
Cavity types – HWRs


IMP β=0.10, f=162.5MHz


FRIB β=0.29, 0.53 f=322MHz


FRIB β=0.29, 0.53 f=322MHz


IFMIF β=0.11, f=175MHz



ANL β=0.112, f=162.5MHz

Typical range:
$0.1 < \beta < 0.5$
$140\ \text{MHz} \leq f \leq 325\ \text{MHz}$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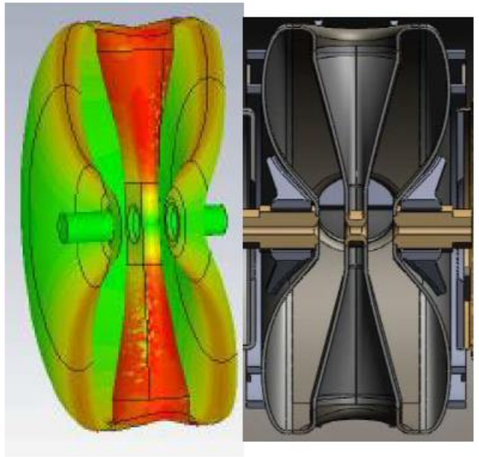
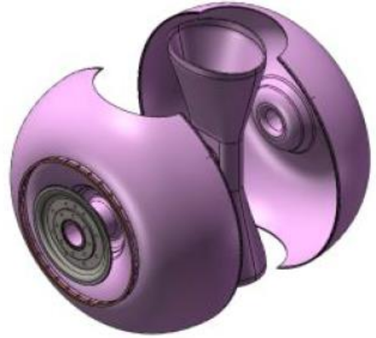
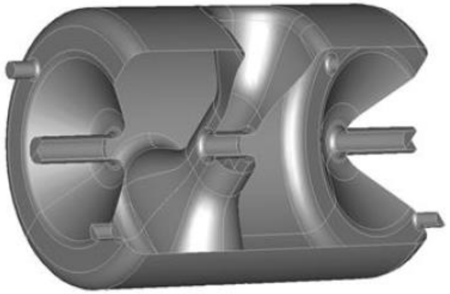
Cavity types – SSRs


IHEP β=0.12, f=325MHz


FNAL β=0.215, f=325MHz


TRIUMF/RISP β=0.3, f=325MHz


325 MHz, $\beta_0 = 0.82$
Single-Spoke Cavity

Typical range:
$0.15 < \beta < 0.7$
$320\ \text{MHz} \le f \le 700\ \text{MHz}$


Photo:
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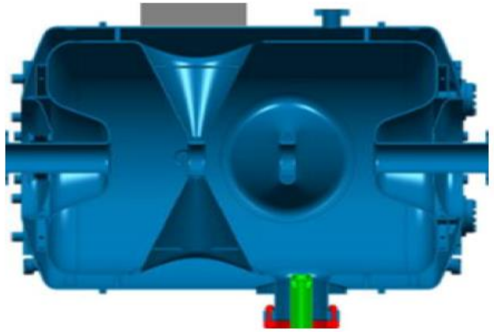
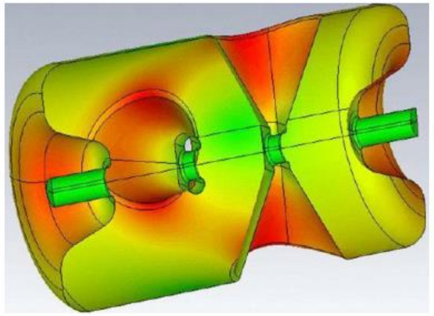
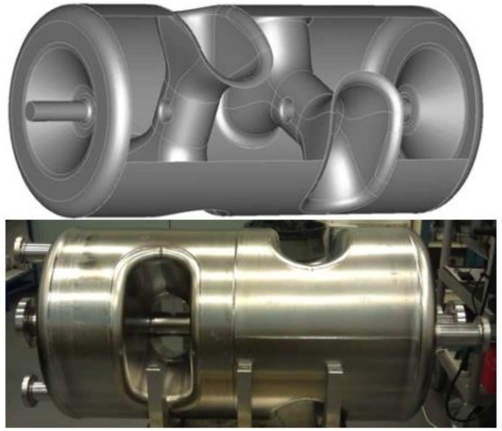
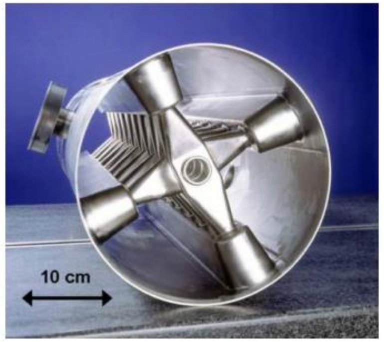
Cavity types – multi-cell


ESS/IPN β=0.50, f=352MHz

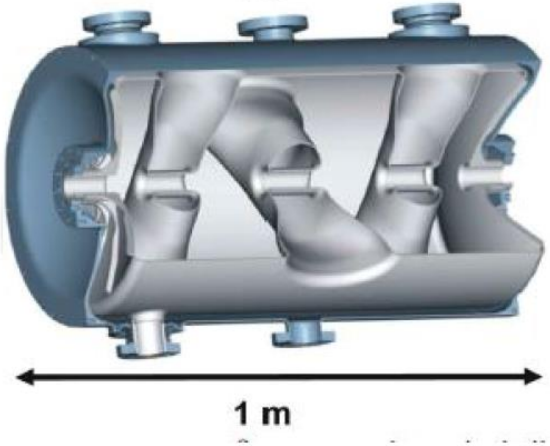




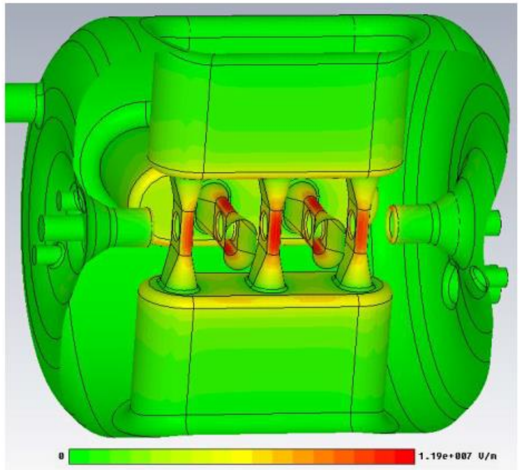


IAP 360 MHz, β_0~0.1
19 gap CH resonator

500 MHz, β_0 = 1
Double-Spoke Cavity



ANL β=0.63, f=345MHz



IMP CH β=0.067, f=162.5MHz

CH: Crossbar H-mode


Photo: Reidar Hahn

Accelerating cavity velocity/frequency chart

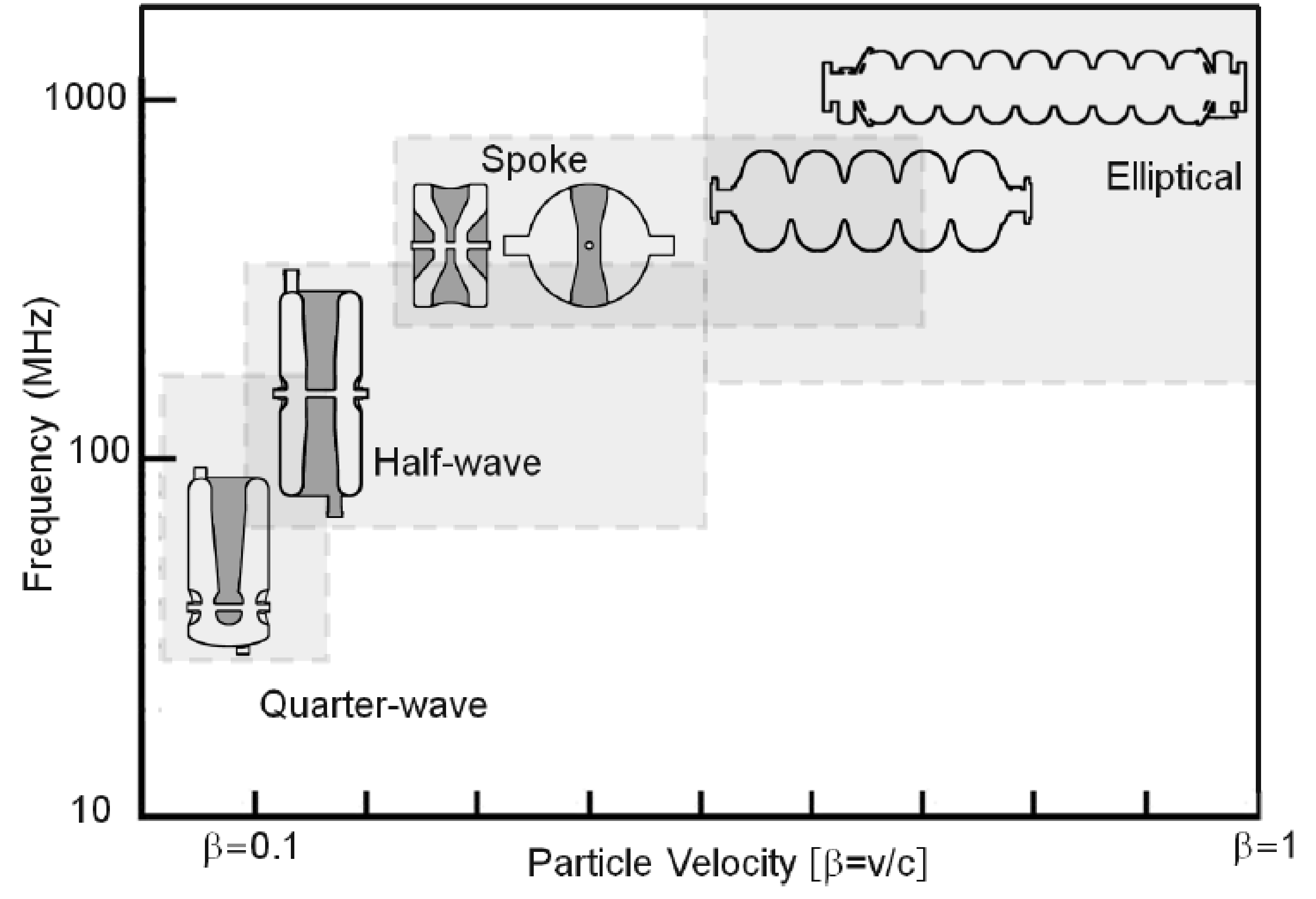
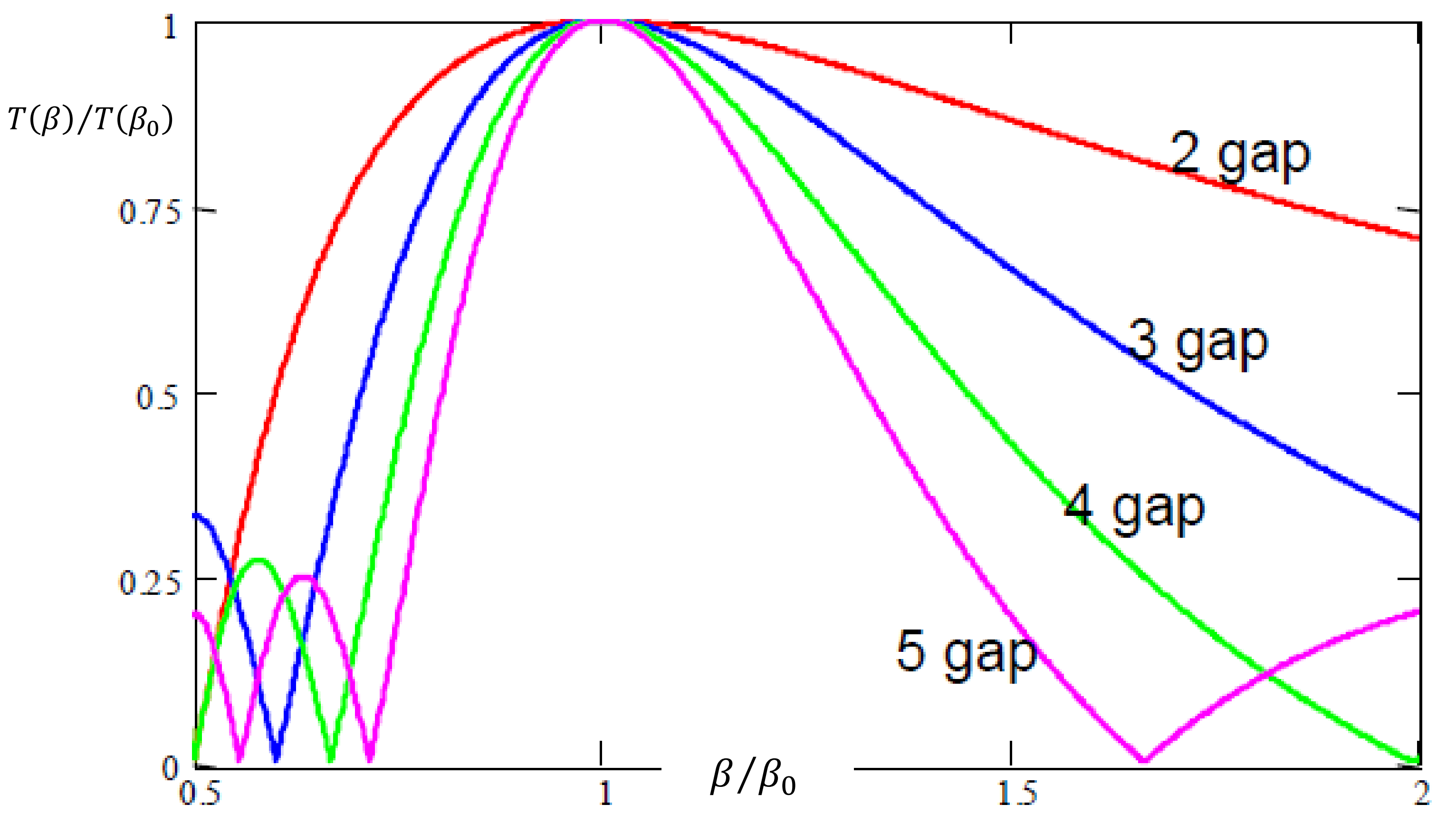


Photo: Reidar Hahn

Transit Time factor vs. β for multiple gaps



Normalized transit time factor curves vs. normalized velocity, for cavities with different number of gap


Photo:
Reidar Hahn

High-β spoke cavities

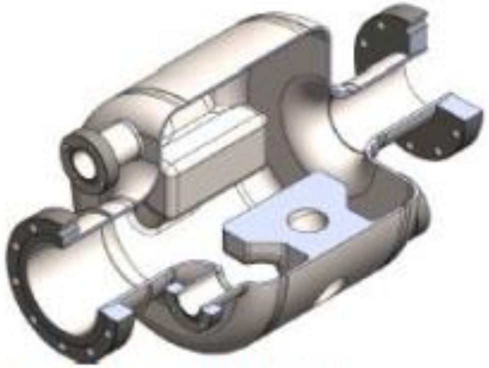
- High velocity spoke cavities with $\beta > 0.8$ are being designed as alternative to elliptical cavities
- Features:
  - relatively compact
    - between 20% and 50% smaller (radially) for low-β cavities
    - for high β diameter close to TM counterparts
  - allows low frequency at reasonable size
  - mechanically stable – high shunt impedance


325 MHz β=0.82 Single Spoke Cavity

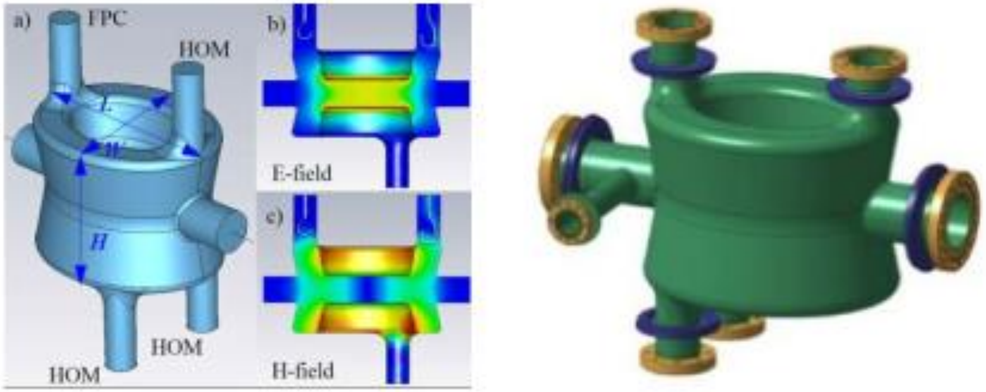

500 MHz β=1.0 Double Spoke Cavity


Photo:
Reidar Hahn

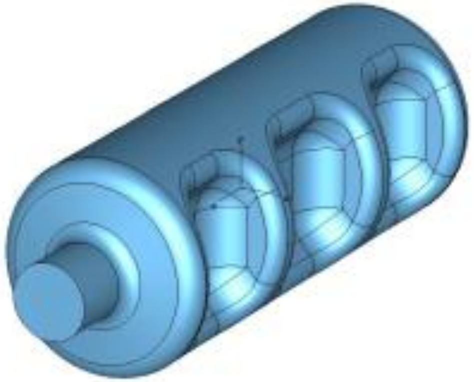
Deflecting mode cavities


TRIUMF 650MHz

double quarter wave (DQW) – 400MHz – BNL/CERN



RFD – multi-cell – 953MHz – ODU



RF Dipole (RFD) – 400MHz – ODU/CERN

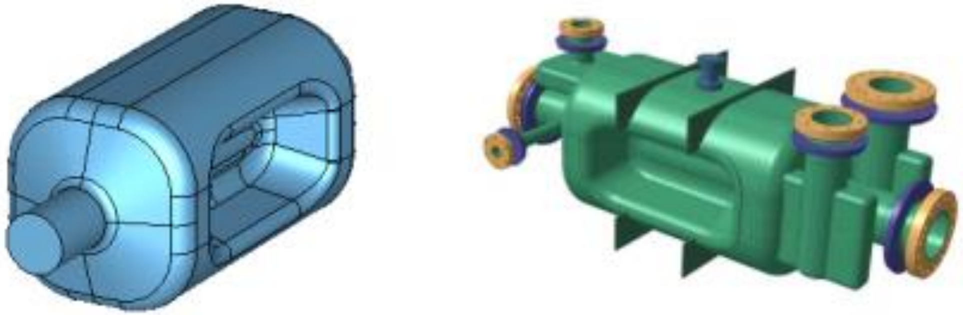
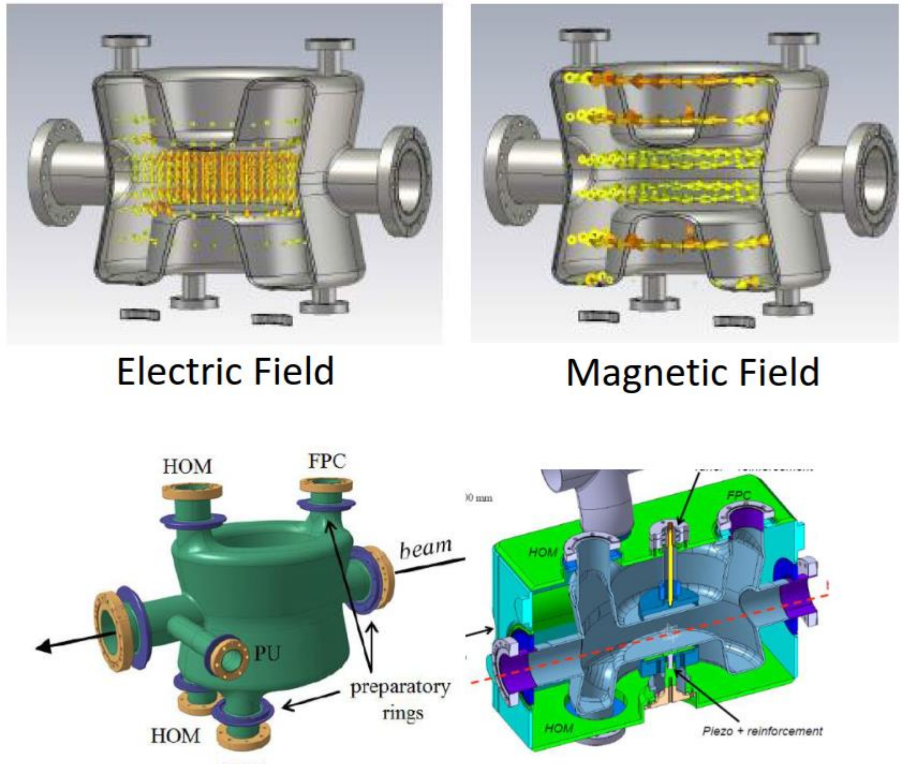



Photo:
Reidar Hahn

Prototype HL-LHC Crab Cavity prototypes

“DQW” (vertical deflection)



“RFD” (vertical deflection)

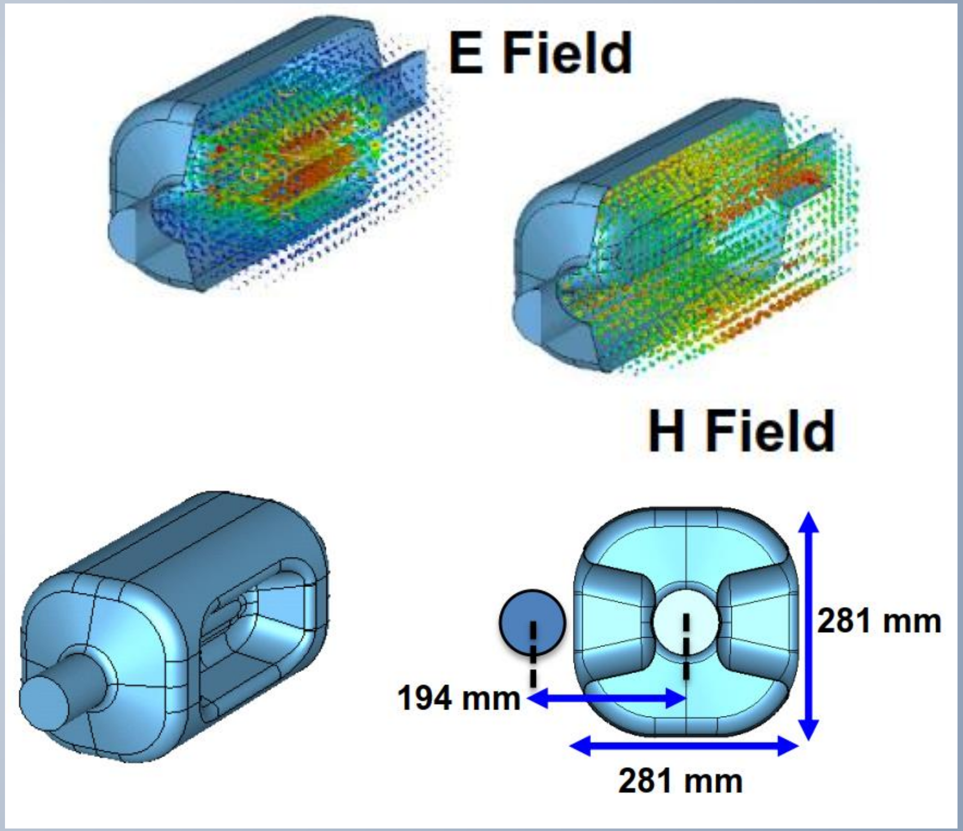
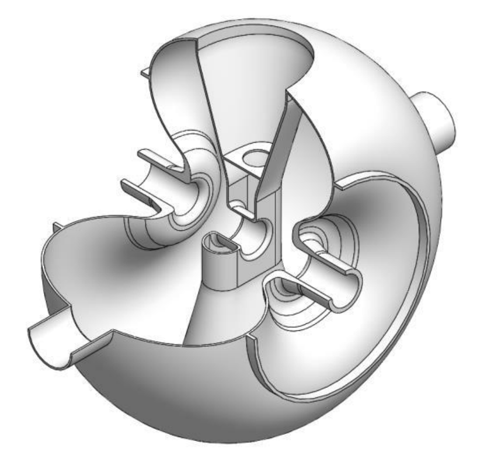
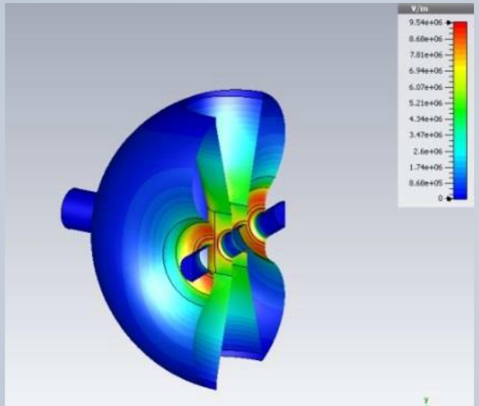


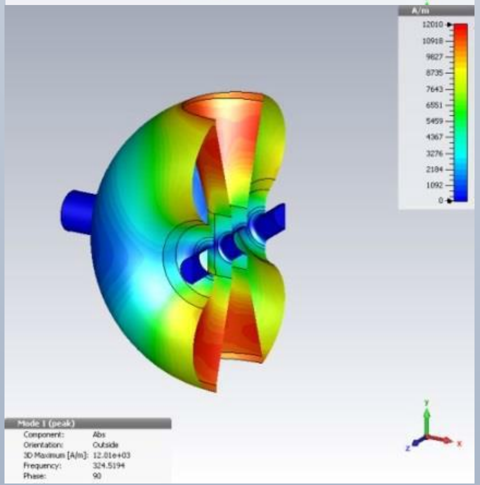
Photo:
Reidar Hahn

Example: TRIUMF/RISP 325 MHz SSR for $\beta = 0.3$ (balloon cavity)

- Geometry optimized to minimize peak field ratios (E_p/E_{acc}, B_{peak}/E_{acc}). Achieved: $E_{peak} = 35\,\mathrm{MV/m}$ and $B_{peak} = 55.3\,\mathrm{mT}$ for $2.5\,\mathrm{MV}$.







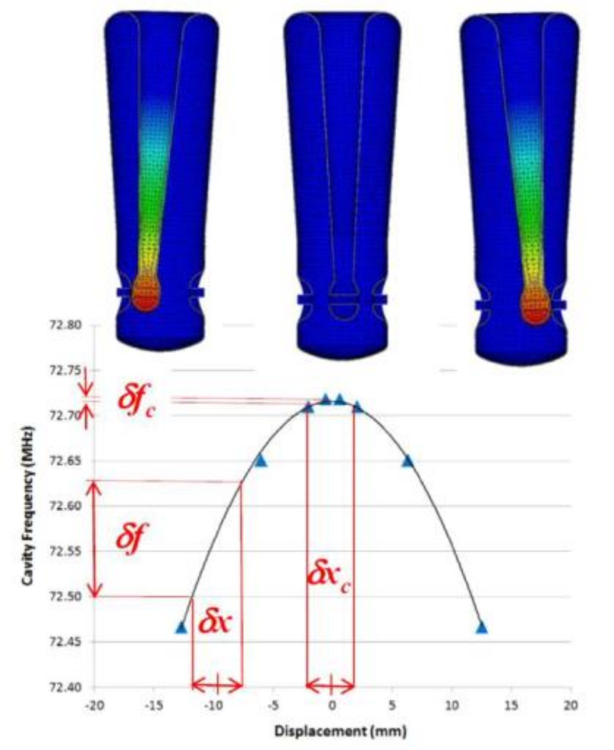
Mode 1 (peak)
Component: Abs
Orientation: Outside
3D Maximum [A/m]: 12.01e+03
Frequency: 324.5194
Phase: 90

Parameters	Values	Units
RF Frequency	325	MHz
E_{peak}/E_{acc}	3.84	
B_{peak}/E_{acc}	6.07	mT/(Mv/m)
G	93	Ω
R/Q	233	Ω
L_{eff} (βλ)	0.277	m

Photo: Reidar Hahn

Microphonics

- Driven by mechanical vibration in the environment.
- QWRs are particularly problematic due to the pendulum action of the inner conductor, which can have very low mechanical frequencies ($(50 \dots 100)\ \mathrm{Hz}$)
  - need to reduce the RMS detuning to $\ll 10\%$ of the available BW to avoid nuisance
  - the other option is to increase the BW (lower Q_L, costs power)
- Mitigation:
  - stiffening during design/manufacture
  - centering the inner conductor by plastic deformation so that $df/dx = 0$.
  - adding passibe dampers
  - reduce environmental noise



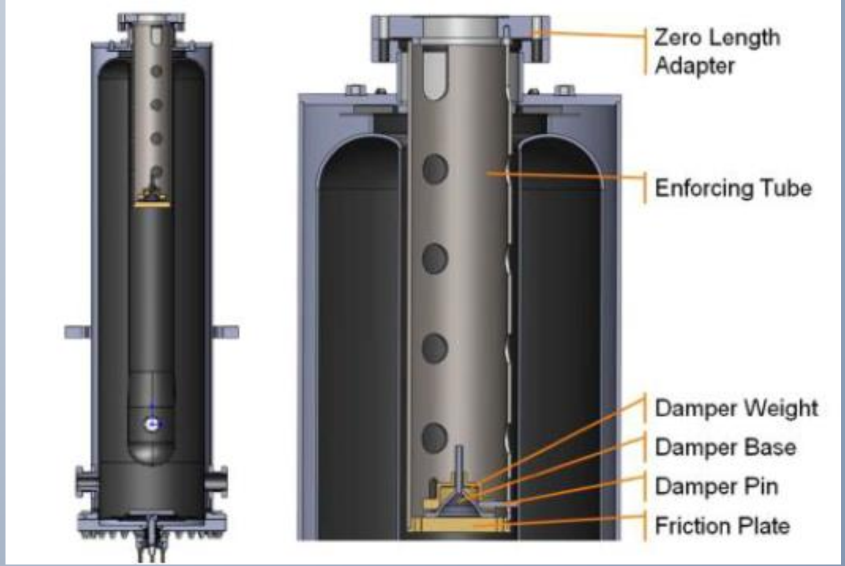
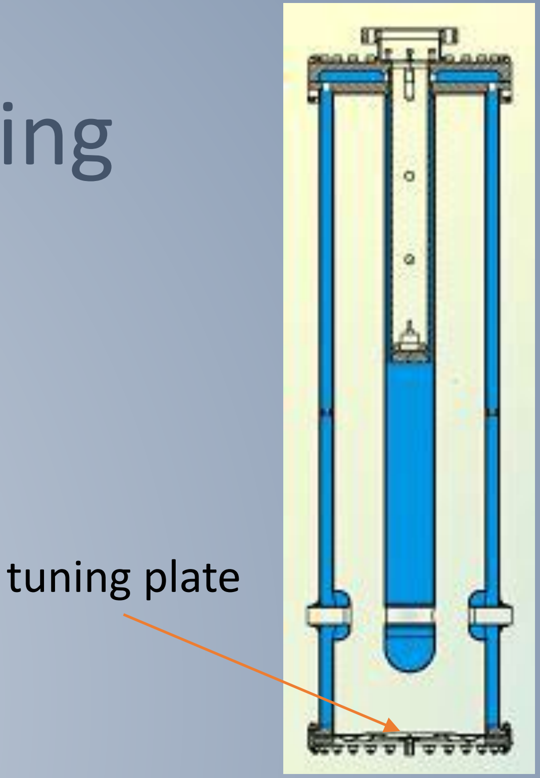



Photo:
Reidar Hahn

Frequency compensation/tuning

- For QWRs a tuning plate at the open end near the beam tube is generally used.
- For QWRs with removable tuning plate, a Nb puck can be welded to it – this reduces the cavity f_0 by increasing the equivalent C.
- This puck can be trimmed after final fabrication



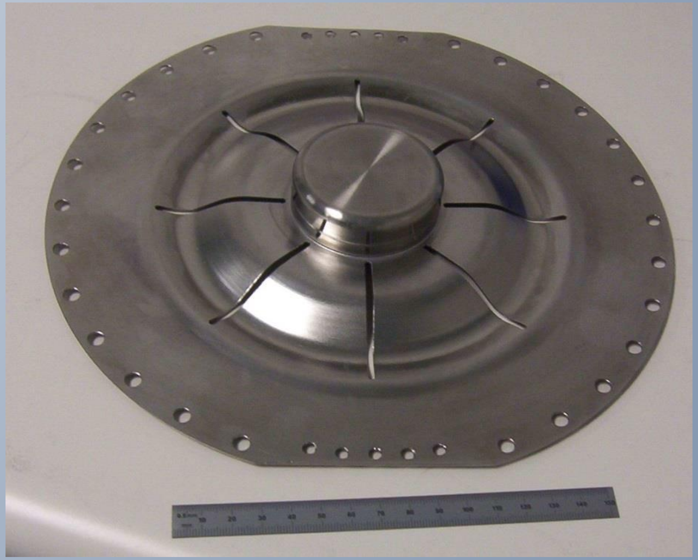



Photo:
Reidar Hahn

End of Non-elliptical cavities

Thank you very much!