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SRF Course Topics at Erice
(My lectures in red)

- Superconductivity – Larbalastier, Ciovati
- General comments on SC cavity design choices for accelerators
- Basics of SRF cavities
  - Structure Types
- Basic RF Cavity Design Principles/ Figures of Merit
  - Gradient, Losses, Q, Shunt Impedance, Peak Fields…
- SC/NC comparison for CW application
- Design Aspects for Multicells
- Higher Order Modes and their importance in cavity design
- Mechanical Aspects of Cavity Design
- Couplers/Tuners/…
- Cavity Performance Aspects/Cavity Technology- Antoine
  - Multipacting, Breakdown (Quench), Field Emission, Q-Slope
- Fundamental critical fields/Ultimate gradient possibilities - Antoine
- Cavity Fabrication /Preparation - Singer
- Cavity Testing - Reschke
- Wide Range of Applications

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Cavity Design and Ancillaries I and 2

- General remarks on literature for SRF
- Design principles
- Single cell cavity design – Chapter 2
- SC/NC comparison for rf losses
- Higher Order Modes – Chapter 15
- Codes - Chapter 2
- Optimizing cavity shape for desired goals
- Mechanical design aspects
- Multicells – Chapter 7
- Couplers – Chapters 16 - 19
- Tuners

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Overall Approach

Mostly Conceptual with pictures
Will go fast through many slides, refer to texts
Some quantitative aspects – references
Draw examples from various accelerator applications

References:
Extensive Literature +
2 Text Books (1998 and 2010)
Lots of Review Papers
SRF Workshop Proceedings (1980, 83, 85….2001)
(including Tutorials)
RAST articles (very recent)

Read Chapters of Book for lots of additional material on
These topics

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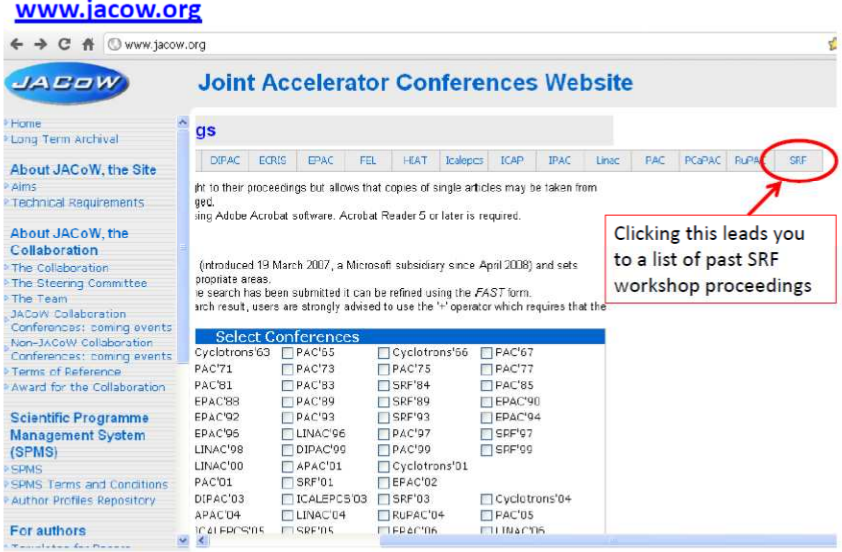
All SRF Workshop/Conference Proceedings can be found at www.jacow.org



General Accelerator Requirements That Drive SC Cavity Design Choices, v/c ~ 1, v/c <1

Voltage needed

Storage Rings

CESR-III: 7 MV, KEK-B HER: 14 MV, LEP-II: 3 GV

Proton Linac: 1 GV SNS, ESS

Linac-Based FEL or ERL : 500 MeV - 5 GeV

Linear Collider: 500 - 1000 GV

Duty Factor (RF on time x Repetition Rate)

Storage Rings: CW

Linac-Based FEL or ERL CW

Proton Linacs: < 10%

Linear Collider: 0.01 - 1%

Beam Current, Ave. Beam Power, Beam loss allowed

Storage Rings: amp, MW

Linac-Based FEL or ERL 50 mA - 100 mA

Proton Linacs: 10 - 100 mA, 1- 10 MW

Linear Collider: few ma, 10 MW

Low Velocity Accelerators

- Transition energies for v< c accelerators

Cavity Design Choices

- Main Choices
  - RF Frequency
  - Operating Gradient
  - Operating Temperature
  - Number of Cells
  - Cell Shapes
  - Type of Structure (low velocity)
  - Beam Aperture
- Optimizations Involve Many Trade-offs
- Best Cavity/Accelerator Performance for Least Risk
- Minimize Capital + Operating Cost
- Discuss parameters/dependencies
  - But not the trade-offs
  - Which are particular to each accelerator design

Example Optimizations

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)

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Ideal Cavity

- Pill-box shape

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Basics for Radiofrequency Cavities

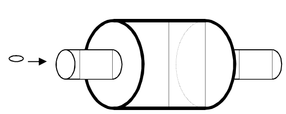
$$E_z = E_0 J_0\left(\frac{2.405\rho}{R}\right) e^{-i\omega t}$$

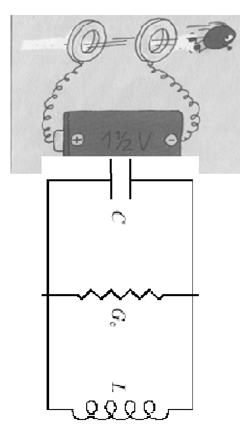
$$H_\phi = -i\frac{E_0}{\eta} J_1\left(\frac{2.405\rho}{R}\right) e^{-i\omega t},$$

$$\omega_{010} = \frac{2.405c}{R},$$

TM_{010} mode

•Add beam tube for charge to enter and exit





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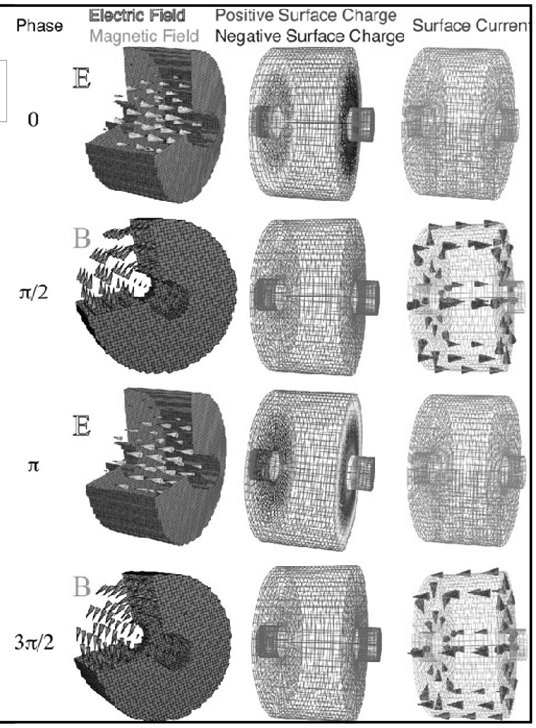
RF accelerator cavities
Fields and Currents



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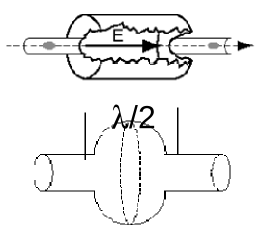
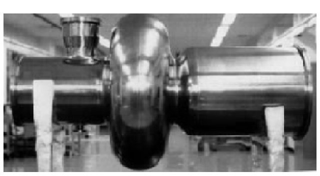
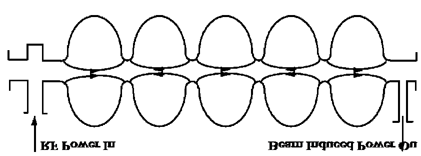
Medium and High Velocity Structures β = v/c = 0.5 -> 1

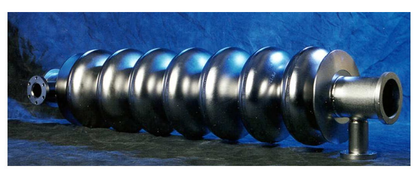


Basic Principle, v/c = 1

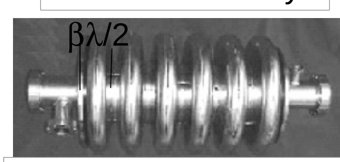


Single Cell





Multi-Cell Cavity



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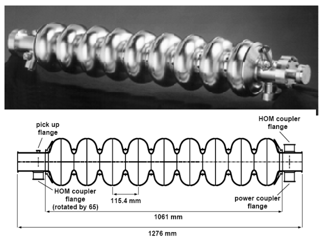
Squeezed Cells for v/c = 0.5

Structure Examples

1300 MHz Structures for Accelerating Particles at v ~ c



TESLA-shape

(DESY, TTF)

Structures for Particles at v < c (SNS)

For protons at 1 ~ GeV

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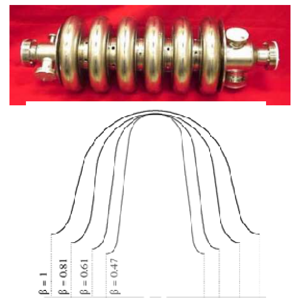
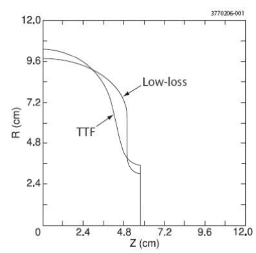
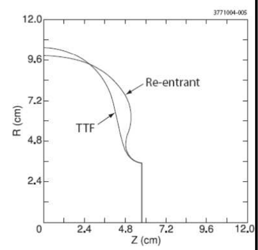


Low-Loss shape (Jlab, KEK…)

Re-entrant shape (Cornell)





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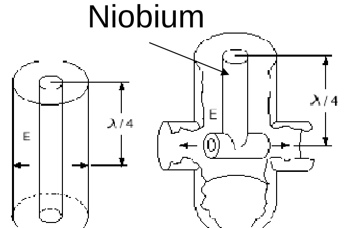
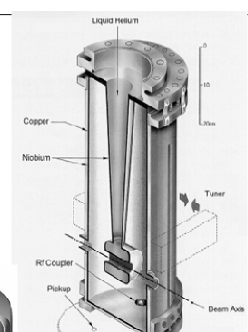
Low Velocity Structures, β = v/c = 0.01 -> 0.2

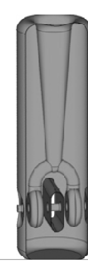
Niobium



Basic Principle

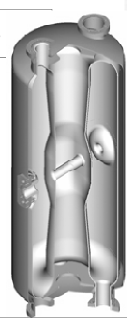


Quarter Wave

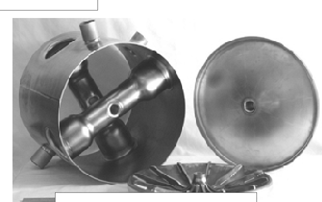


Inter-Digital

Split -Ring



Half-Wave



Spoke

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Range of Velocity and Frequency

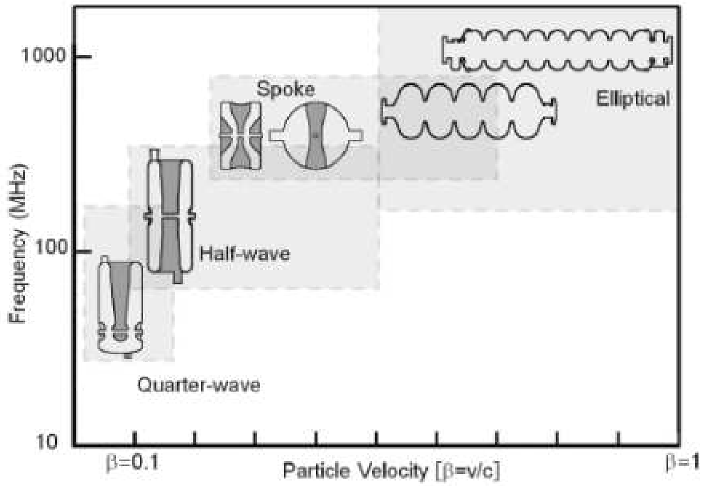

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Table 1. Operational superconducting cavity linacs for low beta.

Facility	Cavity type (s)	Frequency (MHz)	Beta (v/c)	Number of cavities	First operation
Argonne ATLAS	Split-ring, QWR	48–109	0.01–0.15	64	1978
Stony Brook	Split-ring, QWR	150.4	0.07–0.1	40	1983
Florida State	Split-ring	97	0.07–0.1	15	1987
JAERI	QWR	130, 260	0.1	46	1994
INFN Legnaro	QWR	80, 160	0.05–0.13	74	1994
Canberra	Split-ring, QWR	150.4	0.09–0.11	14	1996
TRIUMF	QWR	106, 141	0.057, 0.071	40	2006
New Delhi	QWR	97	0.08	18	2007
SARAF	HWR	176	0.08	6	2009
Michigan State	QWR	80.5	0.045	6	2011

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Table 2. Proposed SRF projects based on $\lambda/2$ cavities.

Facility	Cavity type (s)	Frequency (MHz)	Beta (v/c)	Number of cavities	
SARAF Phase II	QWR	176	0.08–0.12	28	1.0–2.1
MSU FRIB	HWR	322	0.28, 0.53	224	0.8–3.7
RISP	HWR	162.6, 325	0.12, 0.3, 0.53	238	0.5–0.8
Project X	HWR, spoke	162.5, 325	0.10–0.47	61	1.7–3.8
EURISOL	HWR, spoke	176, 352	0.09, 0.15, 0.3	108	0.6–2.0
ESS	2-spoke	352	0.5	32	4.4
IFMIF	HWR	175	0.094	14	0.7
China CAS	HWR	162.5	0.09	16	0.4

Table 1. Fundamental SRF at high-β accelerators around the world.

Accelerator	Laboratory	Country	Accelerator type	Number of cavities	Frequency (MHz)	Active length (m)	Status
SCA	Stanford U.	USA	Linac, CW	8	1300	19.4	Decommissioned
TRISTAN	KEK	Japan	Storage ring/collider	32	508	47	Decommissioned
HERA	DESY	Germany	Storage ring/collider	16	500	19.2	Decommissioned
LEP	CERN	Switzerland	Storage ring/collider	288	352	490	Decommissioned
S-DALINAC	Darmstadt U.	Germany	Recirculating linac	12	2998	10.3	Operational
CEBAF	JLab	USA	Recirculating linac	338	1497	169	Operational
JLab FEL	JLab	USA	Energy recovery linac	30	1497	14.6	Operational
FLASH	DESY	Germany	Linac, pulsed	56	1300	58	Operational
A0 Photoinjector	Fermilab	USA	Linac, pulsed	1	1300	1.0	Operational
ELBE	HZDR	Germany	Linac, CW	6	1300	6.2	Operational
ERL Injector	Cornell U.	USA	Linac, CW	5	1300	1.2	Operational
ALICE	ASTeC	UK	Energy recovery linac	4	1300	4.2	Operational
SNS	ORNL	USA	Linac, pulsed	81 (β = 0.81)	805	81	Operational
KEK-B	KEK	Japan	Storage ring/collider	8	508	2.4	Operational
CESR	Cornell U.	USA	Storage ring/collider/light source	4	500	1.2	Operational
TLS	NSRRC	Taiwan	Storage ring/light source	1	500	0.3	Operational
CLS	Canadian Light Source	Canada	Storage ring/light source	1	500	0.3	Operational
BEPC-II	IHEP	China	Storage ring/collider/light source	2	500	0.6	Operational
Diamond	Diamond Light Source	UK	Storage ring/light source	2	500	0.6	Operational
SSRF	SINAP	China	Storage ring/light source	3	500	0.9	Operational
JAEA ERL-FEL	JAEA	Japan	Energy recovery linac	4	500	2.0	Operational
LHC	CERN	Switzerland	Storage ring/collider	16	400	6	Operational
SOLEIL	Synchrotron SOLEIL	France	Storage ring/light source	4	352	1.7	Operational
CEBAF Upgrade	JLab	USA	Recirculating linac	+80	1497	55	Construction
European XFEL	DESY	Germany	Linac, pulsed	800	1300	664	Construction
Compact ERL	KEK	Japan	Energy recovery linac	3	1300	2.1	Construction
PKU-SETF	Peking U.	China	Energy recovery linac	2	1300	2.1	Construction
ASTA	Fermilab	USA	Linac, pulsed	24	1300	25	Construction
R&D ERL	BNL	USA	Energy recovery linac	1	704	1.1	Construction
CeC PoP at RHIC	BNL	USA	Linac, CW	1	704	1.1	Construction
PLS-II	PAL	Korea	Storage ring/light source	2	500	0.6	Construction
NSLS-II	BNL	USA	Storage ring/light source	2 (4)	500	0.6 (1.2)	Construction
TPS	NSRRC	Taiwan	Storage ring/light source	2	500	0.6	Construction
RHIC	BNL	USA	Storage ring/collider	1	56	—	Construction
Cornell ERL	Cornell U.	USA	Energy recovery linac	384	1300	310	R&D
ILC	—	—	Linear collider	15,764	1300	16,285	R&D
Project X	Fermilab	USA	Linac, pulsed	224	1300	232	R&D
SNS Upgrade	ORNL	USA	Linac, pulsed	+36	805	40	R&D
Project X	Fermilab	USA	Linac, CW	152 (β = 0.9)	650	158	R&D

Table 2. Other SRF systems at high-β accelerators around the world.

Accelerator	Laboratory	Country	Accelerator type	Number of cavities	Frequency (MHz)	Stat
Deflecting/crab cavities:						
PS	CERN	Switzerland	Beamline	2	2865	Decommi
KEK-B	KEK	Japan	Storage ring/collider	2	509	Operatio
APS	ANL	USA	Storage ring/light source	8	2815	R&D
LHC Upgrade	CERN	Switzerland	Storage ring/collider	4 (6)	400	R&D
Harmonic RF systems:						
FLASH	DESY	Germany	Linac, pulsed	4	3900	Operatio
Elettra	Sincrotrone Trieste	Italy	Storage ring/light source	2	1500	Operatio
SLS	PSI	Switzerland	Storage ring/light source	2	1500	Operatio
NSLS-II	BNL	USA	Storage ring/light source	1 (2)	1500	R&D
SRF photoinjectors:						
ELBE	HZDR	Germany	Linac, CW	1	1300	Operatio
PKU-SETF	Peking U.	China	Energy recovery linac	1	1300	Operatio
NPS-FEL	NPS	USA	Linac, CW	1	500	Operatio
R&D ERL	BNL	USA	Energy recovery linac	1	704	Construc
CeC PoP at RHIC	BNL	USA	Linac, CW	1	112	Construc
B*ERL*inPro	HZB	Germany	Energy recovery linac	1	1300	R&D
NPS-FEL	NPS	USA	Linac, CW	1	700	R&D
WiFEL	U. of Wisconsin	USA	Linac, CW	1	200	R&D

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Figures of Merit

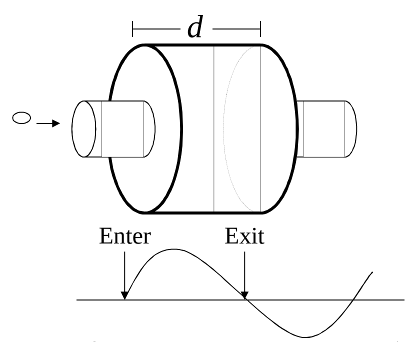
Accelerating Voltage/Field

(*v* = *c* Particles)

- For maximum acceleration need

$$T_{\rm cav} = \frac{d}{c} = \frac{T_{\rm rf}}{2}$$

so that the field always points in the same direction as the bunch traverses the cavity



- Accelerating voltage then is: $$V_{\rm c} = \left| \int_0^d E_z(\rho = 0, z) e^{i\omega_0 z/c} dz \right|$$

$$V_{\rm c} = E_0 \left| \int_0^d e^{i\omega_0 z/c} dz \right| = dE_0 \frac{\sin\left(\frac{\omega_0 d}{2c}\right)}{\frac{\omega_0 d}{2c}} = dE_0 T.$$

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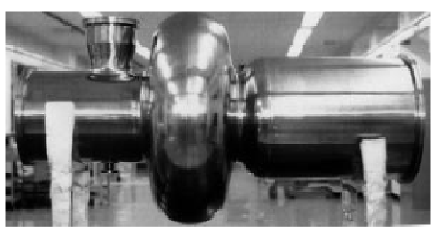
- Accelerating field is: $$E_{\rm acc} = \frac{V_{\rm c}}{d} = 2E_0/\pi.$$

Figures of Merit for SC Cavity

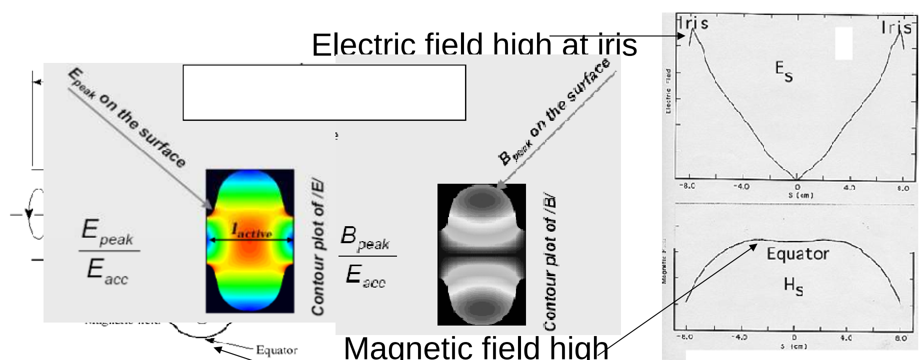
- Accelerating Field and Q: E_{acc}, Q
- Stored Energy, Geometry Factor
- Peak Electric and Magnetic Field Ratios
  - E_{pk}/E_{acc}, H_{pk}/E_{acc}
- Shunt Impedance, Geometric Shunt Impedance: R_a, R_a/Q

Single Cell Cavities

KEK-B Cavity



Electric field high at iris



Magnetic field high at equator

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Figures of Merit

Peak Fields

- *For E_{acc}* → important parameter is $\boldsymbol{E_{pk}/E_{acc}}$,
  - Typically 2 - 2.6
- Make as small as possible, to avoid problems with field emission - more later.
- Equally important is $\boldsymbol{H_{pk}/E_{acc}}$, to maintain SC
  - Typically 40 - 50 Oe/MV/m or 4 – 5 mT/MV/m
- $\boldsymbol{H_{pk}/E_{acc}}$ can lead to premature quench problems (thermal breakdown).
- Ratios increase significantly
  - when beam tubes are added to the cavity
  - or when aperture is made larger.

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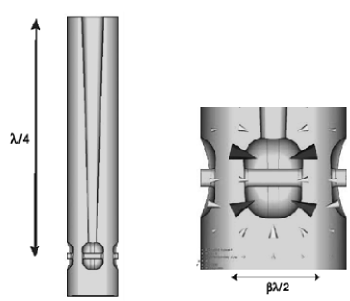
Peak fields for low beta cavities are higher

Typical

Epk/Eacc = 4 - 6

Hpk/Eacc = 60 - 200 Oe/MV/m

Hpk



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Figures of Merit

Dissipated Power, Stored Energy, Cavity Quality (Q)

•Surface currents ($\propto H$) result in dissipation proportional to the surface resistance (R_s): $$\frac{dP_c}{ds} = \frac{1}{2}R_s|\mathbf{H}|^2$$

•Dissipation in the cavity wall given by surface integral: $$P_c = \frac{1}{2}R_s\int_S |\mathbf{H}|^2\, ds$$

•Stored energy is: $$U = \frac{1}{2}\mu_0\int_V |\mathbf{H}|^2\, dv$$

•Define Quality (Q) as $Q_0 = \dfrac{\omega_0 U}{P_c} = 2\pi \dfrac{U}{T_{rf}\, P_c}$

which is ~ 2 π number of cycles it takes to dissipate the energy stored in the cavity → Easy way to measure Q

- $Q_{nc} \approx 10^4$, $Q_{sc} \approx 10^{10}$

Galileo, 1600 AD

Geometry Factor

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Since the time averaged energy in the electric field equals that in netic field, the total energy in the cavity is given by

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

where the integral is taken over the volume of the cavity.

the dissipated power $$P_c = \frac{1}{2} R_s \int_S |\mathbf{H}|^2\, ds,$$

where the integration is taken over the interior cavity surface.

$$Q_0 = \frac{\omega_0 U}{P_c}, \qquad Q_0 = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2\, dv}{R_s \int_S |\mathbf{H}|^2\, ds}.$$

The Q_0 is frequently written as

$$Q_0 = \frac{G}{R_s},$$

where

$$G = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2\, dv}{\int_S |\mathbf{H}|^2\, ds}$$

Pill-Box Results

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For the pill-box TM_{010} mode we find

$$U = E_0^2 \pi d \epsilon_0 \int_0^R \rho J_1^2\left(\frac{2.405\rho}{R}\right) d\rho$$

$$P_c = \frac{R_s E_0^2}{\eta^2}\left\{2\pi \int_0^R \rho J_1^2\left(\frac{2.405\rho}{R}\right) d\rho + \pi R d J_1^2(2.405)\right\}$$

$$\int \rho J_\nu^2(\alpha\rho)\, d\rho = \frac{\rho^2}{2}\left[J_\nu^2(\alpha\rho) - J_{\nu-1}(\alpha\rho) J_{\nu+1}(\alpha\rho)\right]$$

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

$$P_c = \frac{\pi R_s E_0^2}{\eta^2} J_1^2(2.405) R(R+d)$$

$$G = \frac{\omega_0 \mu_0 d R^2}{2(R^2 + Rd)} = \eta \frac{2.405 d}{2(R+d)} = \frac{453\frac{d}{R}}{1+\frac{d}{R}}\,\Omega.$$

G is indeed independent of the cavity's size.

$$G = 257\ \Omega. \qquad \frac{d}{R} = \frac{\pi}{2.405}$$

If $R_s = 20\ \text{n}\Omega$ $$Q_0 = \frac{G}{R_s} = 1.3 \times 10^{10}.$$

A typical length of $d = 10$ cm requires a cavity radius R of 7.65 cm or, equivalently, a resonant frequency of 1.5 GHz. For operation at $V_c = 1$ MV the following results are found to apply:

$$\begin{aligned} E_{acc} &= \frac{V_c}{d} = 10 \text{ MV/m} \\ E_{pk} &= E_0 = \frac{\pi}{2} E_{acc} = 15.7 \text{ MV/m} \\ H_{pk} &= 30.5 \frac{\text{Oe}}{\text{MV/m}} E_{acc} = 305 \text{ Oe} \\ U &= E_0^2 \frac{\pi \epsilon_0}{2} J_1^2(2.405) d R^2 = 0.54 \text{ J} \\ P_c &= \frac{\omega U}{Q_0} = 0.4 \text{ W.} \end{aligned}$$

$$\begin{aligned} \frac{E_{pk}}{E_{acc}} &= \frac{\pi}{2} = 1.6 \\ \frac{H_{pk}}{E_{acc}} &= 2430 \frac{\text{A/m}}{\text{MV/m}} \end{aligned}$$

Figures of Merit
Shunt Impedance (R_a)

- Shunt impedance (R_a) determines how much acceleration one gets for a given dissipation (analogous to Ohm's Law)

$$R_a = \frac{V_c^2}{P_c}$$

→ To maximize acceleration, must maximize shunt impedance.

Another important figure of merit is $\frac{R_a}{Q_0} = \frac{V_c^2}{\omega_0 U}$,

•Ra/Q only depends on the cavity geometry → Cavity design

Evaluation - Analytic Expressions

1.5 GHz pillbox cavity, R = 7.7 cm, d = 10 cm

$$\frac{R_a}{Q_0} = \frac{V_c^2}{\omega_0 U},$$

$$\frac{R_a}{Q_0} = 150\ \Omega\ \frac{d}{R} = 196\ \Omega$$

For Cu: R_s = 10 mohm → Q = 25,700, R_a = 5 Mohm
For Nb: R_s = 10 nohm → Q = 25,700,000,000,
R_a = 5 Tohm!

Figure of Merit for Cryo Losses

For the accelerating mode we often use the product of $G_{acc} \cdot (R/Q)_{acc}$, as a "measure" of the power P dissipated in the metal wall at the given accelerating voltage V_{acc} and the given surface resistance R_s.

$$\frac{P_{dissipated}}{V_{acc}^2} = \frac{R_s}{G_{acc} \cdot (R/Q)_{acc}}$$

This is due to the surface quality; Big improvement possible.

This is due to the geometry of cells; Moderate improvement possible.

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Real Cavities - Codes

- Adding beam tubes reduces R_a/Q by about x2 =>
- for Cu cavities use a small beam hole.
- Peak fields also increase.
  - Can be a problem for high gradient cavities
- Analytic calculations are no longer possible
  - especially if cavity is shaped is to optimize peak fields.
- → Use numerical codes.

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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.***