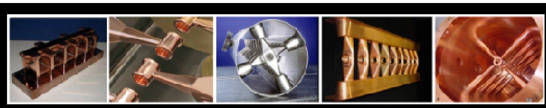
Institut für Angewandte Physik
LINAC AG



517. WE Heraeus-Seminar

“Accelerator Physics for Intense Ion Beams”

15.-18. October 2012

Bad Honnef

RF Structures

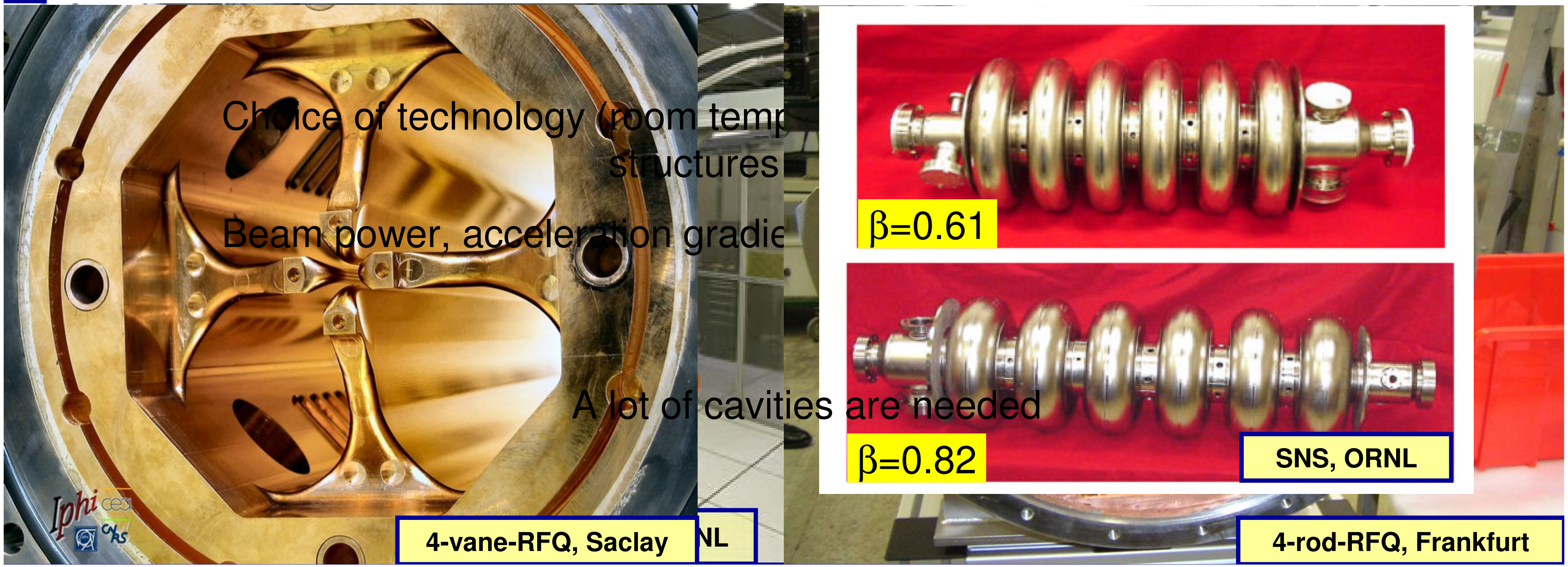
Holger J. Podlech

Institute for Applied Physics (IAP)
University of Frankfurt, Germany

High Intensity Hadronen-Linac

Typical Layout

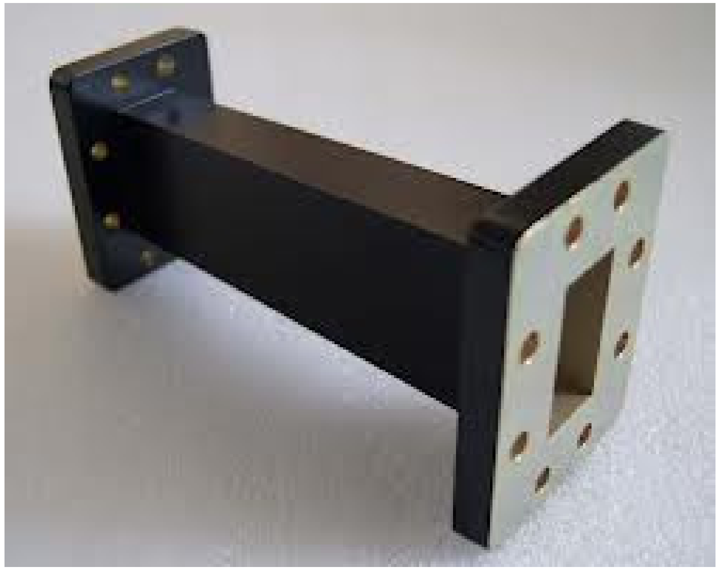
~0.1 MeV	0.5-5 MeV	40-200 MeV	300-1000 MeV
ECR Ion Source	RFQ	DTL	superconducting elliptical cavities

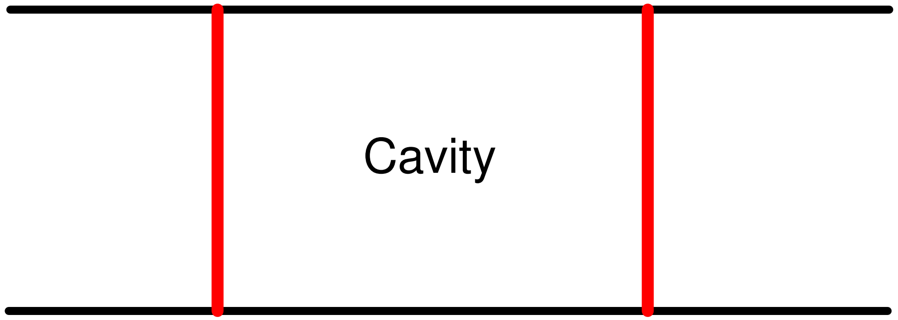


From Wave Guides to Cavities

$$\mathbf{n} \times \mathbf{E} = 0$$

$$\mathbf{n} \cdot \mathbf{H} = 0$$





Metallic Walls
→Additional Boundary Condition for EM Fields
→ Standing EM Waves

Wave Equation for Cylindrical Cavities

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \mathbf{E}}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 \mathbf{E}}{\partial \Phi^2}+\frac{\partial^2 \mathbf{E}}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2}=0$$

$m:$	$0 \leq \Phi < 2\pi$	Number of Zeros in Φ-direction
$n:$	$0 \leq r \leq R$	Number of zeros in radial direction
$p:$	$0 \leq z \leq L$	Number of half periods in z-direction

Set of discrete wave functions (Eigenmodes) which fulfill the boundary conditions

Solutions of Cylindrical Wave Equation: TM

$$
\begin{aligned}
E_z &= E_0 J_m(x_{mn}\rho)\cos(m\Phi)\cos\left(\frac{p\pi z}{L}\right)e^{i\omega t}\\
E_r &= -\frac{p\pi R}{L x_{mn}} E_0 J_m^{'}(x_{mn}\rho)\cos(m\Phi)\sin\left(\frac{p\pi z}{L}\right)e^{i\omega t}\\
E_\varphi &= -\frac{p\pi m R^2}{L x_{mn}^2 r} E_0 J_m(x_{mn}\rho)\sin(m\Phi)\sin\left(\frac{p\pi z}{L}\right)e^{i\omega t}\\
B_z &= 0\\
B_r &= -i\omega\frac{mR^2}{x_{mn}^2\rho c^2} E_0 J_m(x_{mn}\rho)\sin(m\Phi)\cos\left(\frac{p\pi z}{L}\right)e^{i\omega t}\\
B_\Phi &= -i\omega\frac{R}{x_{mn} c^2} E_0 J_m^{'}(x_{mn}\rho)\cos(m\Phi)\cos\left(\frac{p\pi z}{L}\right)e^{i\omega t}
\end{aligned}
$$

Resonance Frequency

$$f_r(TM) = c \cdot \sqrt{\left(\frac{x_{mn}}{2\pi R}\right)^2 + \frac{1}{4}\left(\frac{p}{L}\right)^2}$$

The lowest frequency has the fundamental TM mode (m=0, n=1, p=0)

TM_{010}

$$f_{010} = \frac{c x_{01}}{2\pi R}$$

$$\omega_{010} = \frac{c x_{01}}{R}$$

TM_{010}-Mode: E-Fields

m=0
n=1
p=0

$$E_z = E_0 J_m(x_{mn}\rho)\cos\underbrace{(m\Phi)}_{0}\cos\underbrace{\left(\frac{p\pi z}{L}\right)}_{0} e^{i\omega t} \longrightarrow E_z\text{=const}$$

$$E_r = -\frac{p\pi R}{L x_{mn}} E_0 J_m'(x_{mn}\rho)\sin(m\Phi)\sin\left(\frac{p\pi z}{L}\right) e^{i\omega t} \longrightarrow 0$$

$$E_\Phi = -\frac{p\pi m R^2}{L x_{mn}^2 r} E_0 J_m(x_{mn}\rho)\sin(m\Phi)\sin\left(\frac{p\pi z}{L}\right) e^{i\omega t} \longrightarrow 0$$

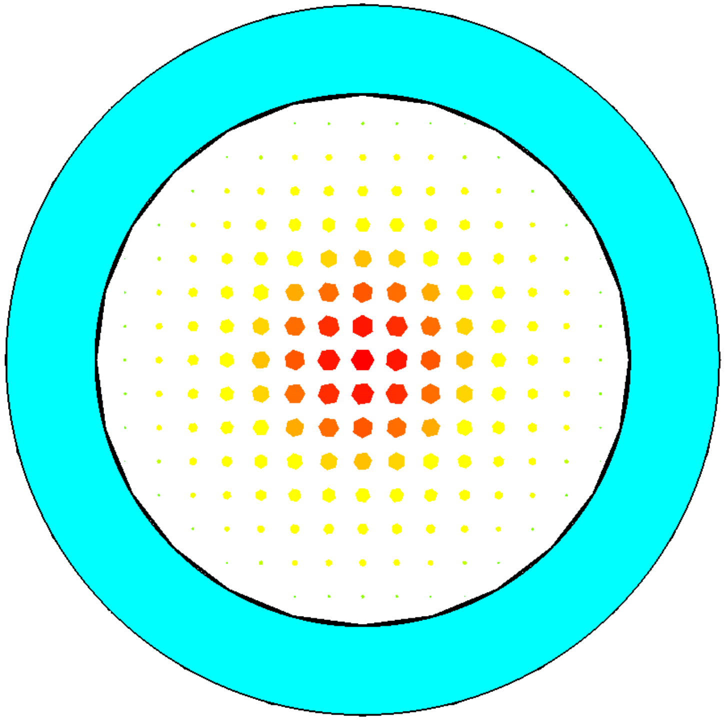
$$B_z = 0$$

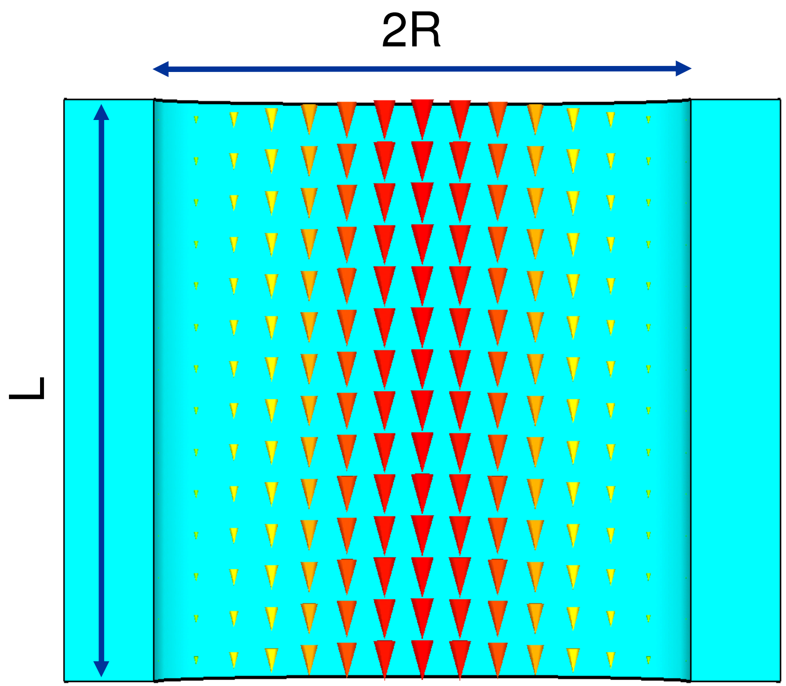
$$B_r = -i\omega\frac{mR^2}{x_{mn}^2\rho c^2} E_0 J_m(x_{mn}\rho)\sin(m\Phi)\cos\left(\frac{p\pi z}{L}\right) e^{i\omega t}$$

$$B_\phi = -i\omega\frac{R}{x_{mn} c^2} E_0 J_m'(x_{mn}\rho)\cos(m\Phi)\cos\left(\frac{p\pi z}{L}\right) e^{i\omega t}$$

$$E_z = E_0 J_0\left(\frac{2.405r}{R}\right) e^{i\omega t}$$

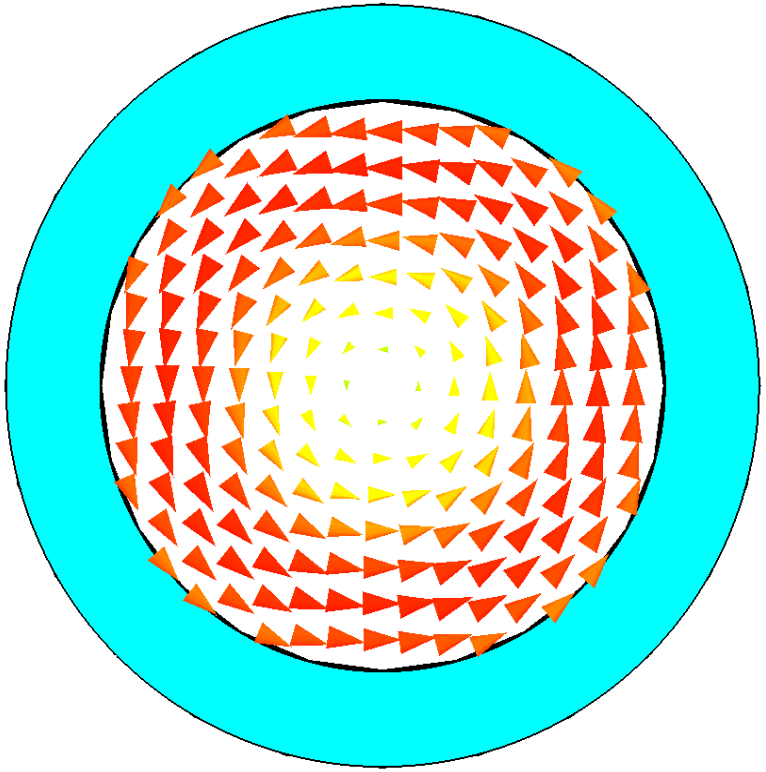
TM_{010}-Mode: E-Fields

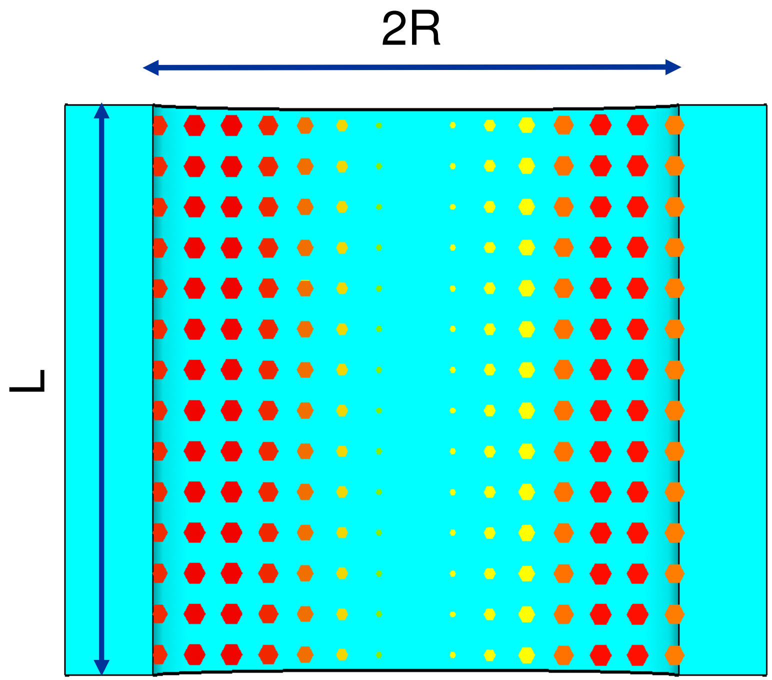




$$E_z = E_0 J_0\left(\frac{2.405r}{R}\right)e^{i\omega t}$$

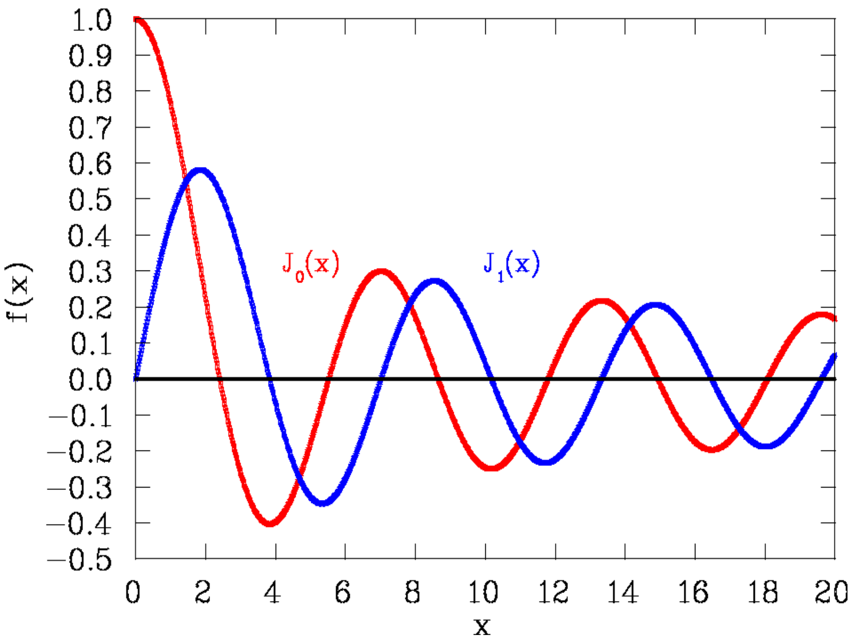
TM_{010}-Mode: B-Fields

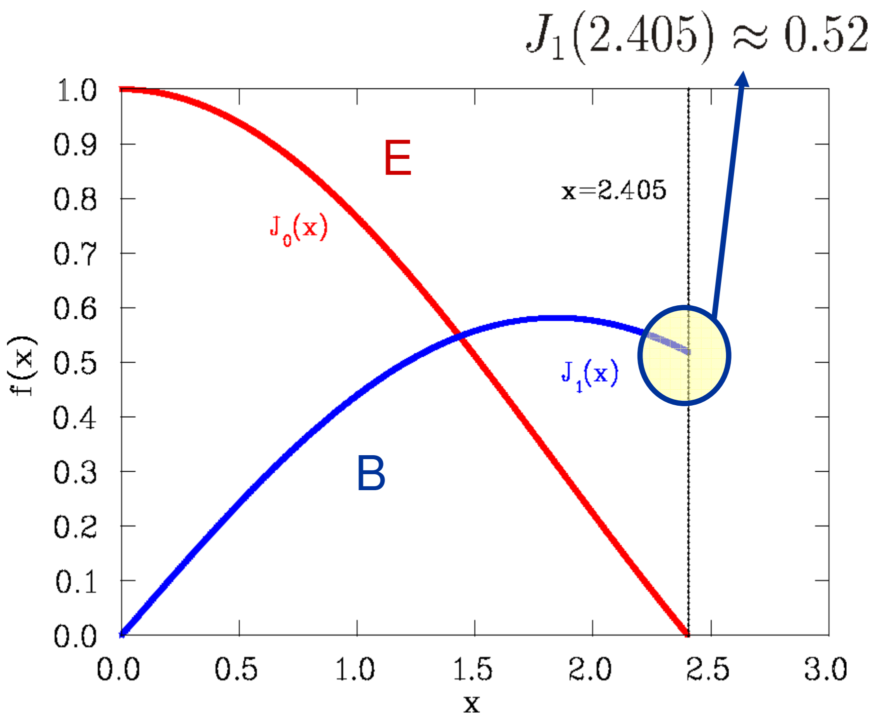




$$B_\Phi = i\frac{E_0}{c} J_1\left(\frac{2.405r}{R}\right) e^{i\omega t}$$

Course of E- und B-Fields



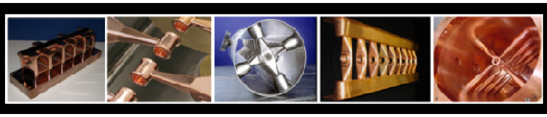


$$E_z = E_0 J_0 \left(\frac{2.405r}{R} \right) e^{i\omega t}$$

$$B_\Phi = i \frac{E_0}{c} J_1 \left(\frac{2.405r}{R} \right) e^{i\omega t}$$

RF Parameter

- Surface Resistance R_s
- Stored Energy W
- RF Power Losses P_c
- Peak-Fields (E,B)
- Quality Factor Q_0
- (Shunt-) Impedance R_a
- Geometrical Factor G
- Geometrical Impedance R_a/Q_0
- Cryogenic Load R_sR_a



Surface Resistance R_s

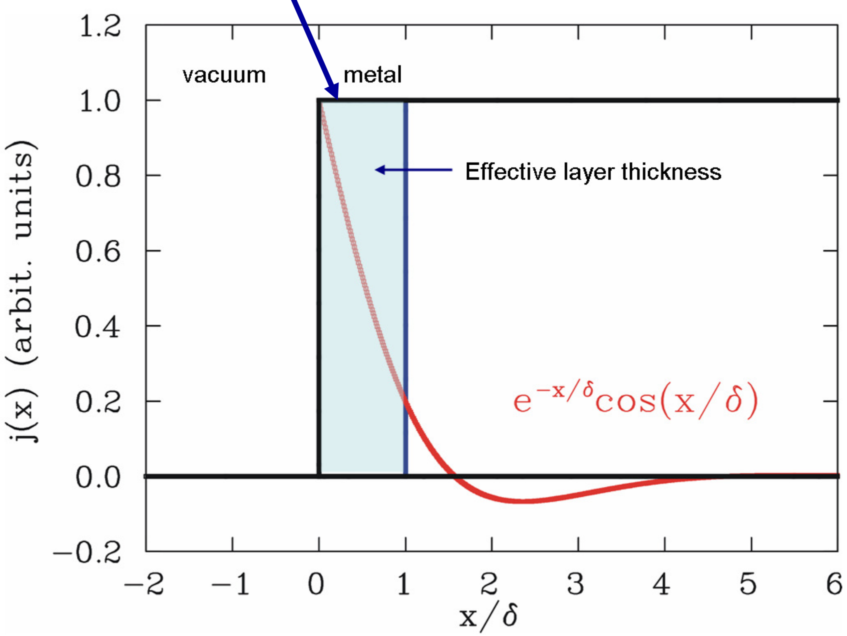
$$\delta = \sqrt{\frac{2}{\sigma \mu_r \mu_0 \omega}}$$

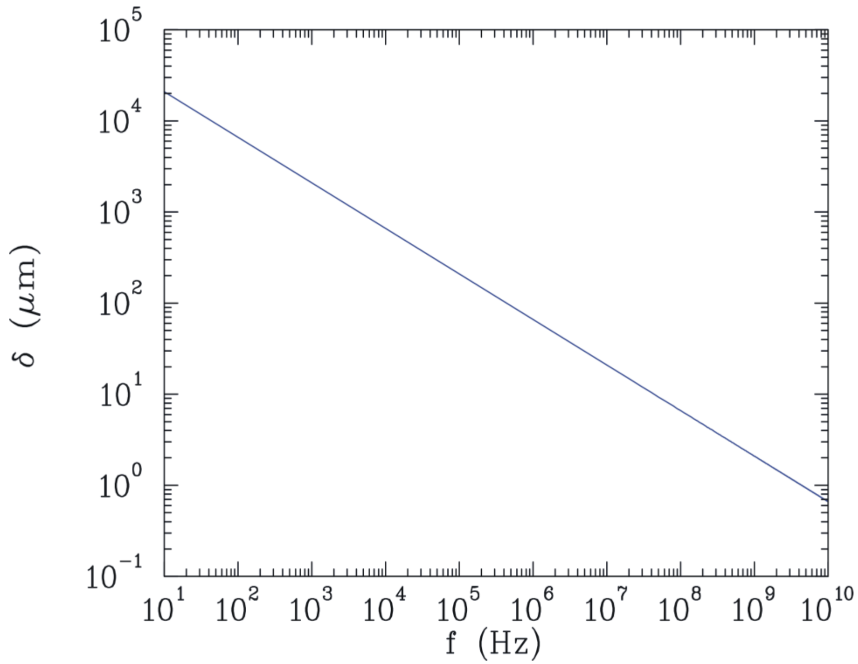
Room Temperature

σ=Conductivity

$\delta \approx 3.5\ \mu m$
(350 MHz, Cu)

Skin-Effect





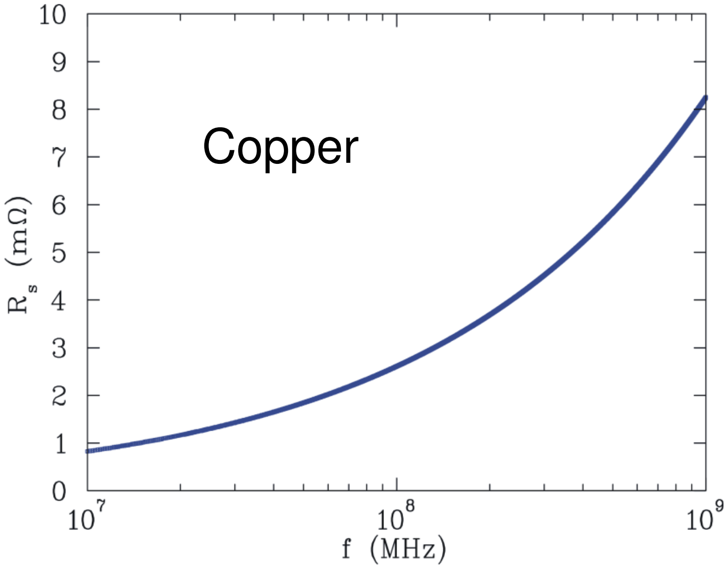
Surface Resistance R_s

Room Temperature

$$\delta = \sqrt{\frac{2}{\sigma \mu_r \mu_0 \omega}}$$

$$R_s = \frac{1}{\sigma \delta}$$

$R_s \approx m\Omega$



$$R_s = \sqrt{\frac{\mu_r \mu_0 \omega}{2\sigma}}$$

$$R_s \propto \sqrt{\omega}$$

Surface Resistance Superconductivity

Room Temperature	Superconductivity
$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0\omega}{2\sigma}}$$	$$R_s(BCS) = 2 \cdot 10^{-4} \frac{1}{T}\left(\frac{f}{1.5}\right)^2 \exp\left(-\frac{17.67}{T}\right)$$
→ 1-10 mΩ	→ 1-100 nΩ

Typically 5 Orders of magnitude lower Resistance

Stored Energy W

$$W = \frac{1}{2}\mu_0 \int_V |\mathbf{H}|^2 \, dV = \frac{1}{2}\epsilon_0 \int_V |\mathbf{E}|^2 \, dV$$

E=1 MV/m
„Homogeneous“
V=1 m^3

→ **4.4 J**

Pillbox-cavity TM_{010}-Mode

$$W = \frac{\pi \epsilon_0 E_0^2 L R^2}{2} J_1^2(2.405)$$

RF Power Losses P_c

$$\frac{dP_c}{dA} = \frac{1}{2} R_s |\mathbf{H}|^2$$

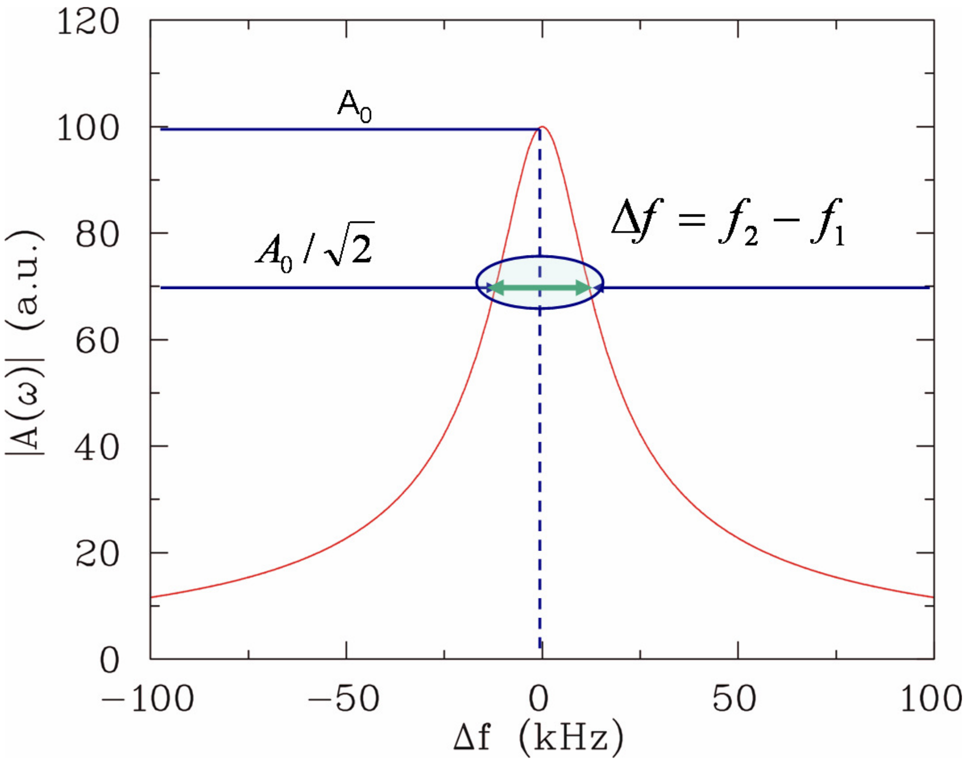
$$P_c = \frac{1}{2} R_s \int_S |\mathbf{H}|^2 \, dA$$

Power losses for superconducting cavities significantly reduced because of much smaller surface resistance

Pillbox-cavity TM_{010}-Mode

$$P_c = \frac{\pi R_s E_0^2 J_1^2(2.405)}{\mu_0^2 c^2} (L+R) R$$

Quality Factor Q



$$|A(\omega)| = \frac{|A_0|}{\sqrt{1 + Q_0^2(\Delta\omega/\omega)^2}}$$

Lorentz-Curve

$$Q_0 = \frac{f}{f_2 - f_1} = \frac{f}{\Delta f}$$

Quality Factor Q_0

NL: 10^3-10^5

$$Q_0 = \frac{\omega W}{P_c}$$

SL: 10^7-10^{11}

$$Q_0 = 2\pi \frac{W}{W_T} = 2\pi N$$

Q-value: Number of RF periods until stored energy is dissipated

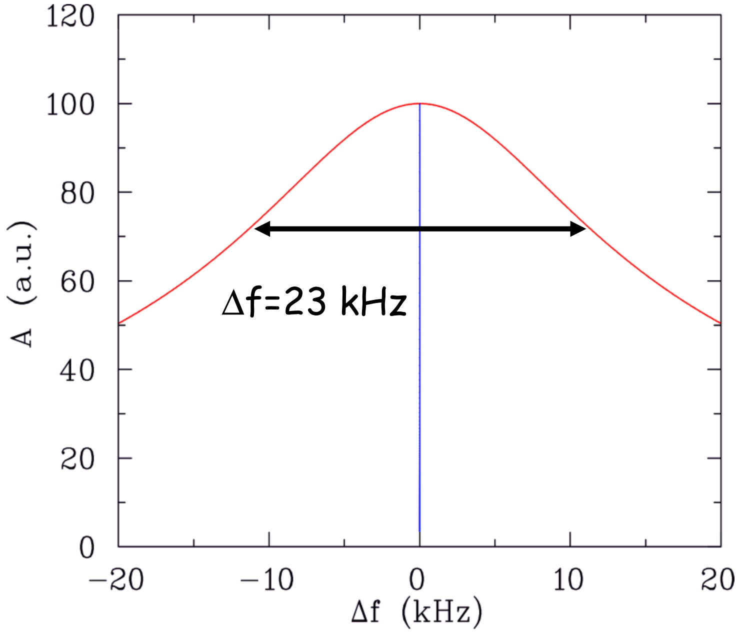
Pillbox-cavity TM_{010}-Mode

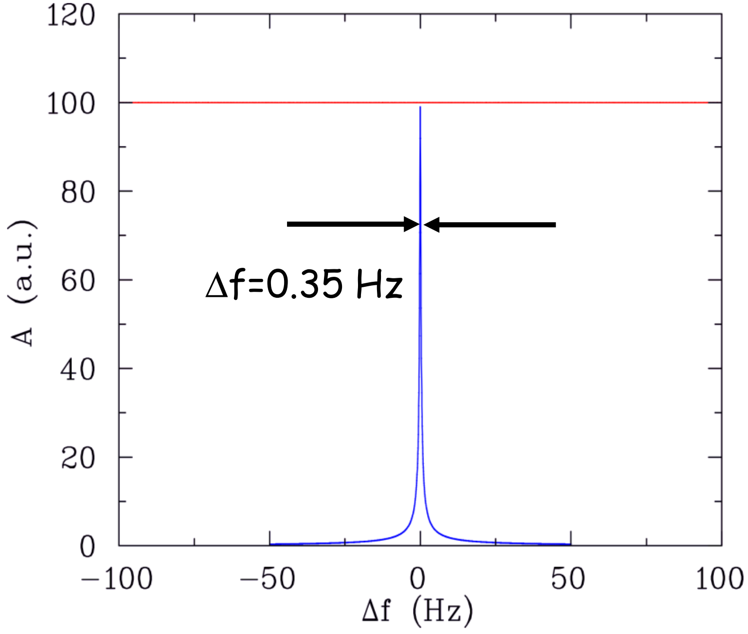
$$Q_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \cdot \frac{2.405L}{2R_s(L+R)}$$

Quality Factor

Room Temperature
f=350 MHz
$Q_0=1.5 \times 10^4$
$\Delta f=23$ kHz

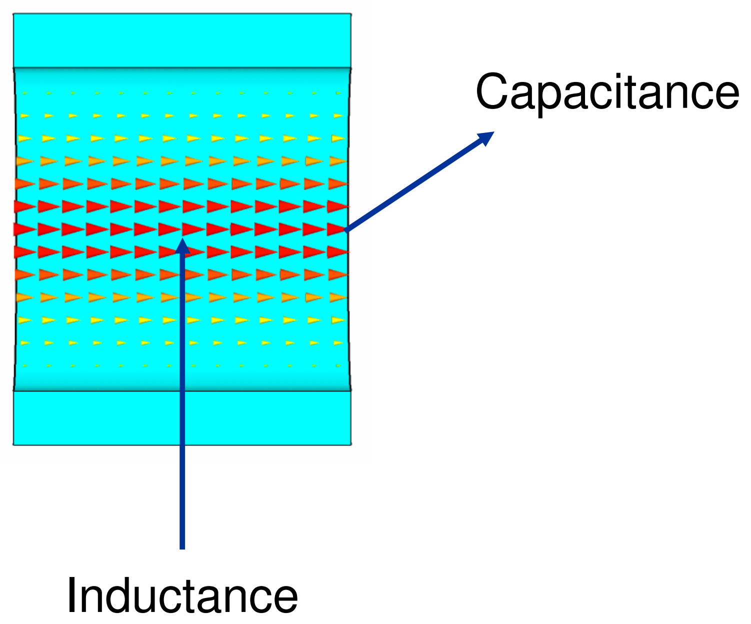
Superconducting
f=350 MHz
$Q_0=1 \times 10^9$
$\Delta f=0.35$ Hz



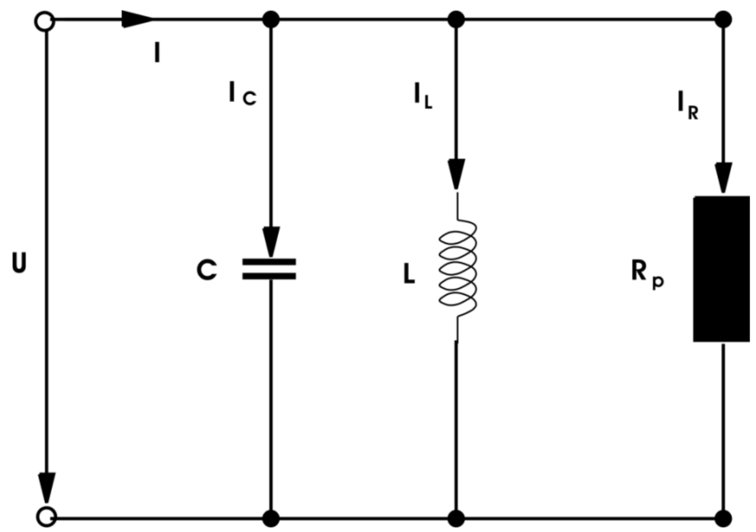


(Shunt-)-Impedance R

Every RF structure can be described by an oscillator circuit



(Shunt-)-Impedance R



$$\dot{I}_g = C\ddot{U} + \frac{U}{L} + \frac{\dot{U}}{R_p}$$

$$Z^\star(\omega) = \frac{1}{i\omega C + \frac{1}{i\omega L} + \frac{1}{R_p}}$$

Resonance ⟶ $Z^\star = R_p$

(Shunt-)-Impedance R

$$R_a = \frac{U_a^2}{P_c} = R_0 T^2$$

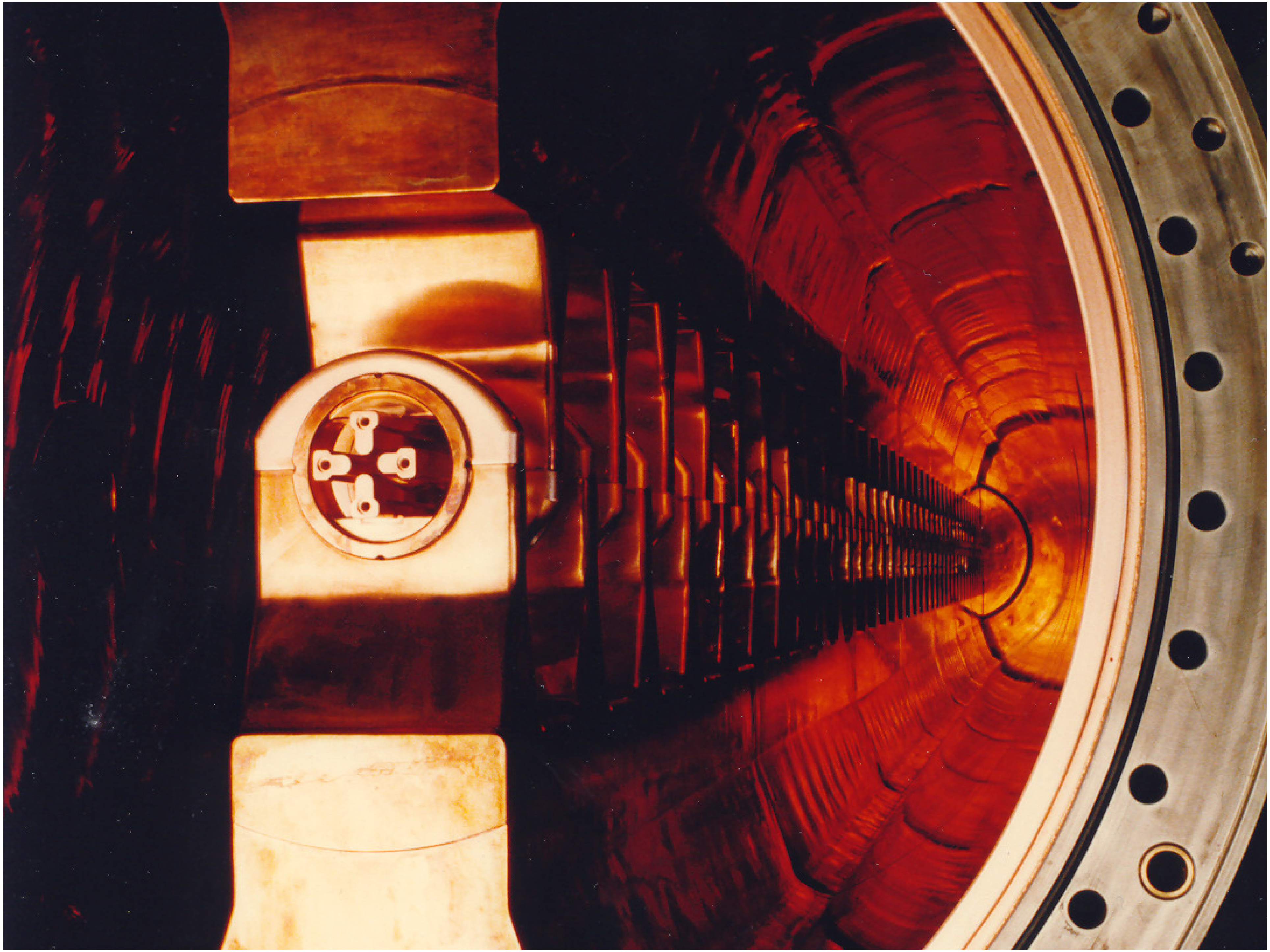
$$Z_a = \frac{U_a^2}{P_c L}$$

DTL
RFQ

$$R_p = \frac{U^2}{P_c} L$$

Pillbox-cavity TM_{010}-Mode

$$R_a = \frac{U_a^2}{P_c} = \frac{4L^2 \mu_0^2 c^2}{\pi^3 R_s J_1^2(2.405) R(R+L)} \quad [\Omega]$$



RFQ Structures

Problem

•DC Beam from ion sources must be prepared for drift tube structures
→ Bunching, acceleration

•Beam transport, focusing

Solution

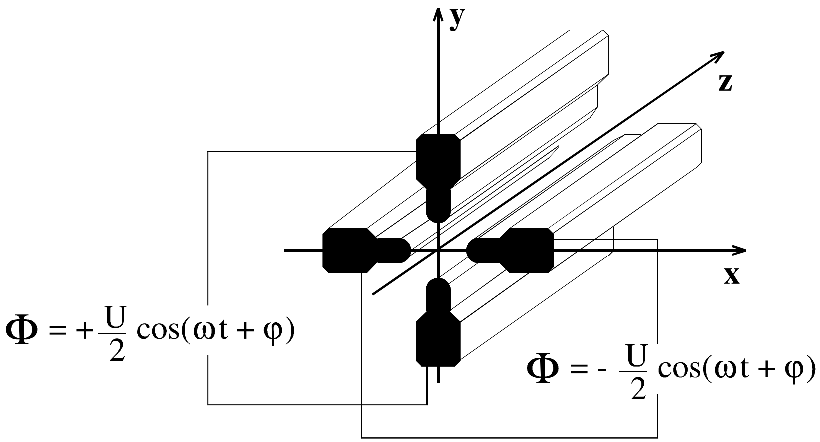
Radio Frequency Quadrupoles (RFQ)

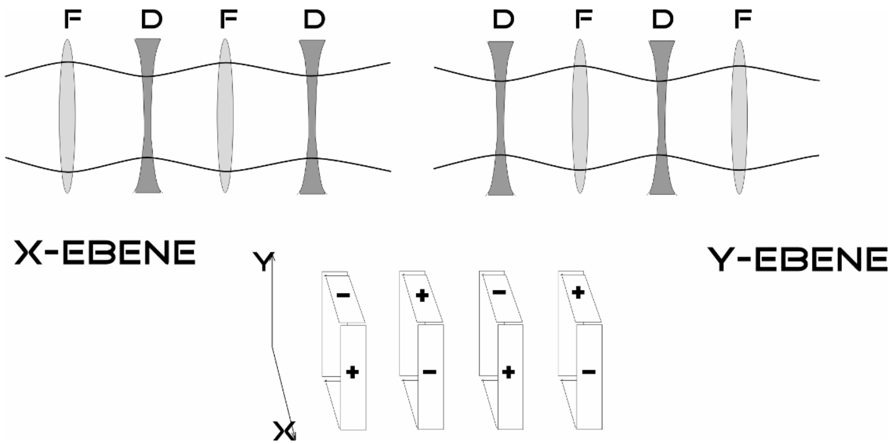
Bunching, focussing and acceleration within one cavity

RFQ Structures

RFQ structures using electric RF quadrupol fields

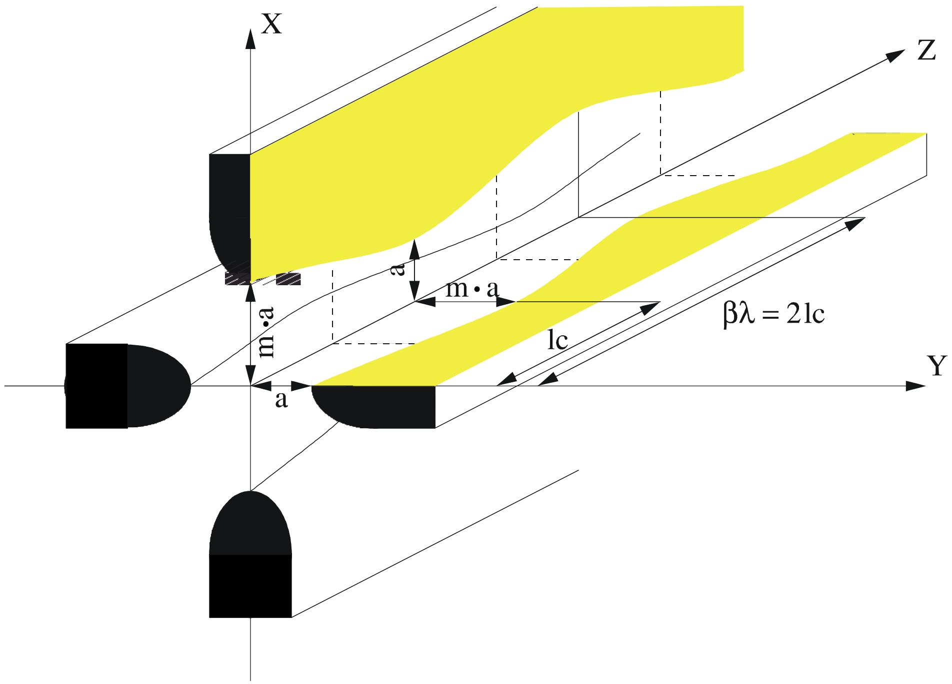
→ Strong electric (velocity independent) focusing

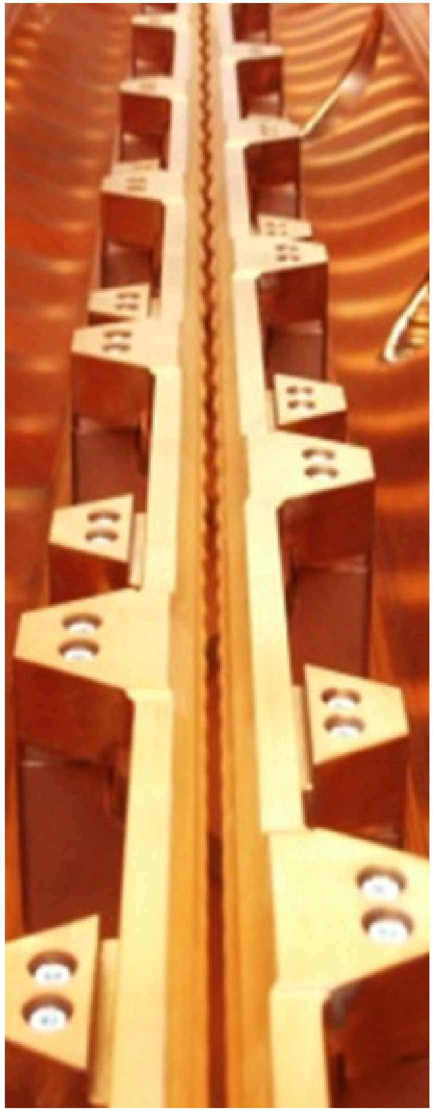




RFQ Structures

Mechanical modulation on electrodes
→ Longitudinal field components for bunching and acceleration

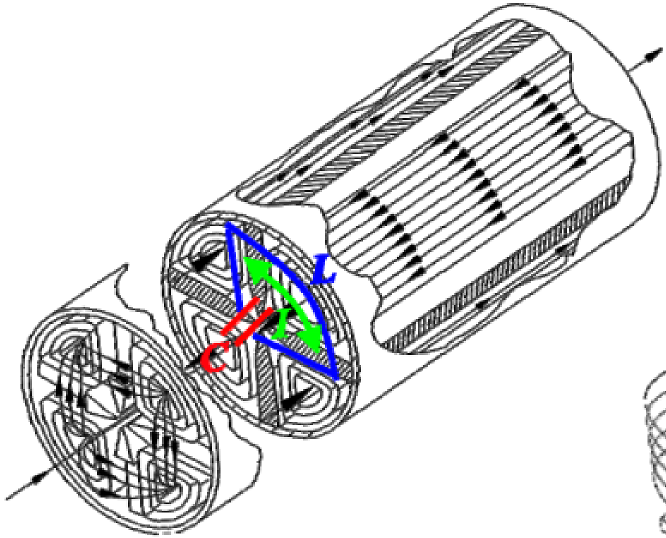


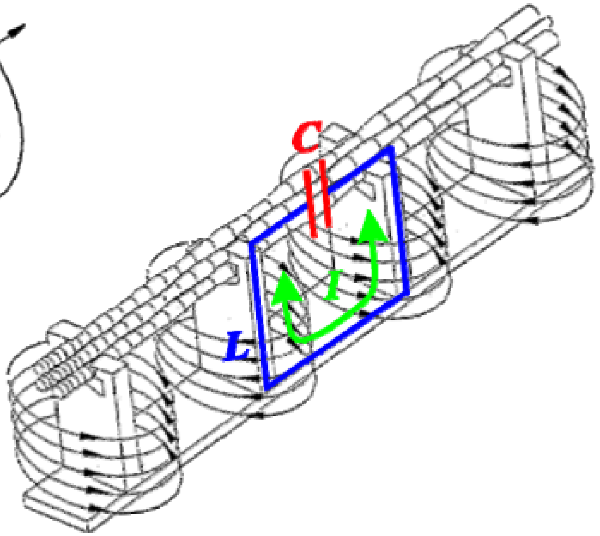


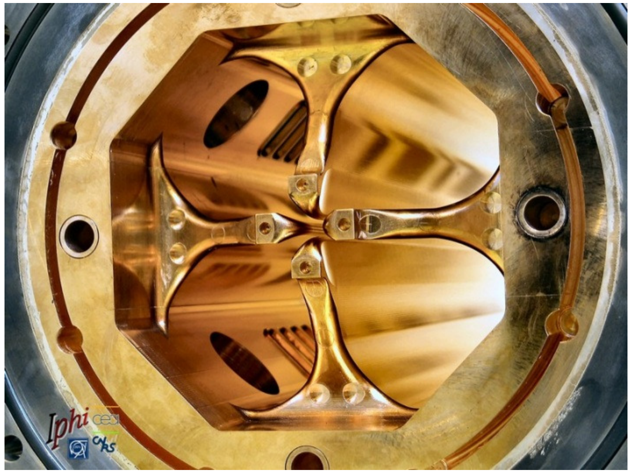
RFQ Structures

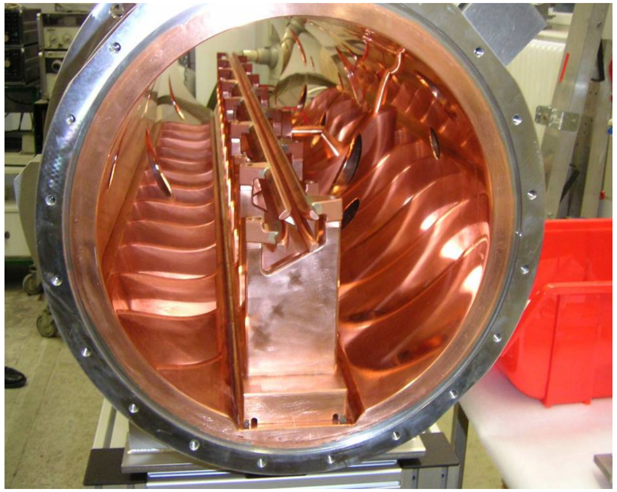
4-Vane

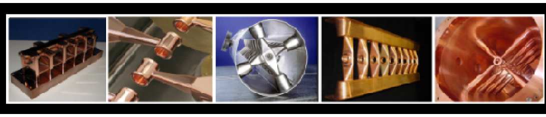
4-Rod







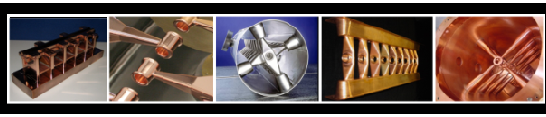




Classification of Drift Tube RF Structures

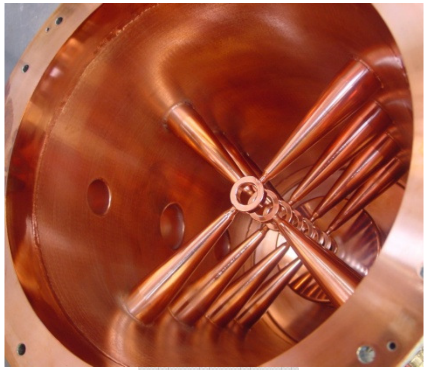
TM-Class	TEM-Class	H-Class
TM_{010}/E_{010}	TEM	$TE_{111/211}/H_{111/211}$
Alvarez DTL Elliptical Cavities	QWR HWR Spoke	IH/CH-Structure Multi-Spoke

Additional RF structures:
transmission line resonators, SCL, CCL,…



Room Temperature RF Structures

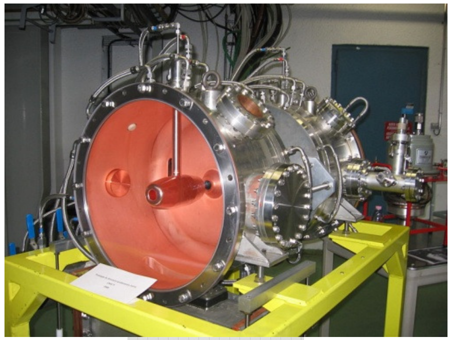
IAP Frankfurt



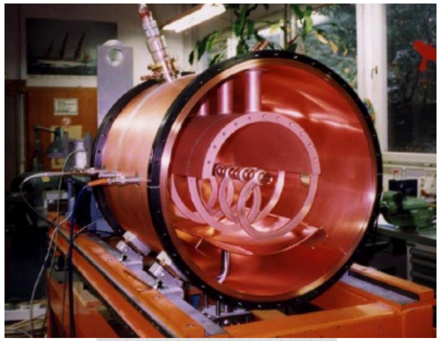
IAP

GSI

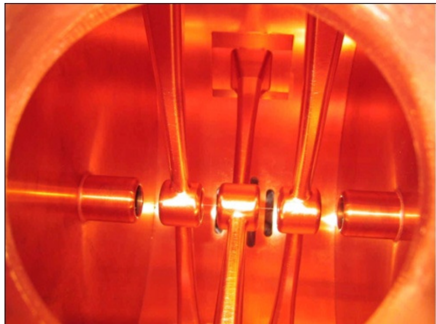
INFN Legnaro



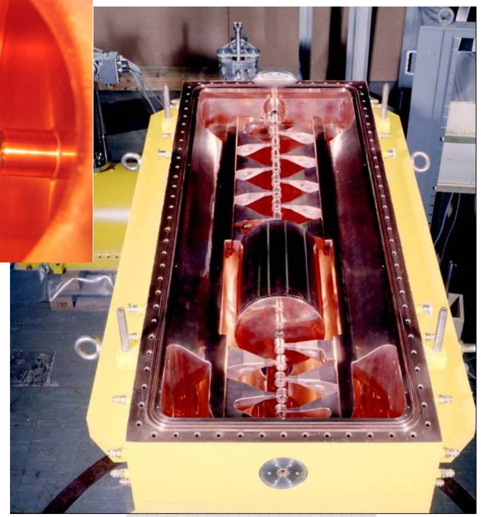
CERN



MPI-HD

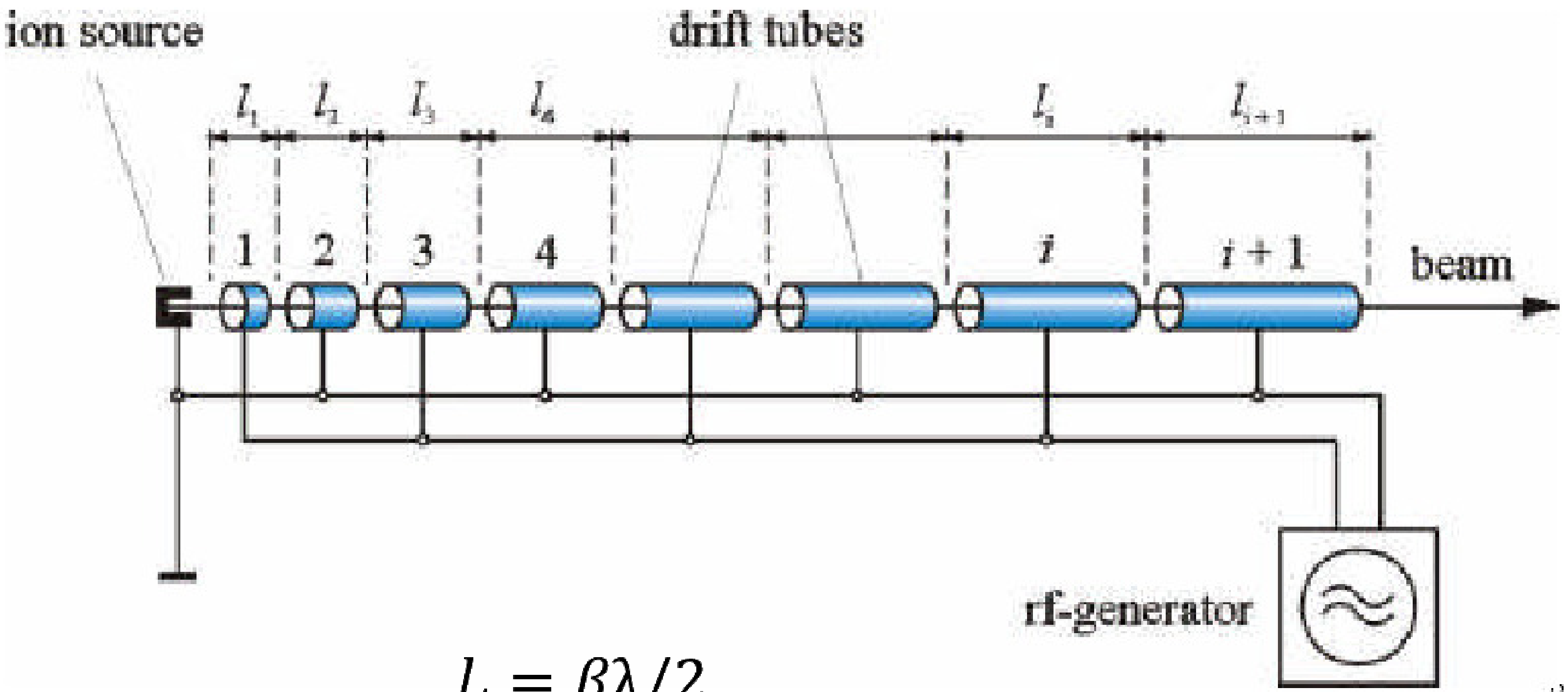


FNAL



REX-ISOLDE

Wideröe DTL



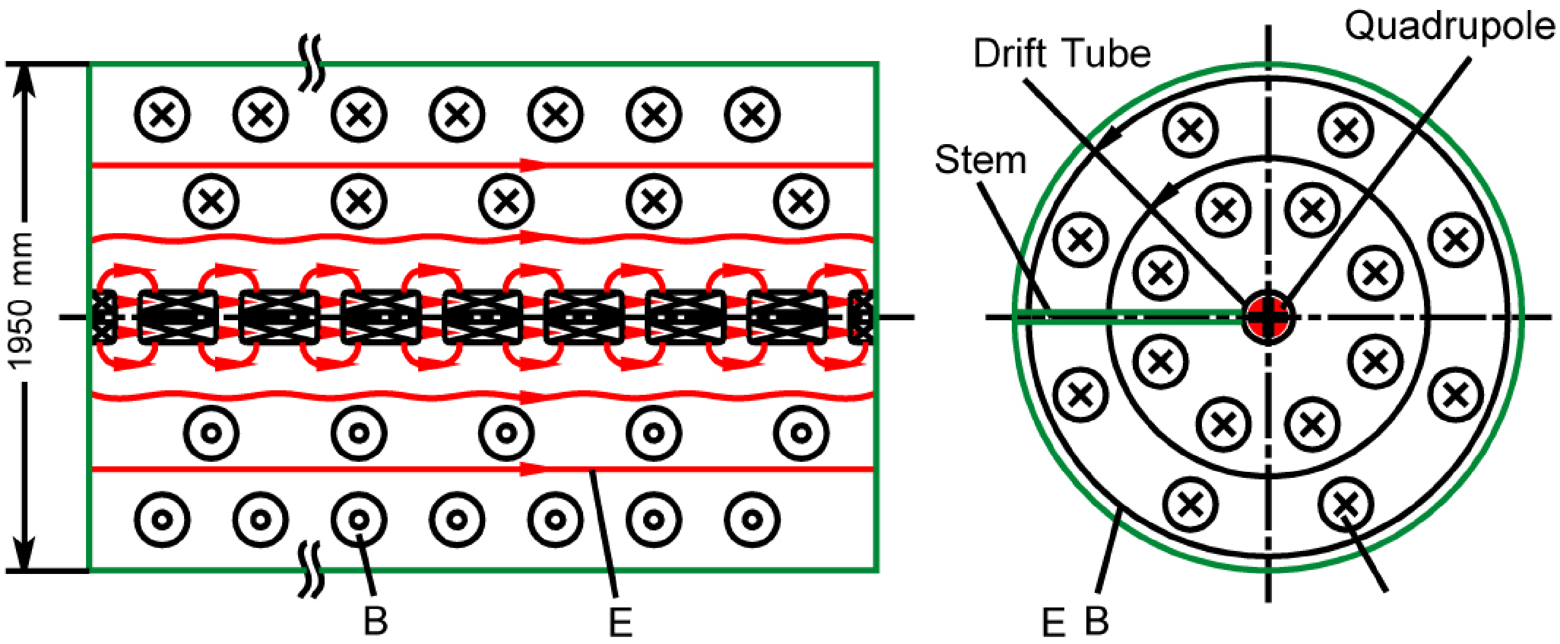
$$l_i = \beta\lambda/2$$

Cell length correspons to the flight time during half of the RF period

Alvarez DTL

- Cylindrical cavity in TM_{010}-Mode → constant electric field E_z
- Drift tubes are used to shield the deceleration field from the particles
- Drift tubes housing quadrupol lenses for transverse focusing
- Cell length is $\beta\lambda$

ALVAREZ - Cavity , E_{010} , 108 MHz

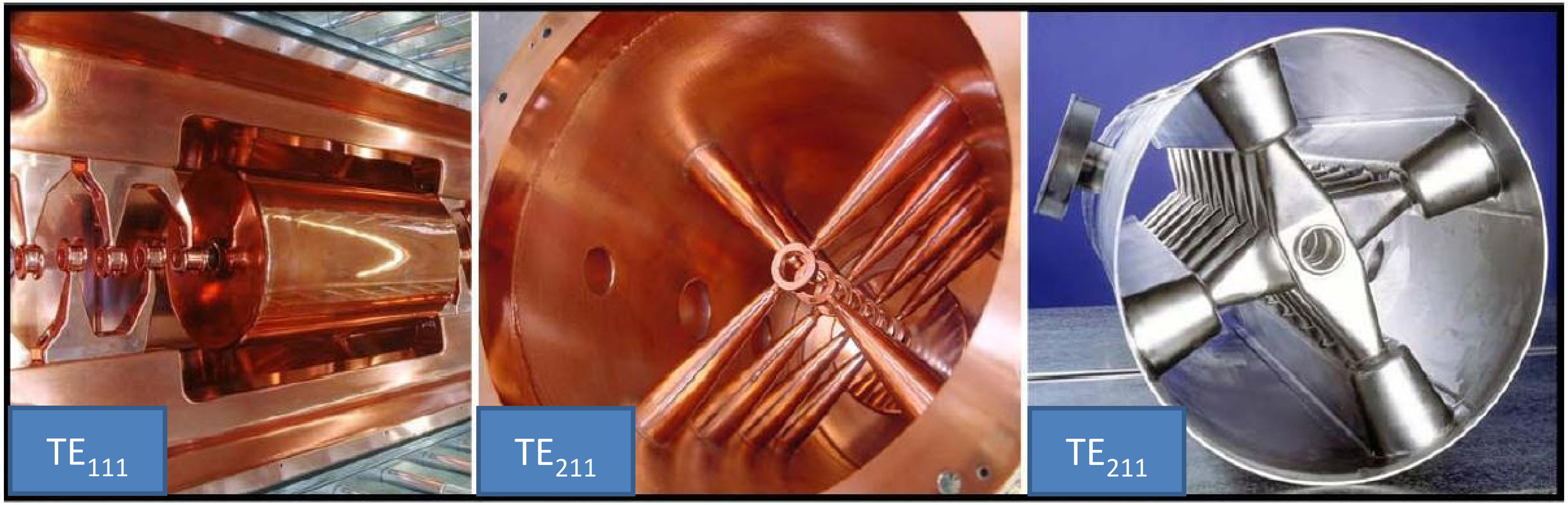


Alvarez DTL

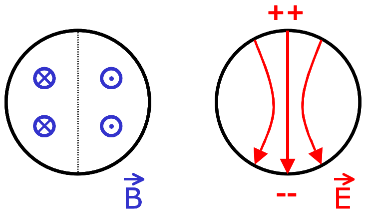
200 MHz DTL FNAL

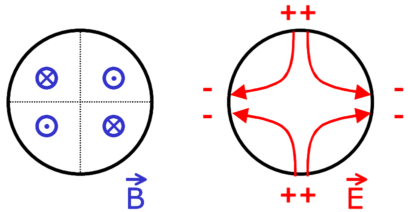
108 MHz DTL GSI

H-mode DTL- cavities

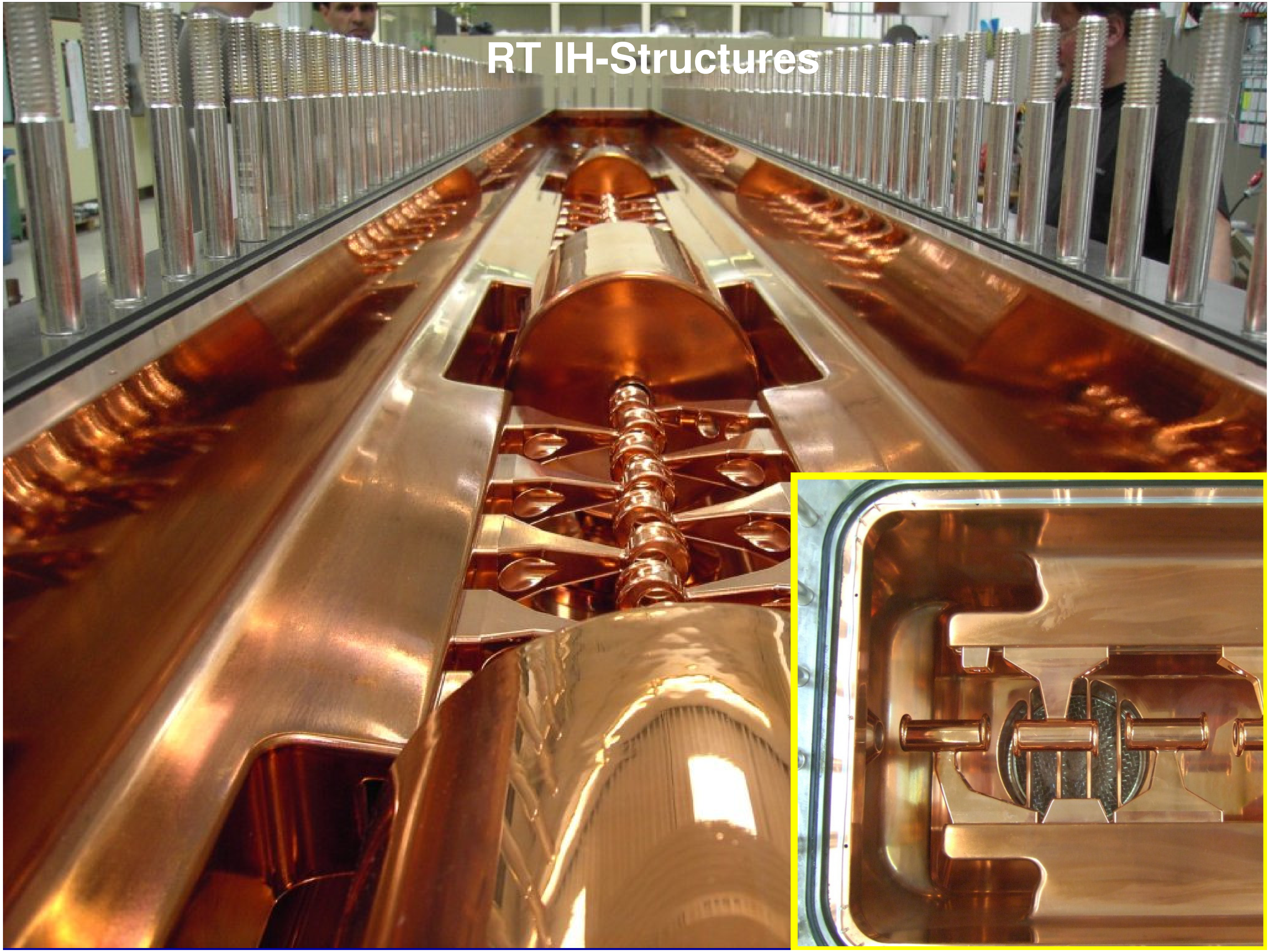


rt IH	rt CH	sc CH
E< 30 AMeV 30<f<250 MHz	E< 100 AMeV 150<f<700 MHz	E< 100 AMeV 150<f<700 MHz

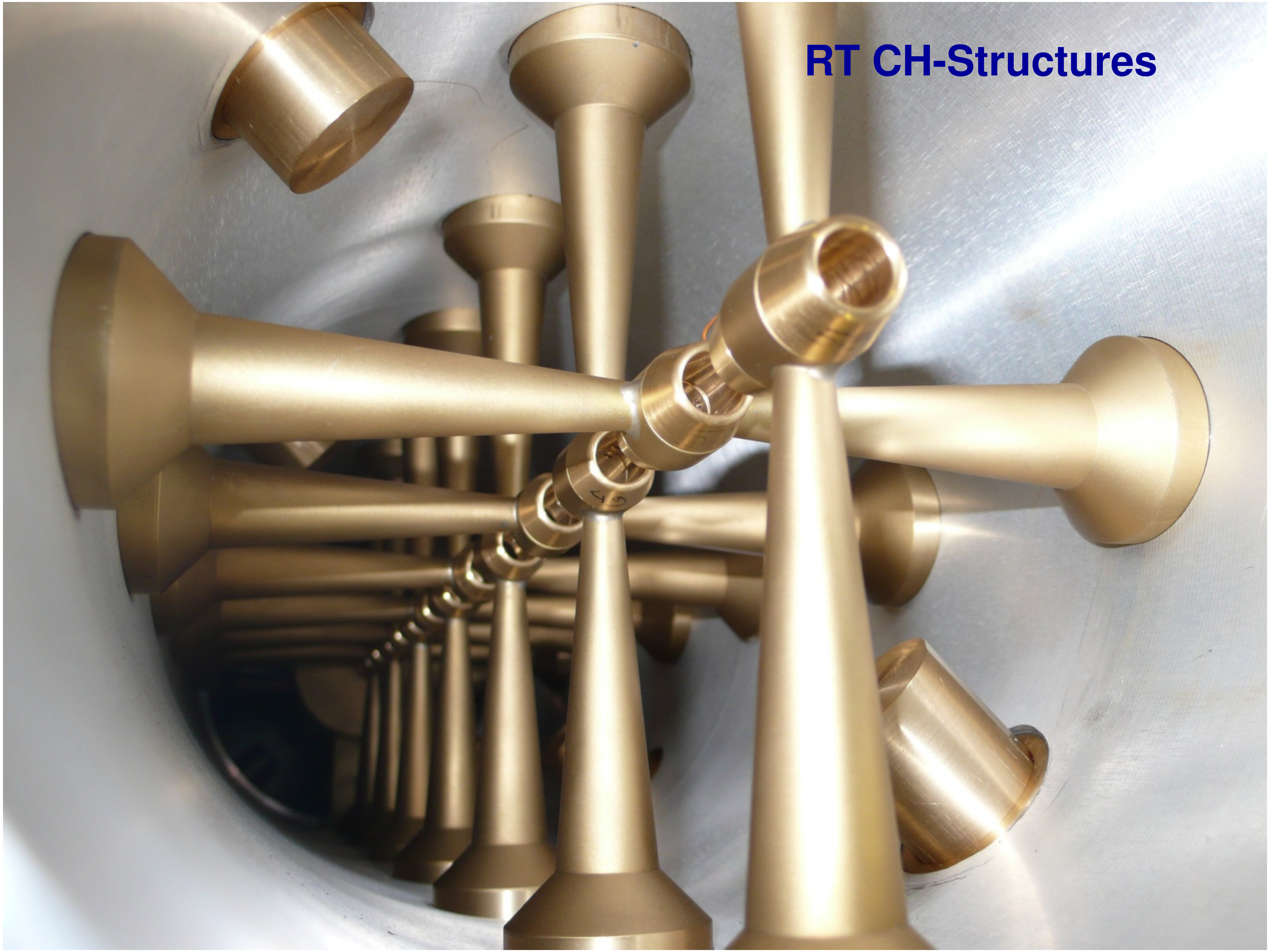




RT IH-Structures

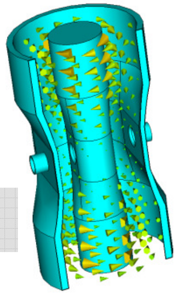


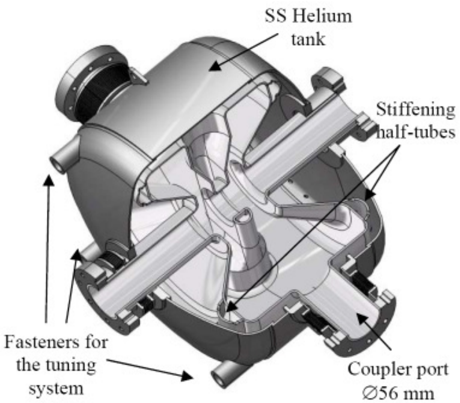
RT CH-Structures



Superconducting RF Structures

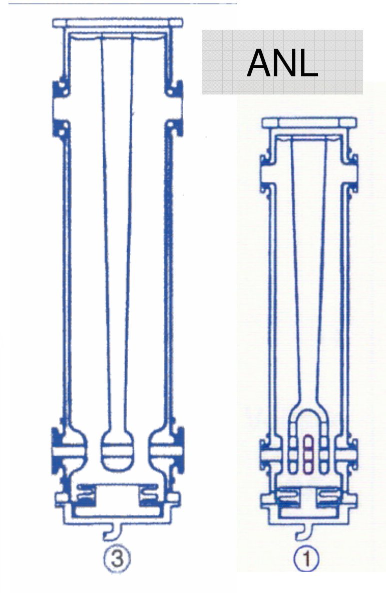

INFN Legnaro


MSU

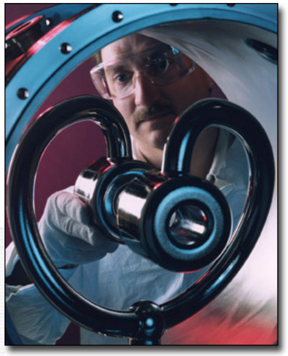


IPN, Orsay


ANL



ANL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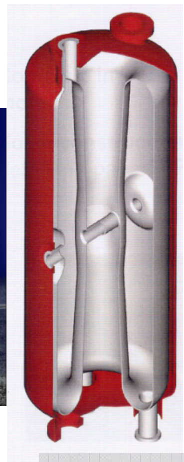
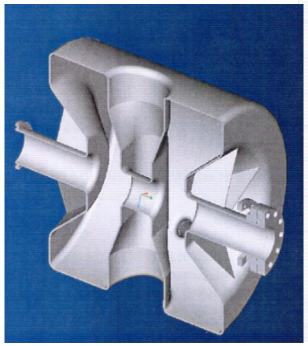
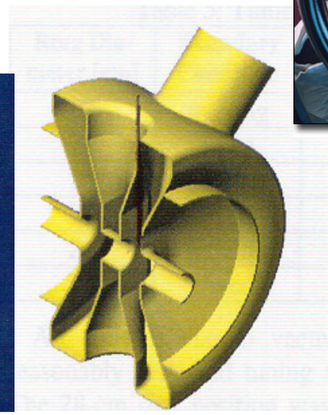
IAP Frankfurt


ANL


IPN, Orsay


LANL


SNS

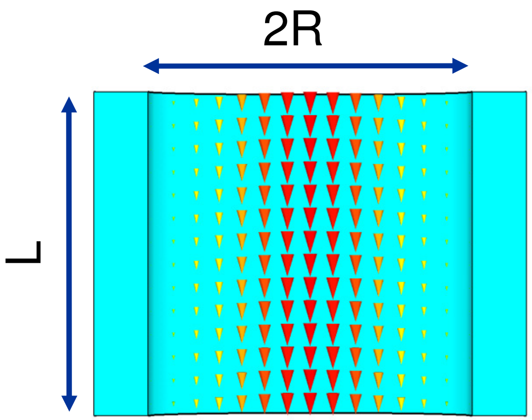
Power Consumption P_c

$$P_c = \frac{1}{2} R_s \int_S |\mathbf{H}|^2 \, dA$$

Power consumption of sc cavities significantly lower (factor 10^4-10^5)

$$P_c = \frac{U_a^2}{\underbrace{R_a}_{\text{Impedance}}} = \frac{U_a^2}{\underbrace{(R_a/Q_0)}_{\text{Geometrical Impedance}} Q_0}$$

RF Parameter Comparison



Pillbox Cavity

Fundamental mode TM_{010}

f=1.5 GHz

L=10 cm

NC

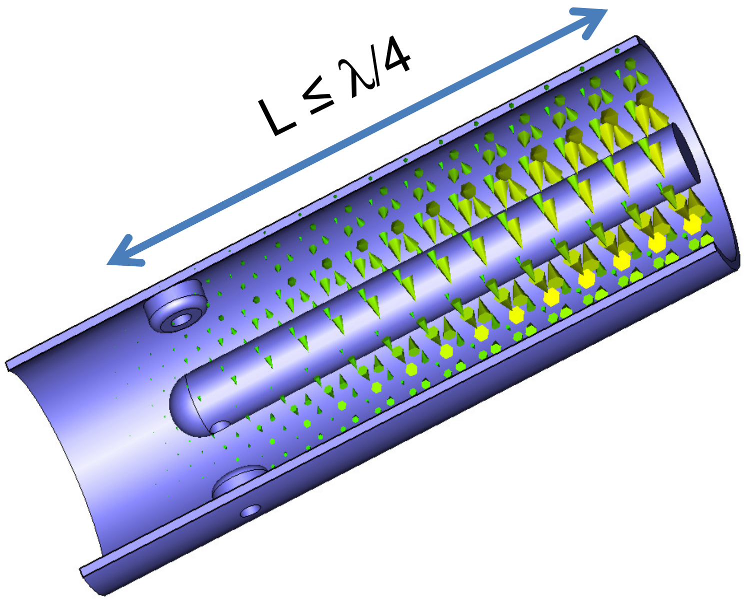
$$\begin{aligned} E_a &= 10\ \mathrm{MV/m} \\ R_s &= 10\ \mathrm{m}\Omega \\ Q_0 &= 25500 \\ R_a &= 5 \cdot 10^6\ \Omega \\ P_c &= 198000\ \mathrm{W} \end{aligned}$$

SC

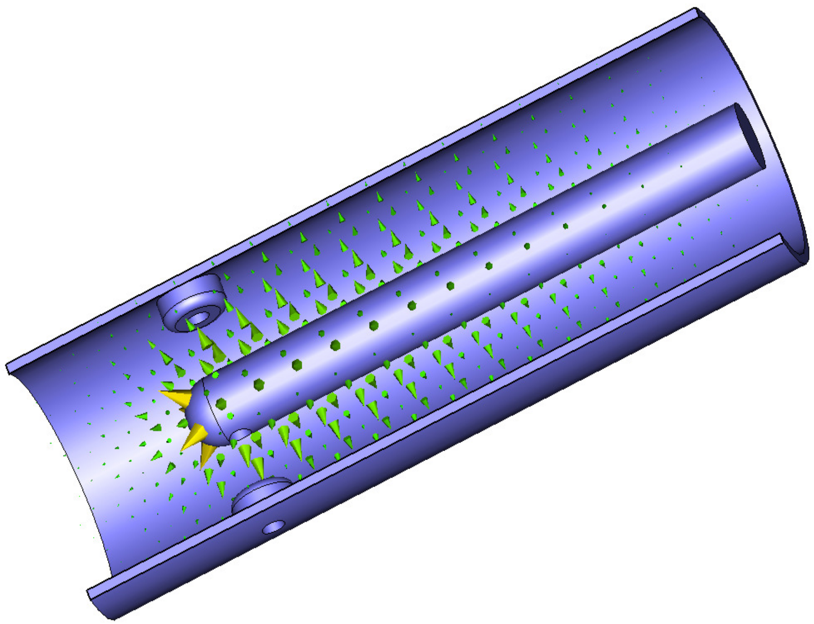
$$\begin{aligned} E_a &= 10\ \mathrm{MV/m} \\ R_s &= 20\ \mathrm{n}\Omega \\ Q_0 &= 1.3 \cdot 10^{10} \\ R_a &= 2.5 \cdot 10^{12}\ \Omega \\ P_c &= 0.4\ \mathrm{W} \end{aligned}$$

Quarter-Wave-Resonators

50 MHz ≤ f ≤ 200 MHz



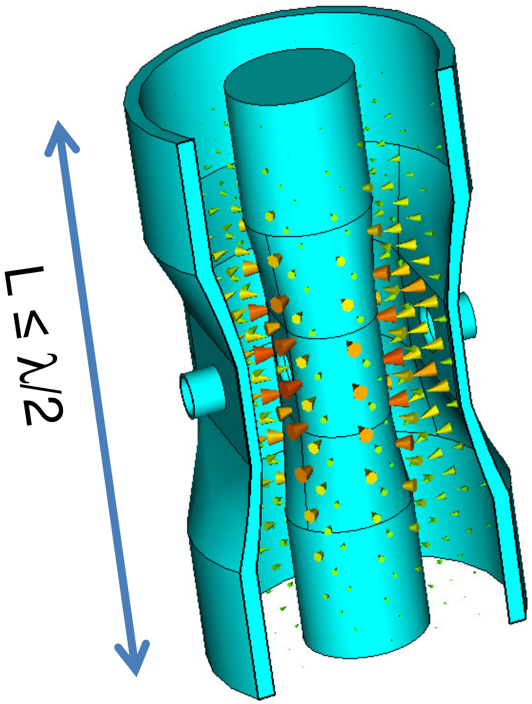
B-Field



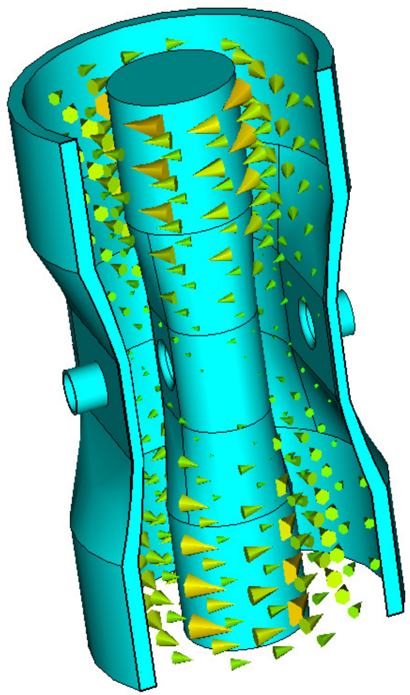
E-Field

Half-Wave-Resonators

150 MHz ≤ f ≤ 700 MHz



B-Field

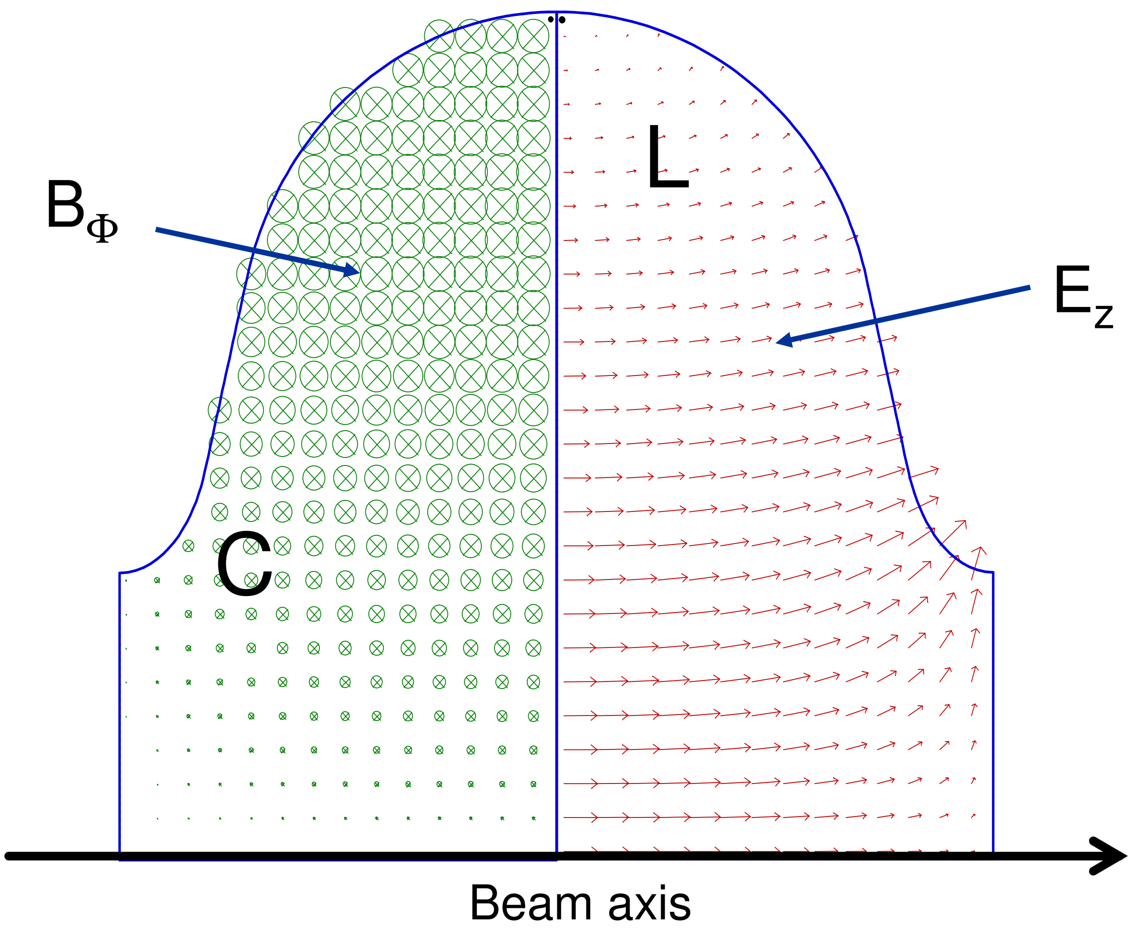


E-Field

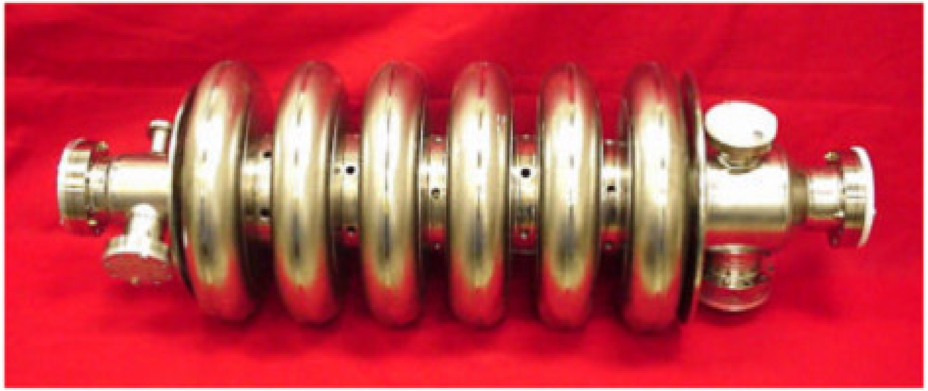

SC CH-Cavities
150 MHz ≤ f ≤ 500 MHz

Elliptical Cavities

350 MHz ≤ f ≤ 3000 MHz



Elliptical Cavities



Spallation-Neutron Source (SNS)

f=805 MHz

$\beta=0.61$

$\beta=0.82$

SNS, Oak Ridge National Laboratory (ORNL)

Power Consumption Considerations

Power is a major issue for accelerators

→ Capital and operational costs

RF Power

Gradient
Beam Current
Shunt Impedance

Plug Power

Gradient
Beam Current
Shunt Impedance
Duty Factor
Efficiency cryogenics

Power Consumption P_c

Without Beam, cw

Normal conducting	Superconducting
U_a=3 MV L=1 m R_a/Q_0=2000 Ω R_s=3.7 mΩ $Q_0=2\cdot10^4$	U_a=3 MV L=1 m R_a/Q_0=2000 Ω R_s=12.6 nΩ Q_0(BCS)$=6\cdot10^9$
P_c=225000 W	P_c= 0.75 W

$$P_c = \frac{U_a^2}{R_a} = \frac{U_a^2}{\left(\frac{R_a}{Q_0}\right) Q_0}$$

Power Consumption P_c

Power consumption of sc cavities significantly lower (factor 10^4-10^5)
BUT: Real life is more complicated

$$R_s = R_{BCS} + \underbrace{R_{magnet} + R_0}$$

Additional resistance
(magnetic fields, material properties, surface preparation)

Superconducting

R_s=60 nΩ

P_c= 3.6 W

Efficiency of the cryogenic system

$$\eta = \left(\frac{4\ \mathrm{K}}{300\ \mathrm{K} - 4\ \mathrm{K}}\right) \cdot 0.25 \approx 0.003$$

Power Consumption (Plug Power P_{eff})

Without Beam, cw

Normal conducting

P_c=225000 W

η = 0.6 (RF amplifier)

P_{eff}=375000 W

Superconducting

P_c= 3.6 W

15 W static losses

P_{tot}= 18.6 W

η = 0.003 (cryogenic system)

P_{eff}= 6200 W

$$\boxed{\frac{P_{nc}}{P_{sc}} \approx 60}$$

Power Consumption (Plug Power P_{eff})

With 20 mA Beam, cw
P_{beam}=UI

Normal conducting		Superconducting
P_c=225000 W	η = 0.6 (RF amplifier)	P_{cryo}= 6200 W
P_{beam}=60000 W		P_{beam}= 60000 W
P_{eff}=475000 W		P_{eff}= 106200 W

$$\boxed{\frac{P_{nc}}{P_{sc}} \approx 4.5}$$

Choice of Technology (NC-SC)

Normal Conducting	Superconducting
Low Energy	High Energy
High Beam Power	Low Beam Power
Low Duty Factor	High Duty Factor

Summary

- RF parameter of cavities
- RFQ-Structures
- RT Cavities
- SC Cavities
- Comparison of power consumption rt-sc

Not topic of this talk, but very important:

Tuning, power coupling, many other effects as multi pacting, Lorentz force detuning, field emission, ……


Thank you