ECPM 2012 Tutorial session

RF SYSTEMS

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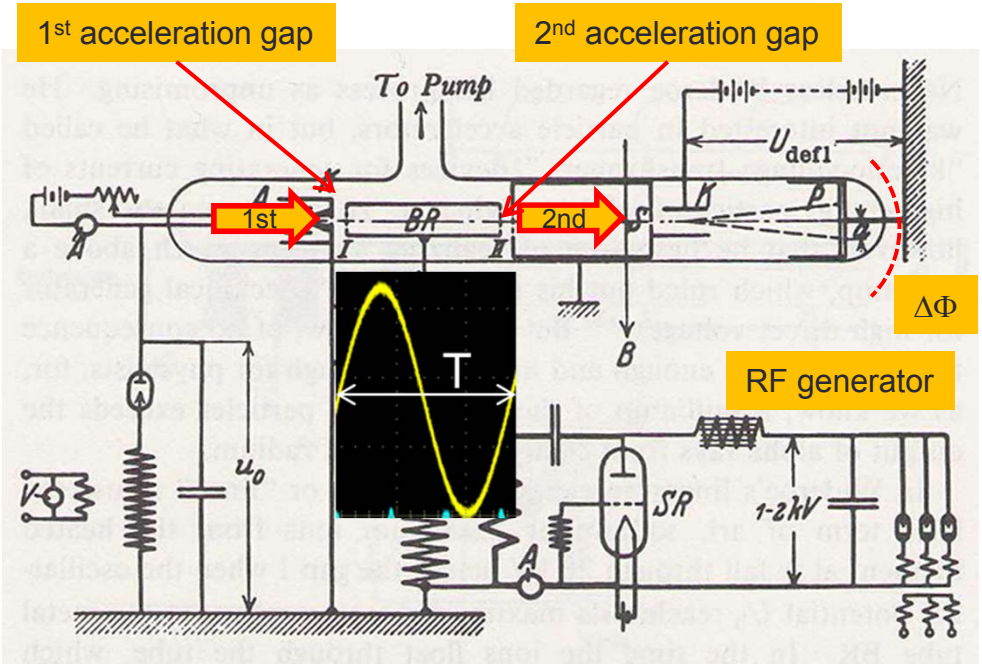
INFN-LNS

From a historical point of view a cyclotron can be seen as a Wideröe linear accelerator

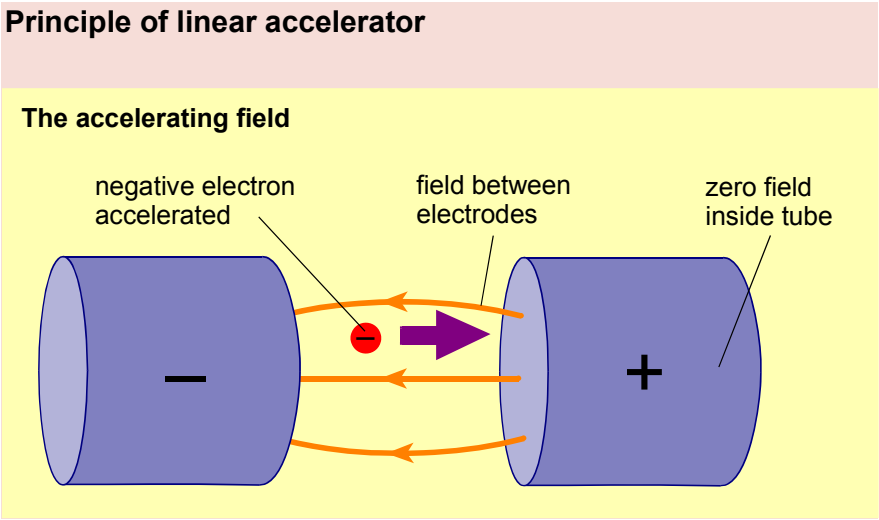


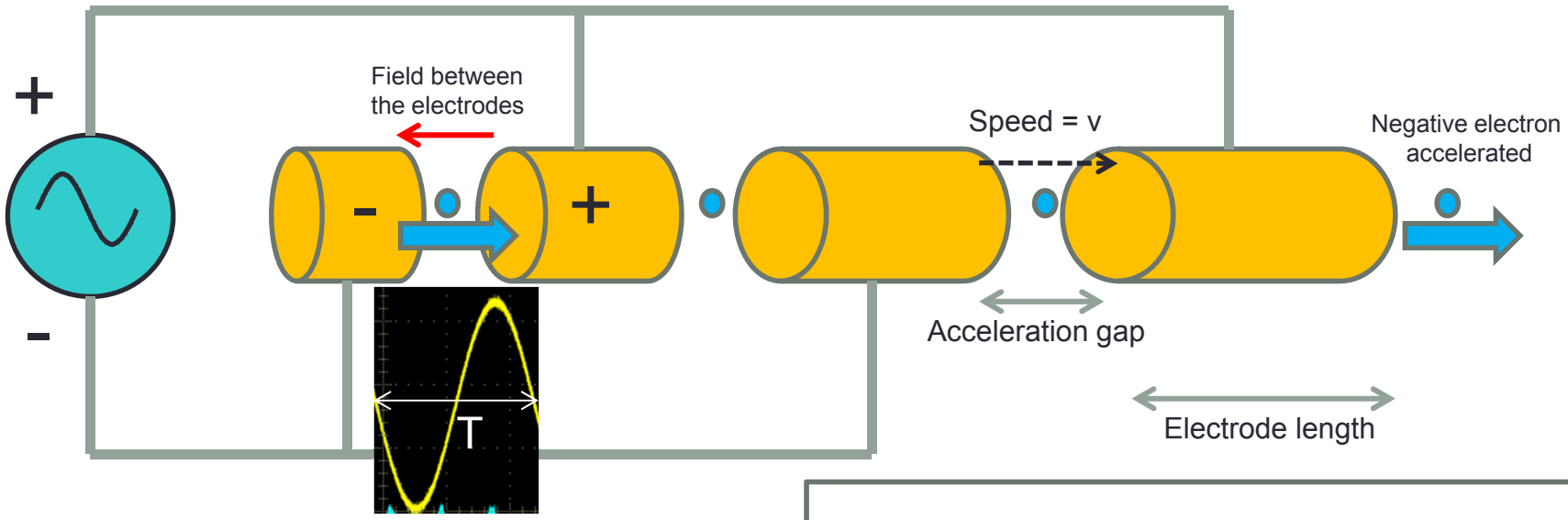
R. Wideröe, Arch. Elektrotech. 21, 387 (1928)

Diagram of the apparatus used by R. Wideröe in 1928 to demonstrate the **doubling of the energy of <u>heavy ions in resonance with a radiofrequency</u> electric field**. A radiofrequency generator produces RF voltages across two gaps I-II at the ends of a tubular electrode BR through which ions from the source K (at the left of BR) are accelerated.

which has been wrapped up into a flat spiral and encased in an evacuated chamber, with the addition of a steady magnetic field perpendicular to its plane (Ernest O. Lawrence)

If we reiterate the Rolf Wideroe principle using a series of acceleration gaps through tubular acceleration electrodes the energy can be increased many times, but try to imagine the technology, in the late 1920s. At that time Ernest Lawrence was looking for a method to accelerate particles to higher energies than could be attained with DC potentials, in order to study “nuclear excitation”. Lawrence realized that extension of Wideroe’s machine to such high energy would require a very long array of electrodes. Ernest Orlando Lawrence’s intuition was: why force the particles into a straight line path? With a magnetic field we can bend the particles in a circular path.





$$2t = T\ (RF\ period)$$

$$\frac{1}{T} = f\ (RF\ frequency)$$

$$f = \frac{c}{\lambda}$$

c is the speed of light
λ is the wave length

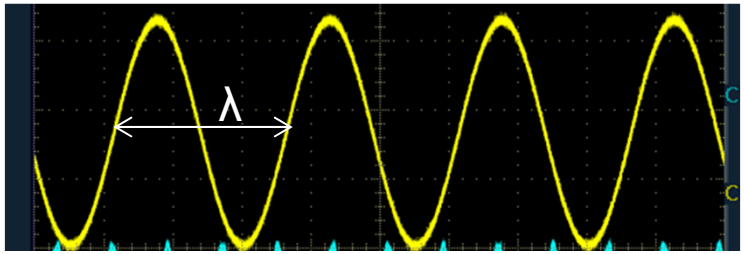
$$\frac{electrode\ lenght}{velocity} = \mathrm{t}\ (\mathrm{constant})$$

This rate is a constant time: t

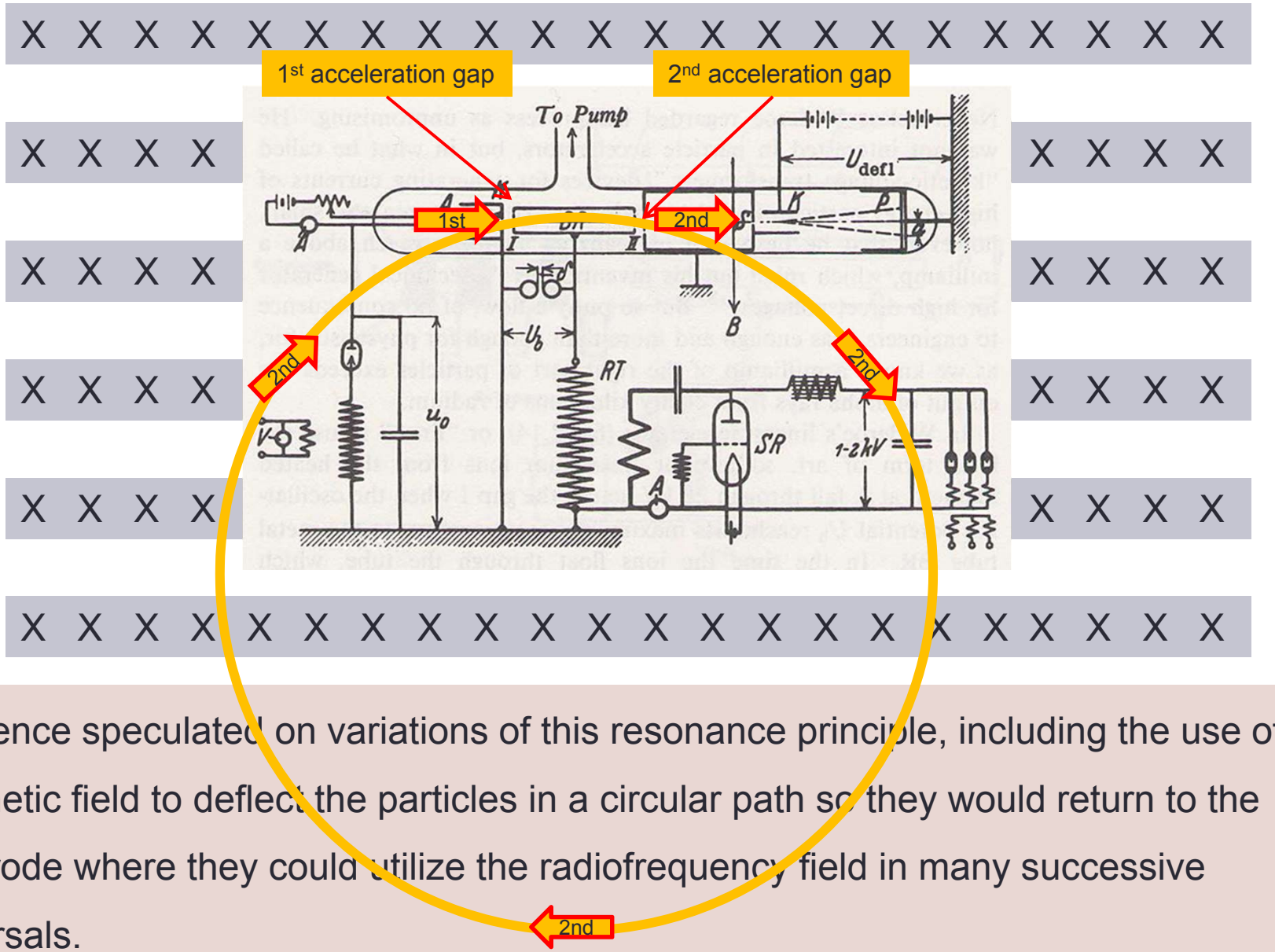
The length increases with the speed

with β= v/c ⇨ $l = \frac{T}{2}v$ ⇨ $\boldsymbol{l = \beta\ \frac{\lambda}{2}}$

Electrode length

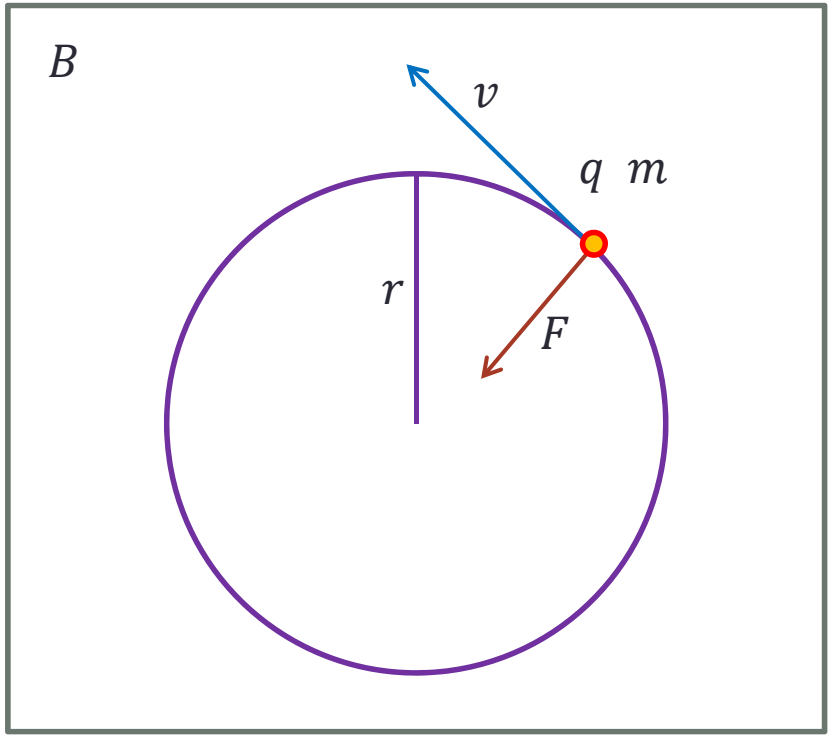


From R. Wideröe(1928) to Lawrence (1929)



Lawrence speculated on variations of this resonance principle, including the use of the magnetic field to deflect the particles in a circular path so they would return to the electrode where they could utilize the radiofrequency field in many successive traversals.

The property of ions moving in a circular path in a magnetic field is extremely important and easy to understand. **At every instant the electromagnetic force F_B supplies the centripetal force F_r required for a circular path**



Circular path of the particle

B magnetic field strength
r radius of the curvature path
F centripetal-magnetic force
q charge of the particle
m mass of the particle
v velocity of the particle

$$F_r = \frac{mv^2}{r} \qquad F_B = qvB$$

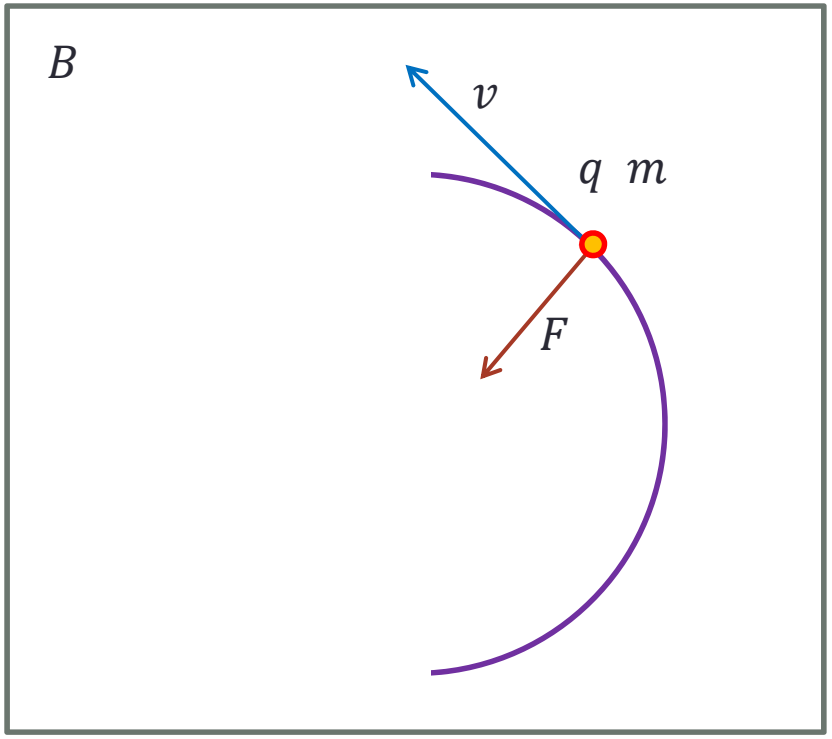
thus:

$$\frac{mv^2}{r} = qvB \qquad mv/r = qB$$

$$\omega = 2\pi f = v/r$$

substitute:

$$\boldsymbol{\omega = qB/m}$$ (*cyclotron frequency*)



and Wideroe? $2\pi f = \frac{v}{r}$

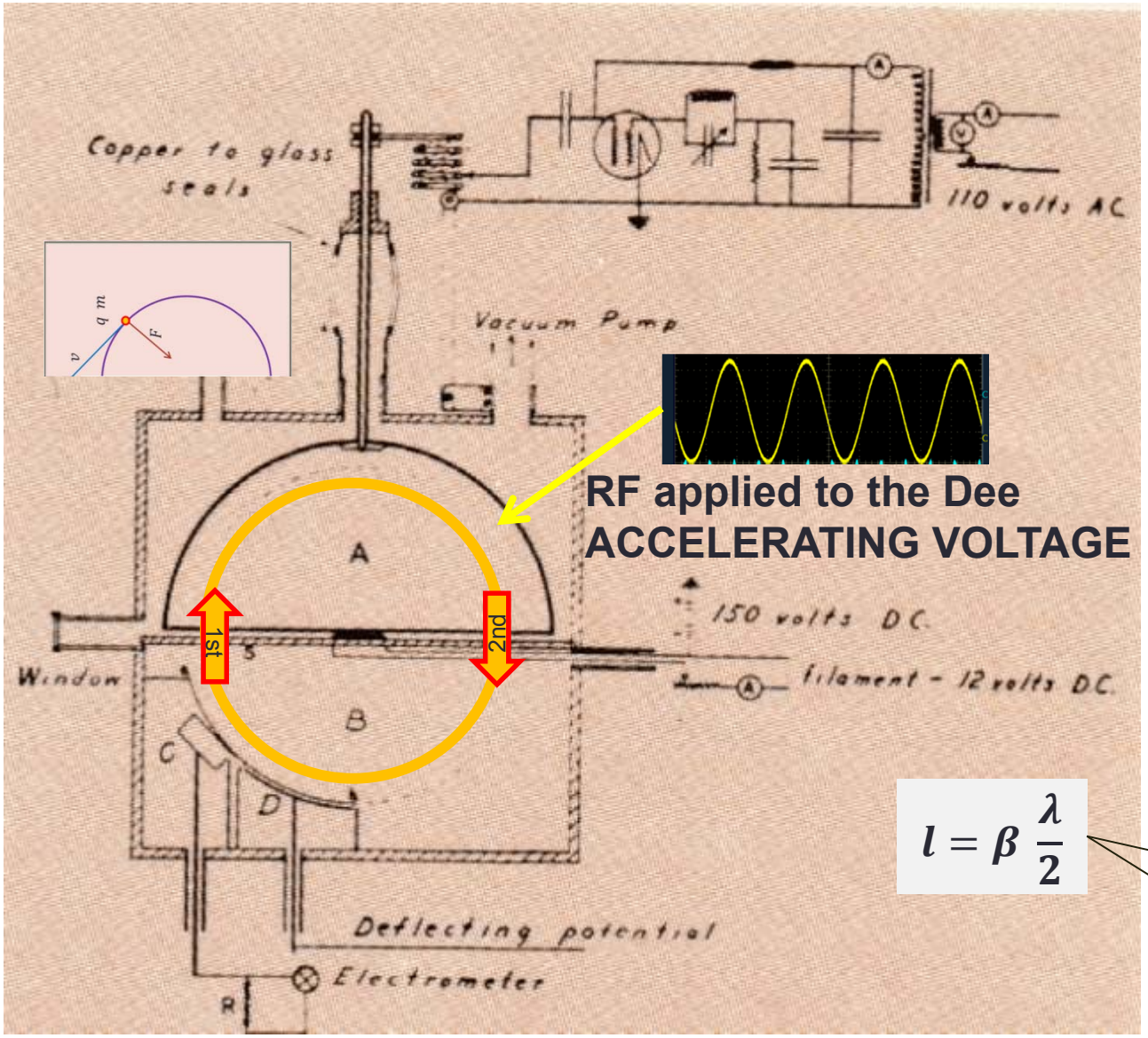
$$\pi r = \frac{v}{2f}$$

$$l = \frac{T}{2} v$$

$$\lambda = \frac{c}{f} \qquad T = \frac{1}{f} \qquad T = \lambda/c$$

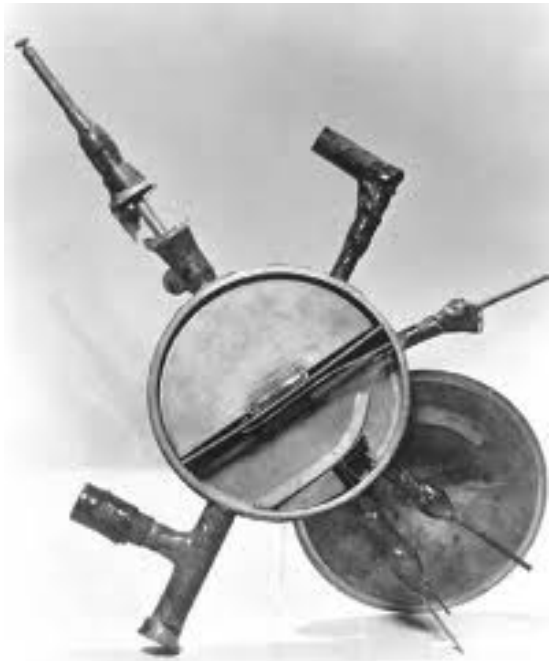
with β= v/c ⇒ $l = \frac{T}{2} v$ ⇒ $\boldsymbol{l = \beta \frac{\lambda}{2}}$

Electrode length



RF applied to the Dee
ACCELERATING VOLTAGE

$$l = \beta \frac{\lambda}{2}$$



The first successful cyclotron,

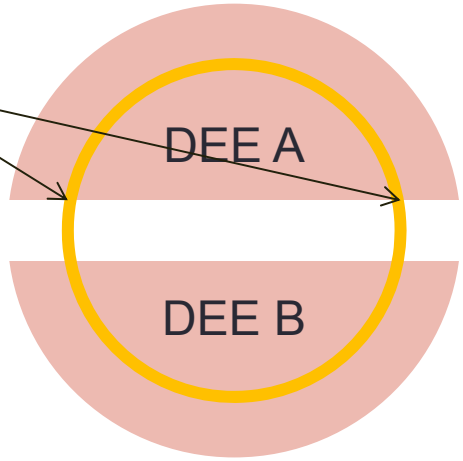
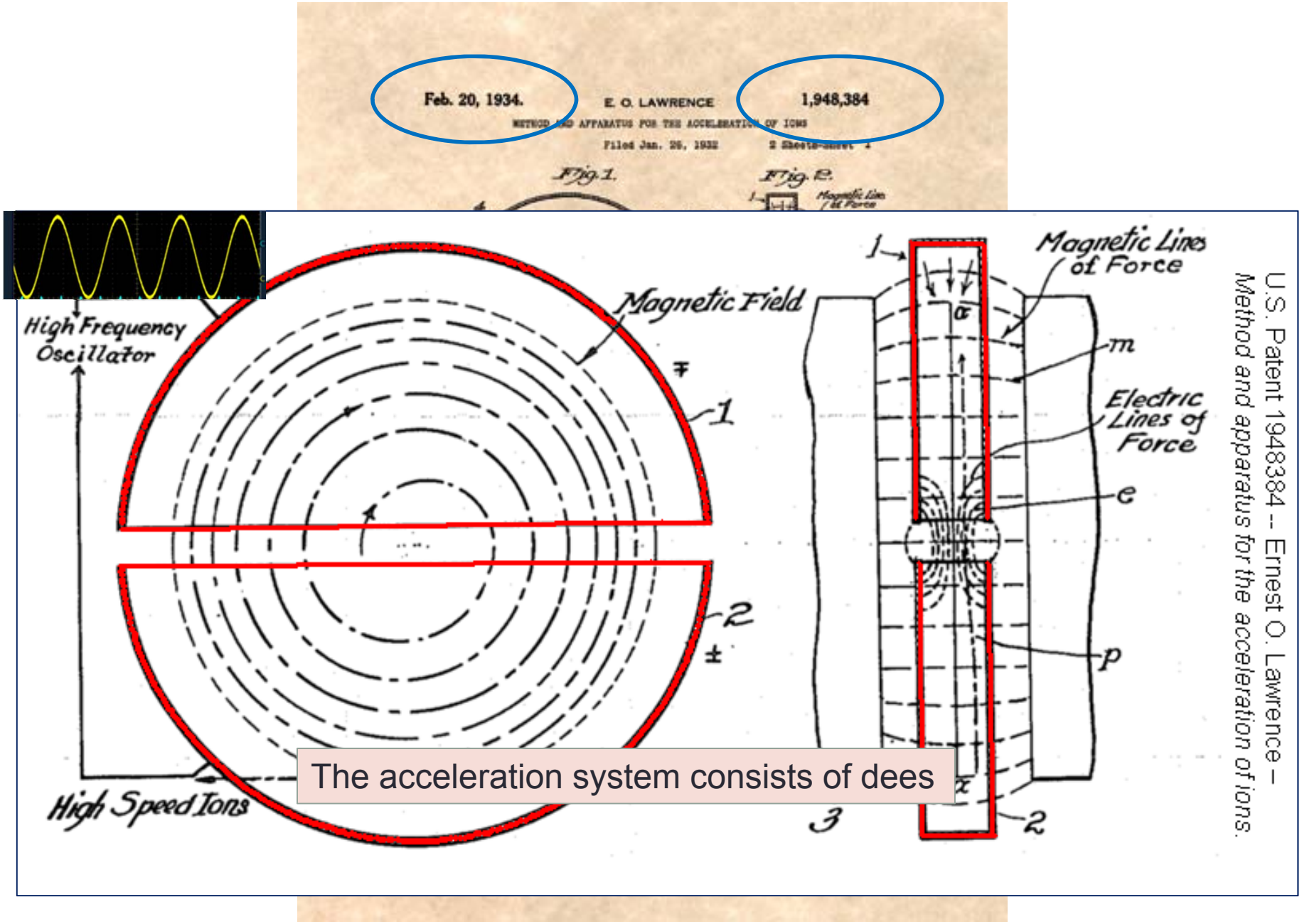
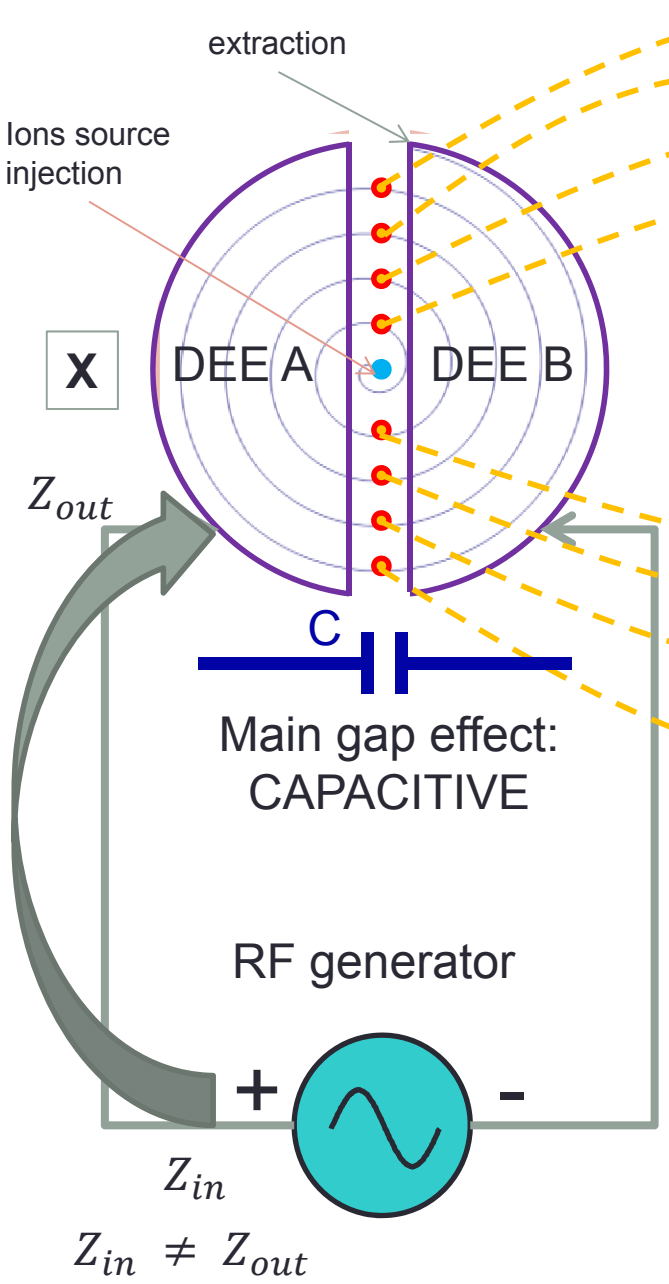


Diagram of the first successful cyclotron constructed by Lawrence and M. S. Livingston. The single Dee is five inches in diameter.

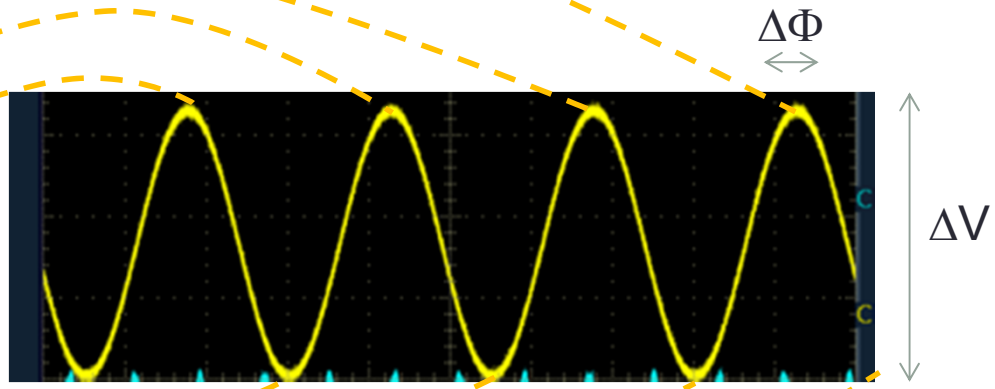


U.S. Patent 1948384 -- Ernest O. Lawrence – *Method and apparatus for the acceleration of ions.*

The acceleration system consists of dees



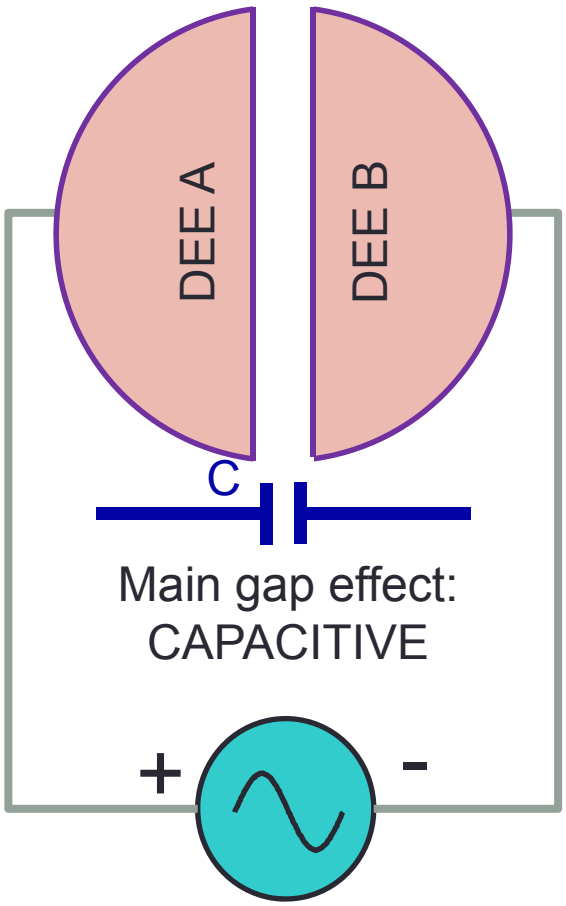
Simplified view of RF acceleration



$$f = \frac{qB}{2\pi m}$$

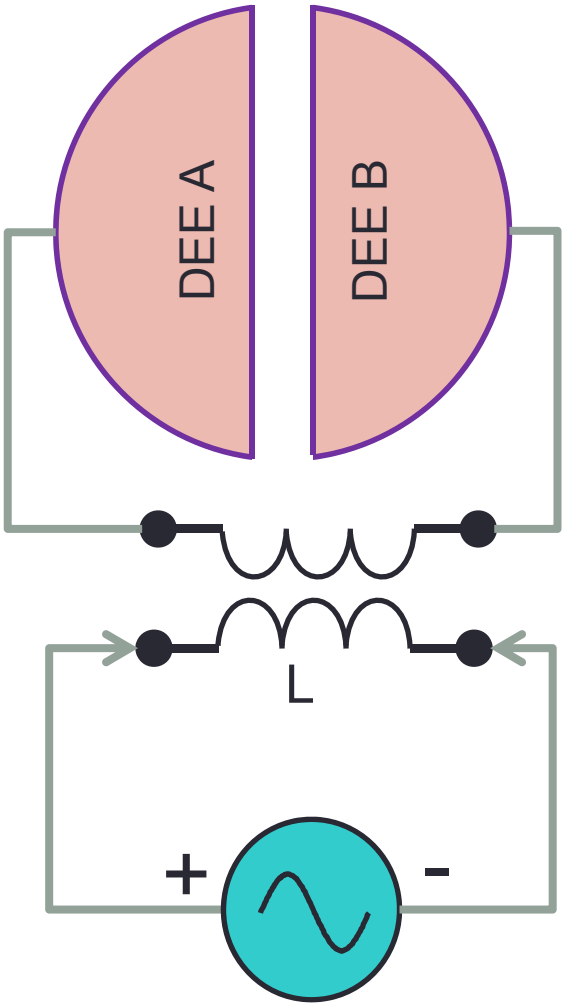
$$\omega = 2\pi f$$

Spiral trajectory for the particles - each turn the energy increase according to the radiofrequency electric field. Phase and amplitude stability are mandatory to allow perfect synchronisation between acceleration beam and electric field

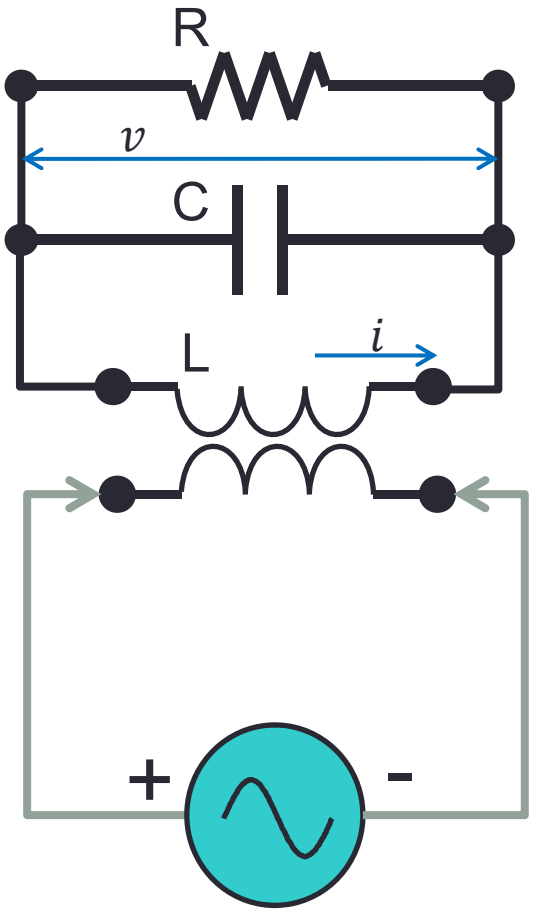


Main gap effect:
CAPACITIVE

Very poor efficiency and extremely critical for the RF generator



Resonant Circuit



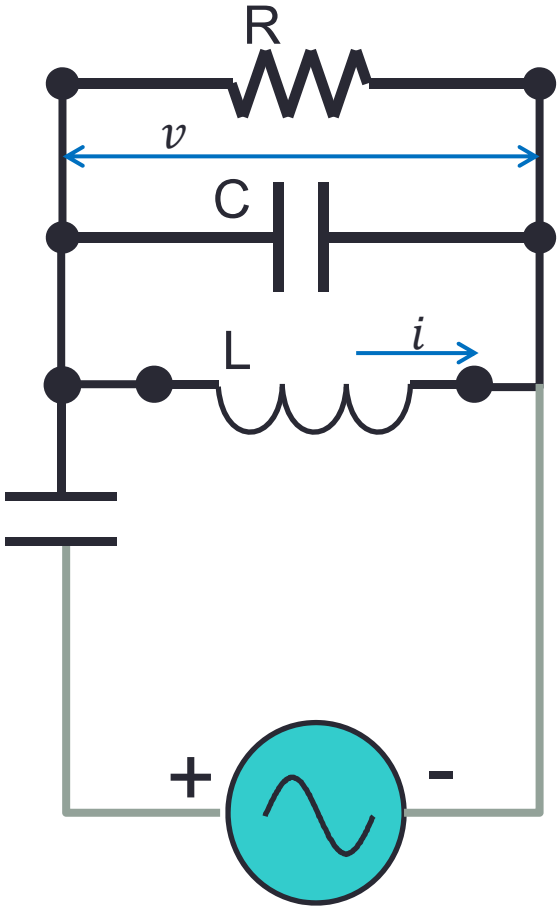
$\omega = 2\pi f$ In resonance condition we have: $X_C = X_L$

$$\frac{1}{j\omega C} = j\omega L \Rightarrow \omega^2 = 1/\sqrt{LC} \Rightarrow \boldsymbol{f = 1/2\pi\sqrt{LC}}$$

Capacitive coupling

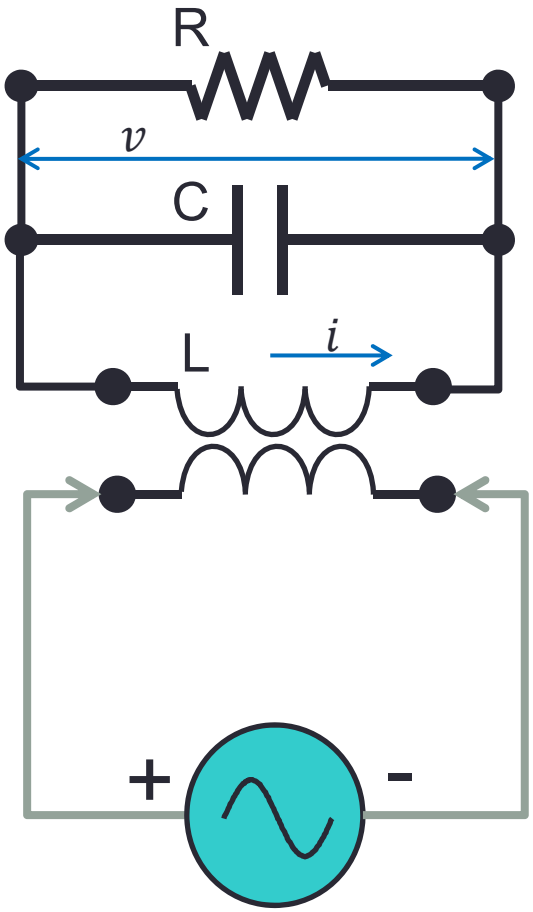
RESONANT CIRCUIT

Inductive coupling

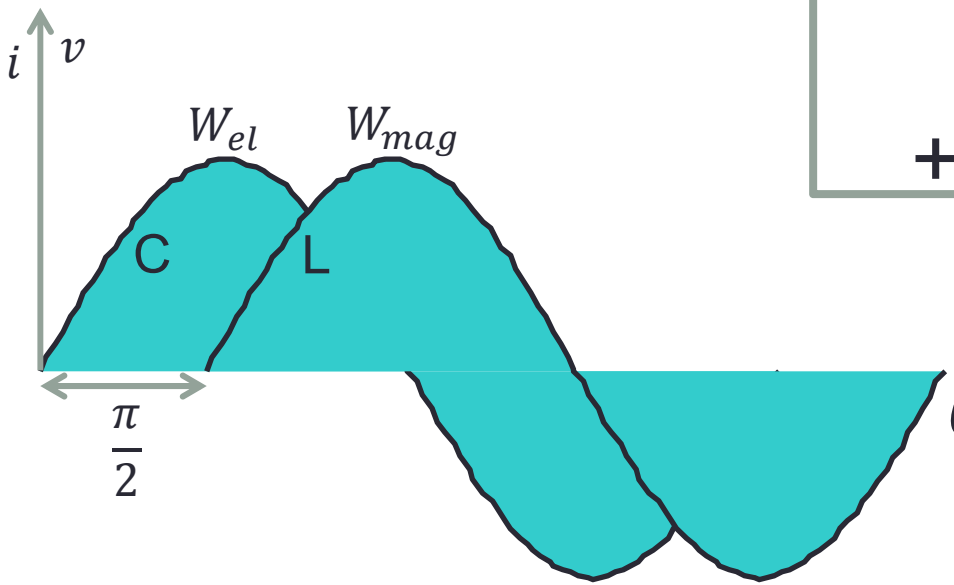


$$W_{el} = \frac{1}{2} C v^2$$

$$W_{mag} = \frac{1}{2} L i^2$$



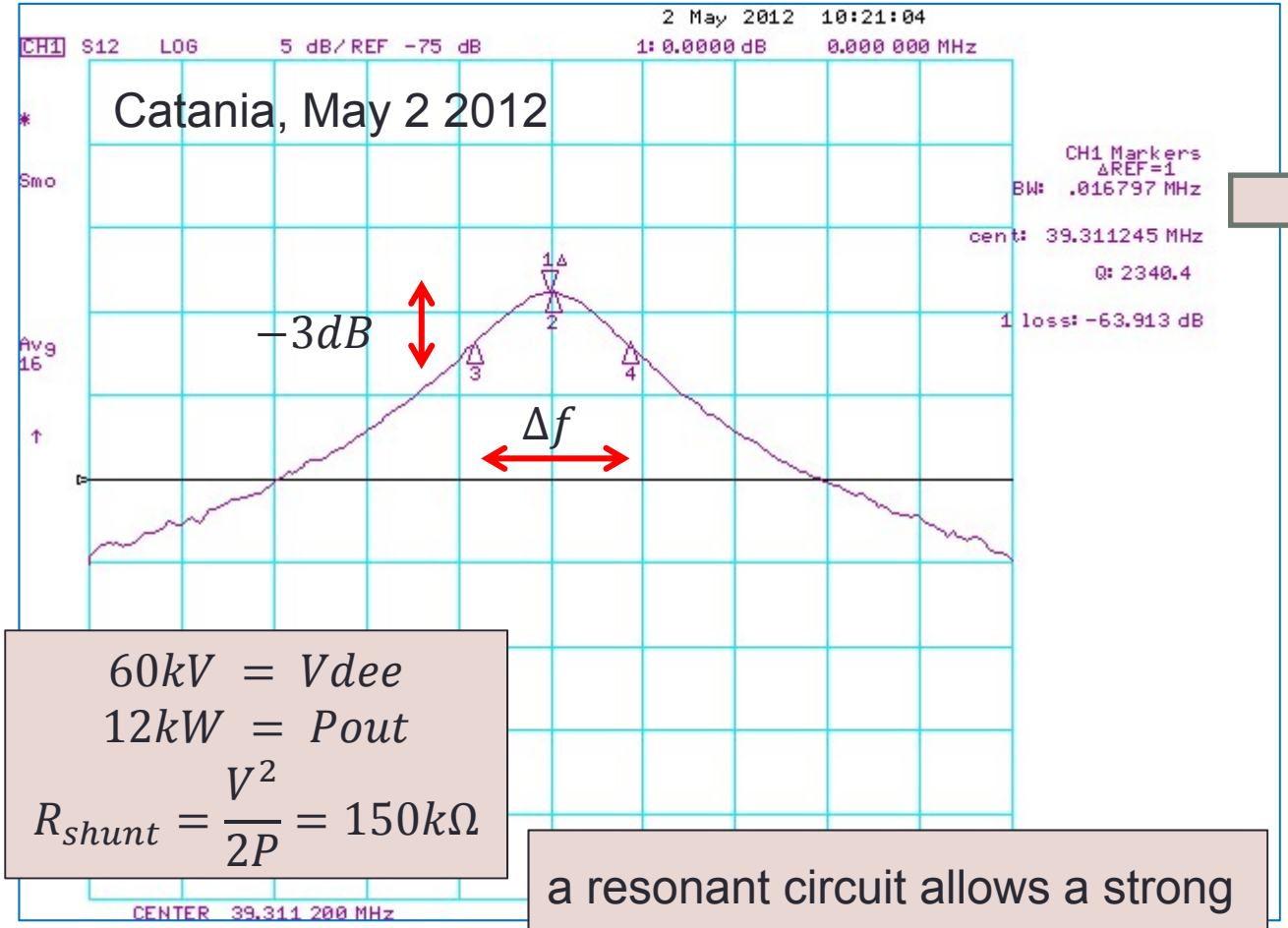
$$Q = 2\pi \frac{stored\ energy}{dissipated\ energy}$$



$$Q = \omega R C$$

$$Q = \frac{R}{\omega L}$$

RF resonator n.3 of the INFN k-800 Cyclotron



$$60kV = Vdee$$
$$12kW = Pout$$
$$R_{shunt} = \frac{V^2}{2P} = 150k\Omega$$

$$12kW/50\Omega$$
$$P = V^2/2R$$
$$V = \sqrt{2PR}$$
$$V = 1095V$$

a resonant circuit allows a strong multiplier effect at the resonance. Dee voltage runs from kV to MV. What kind of resonant circuit?

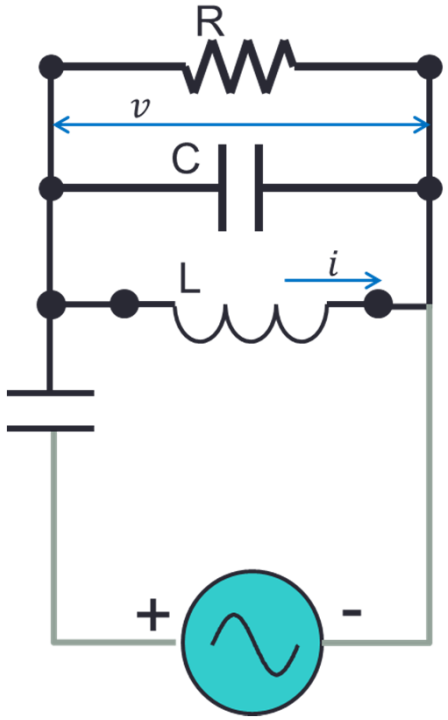
Also defined as

$$Q = f_0/\Delta f$$

$$f = 39.3112\ MHz$$

$$\Delta f \cong 16.8\ kHz$$

$$Q_{loaded} = 2340$$



RF operational parameters:

- Acceleration Voltage 50 – 100 kV (typical), max. 1 MV
- RF Power 10 – 100 kW (typical), max 1 MW
- Q values several thousands
- $f_{RF} = h\, f_{orb}$

Valleys dimensions ⇒ shape of the accelerating electrodes

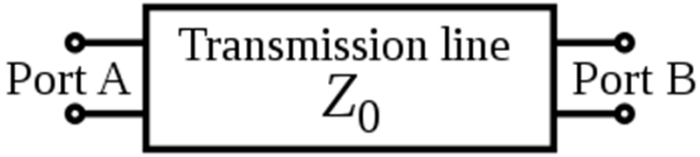
Resonant circuits, choice is obliged

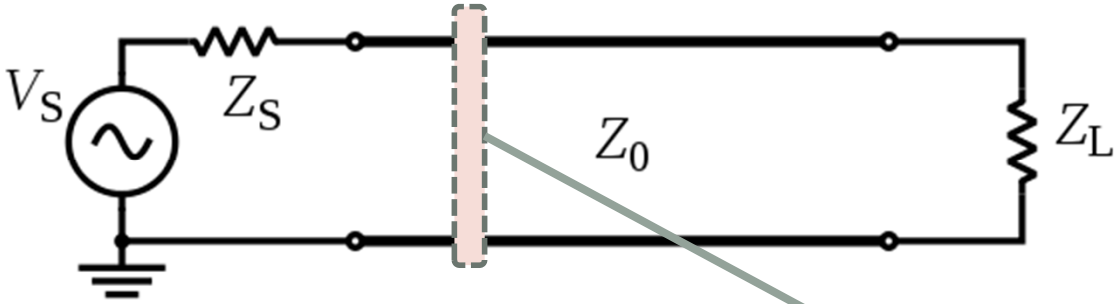
RLC circuits (Q ~ 100)

T-lines circuits/cavities (Q = several 1000)

Wave guide resonators (Q > 10000)

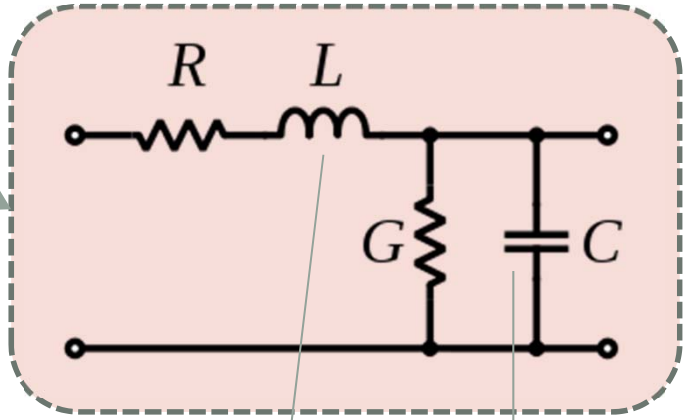
The step from R-L-C to TRANSMISSION LINE

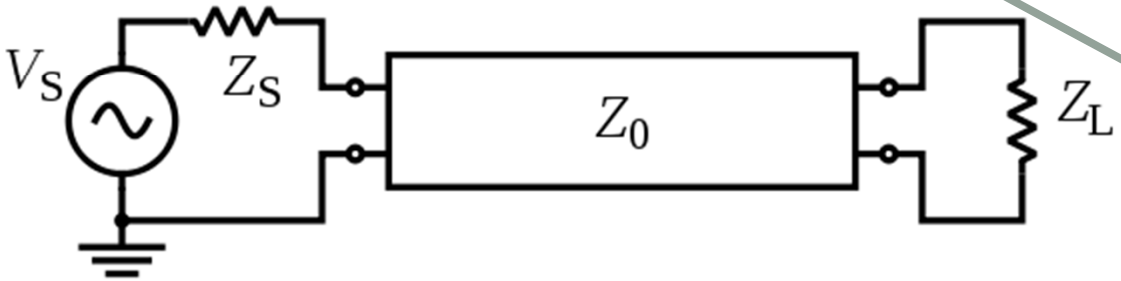


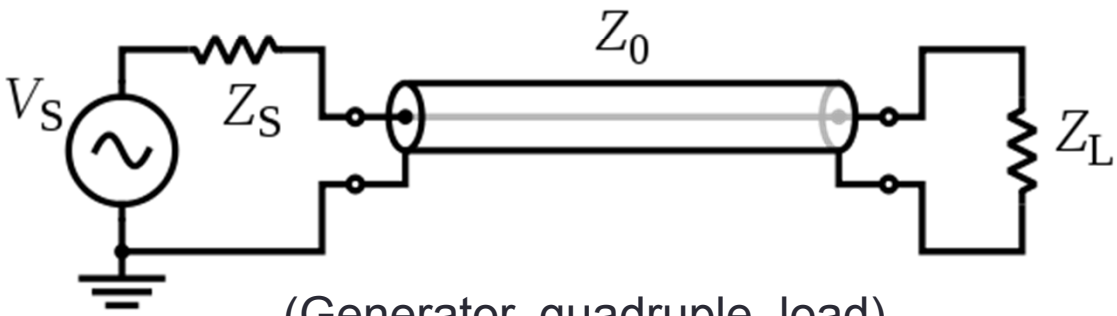


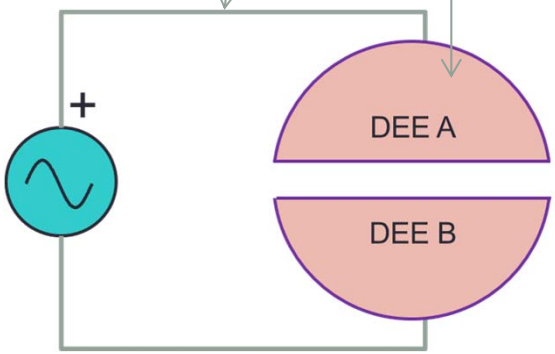
$$\frac{\partial}{\partial x} I(x,t) = -C\frac{\partial}{\partial t} V(x,t) - GV(x,t)$$

$$\frac{\partial}{\partial x} V(x,t) = -L\frac{\partial}{\partial t} I(x,t) - RI(x,t)$$



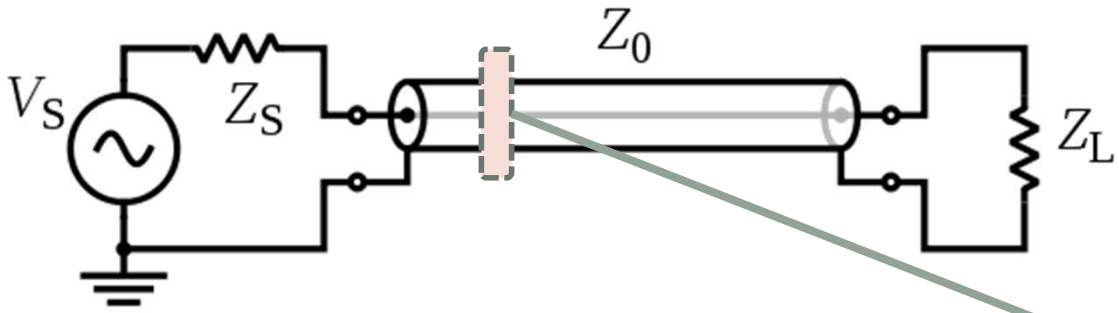




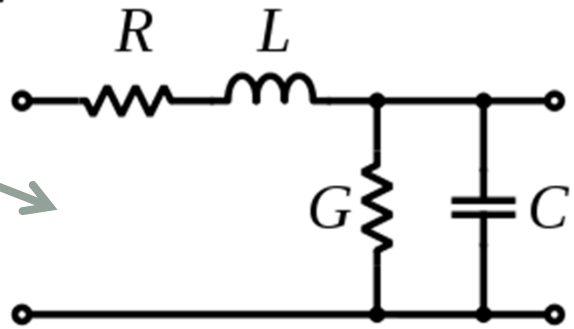


(Generator, quadruple, load)

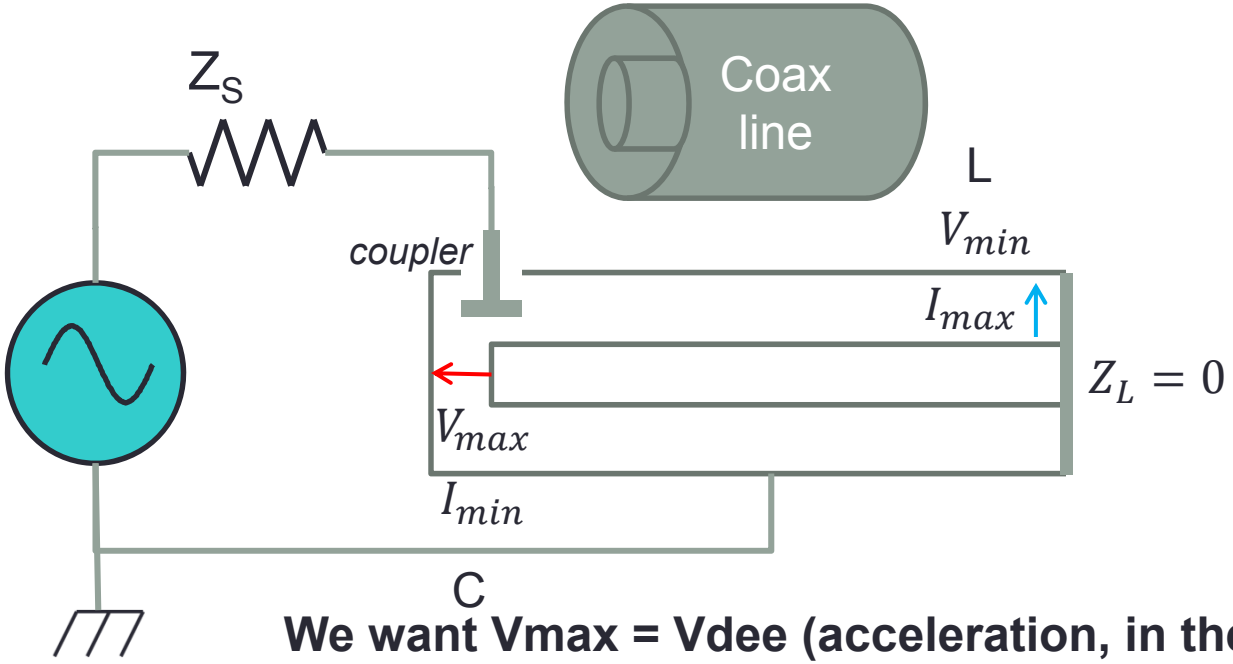
Matching = Max Transmission

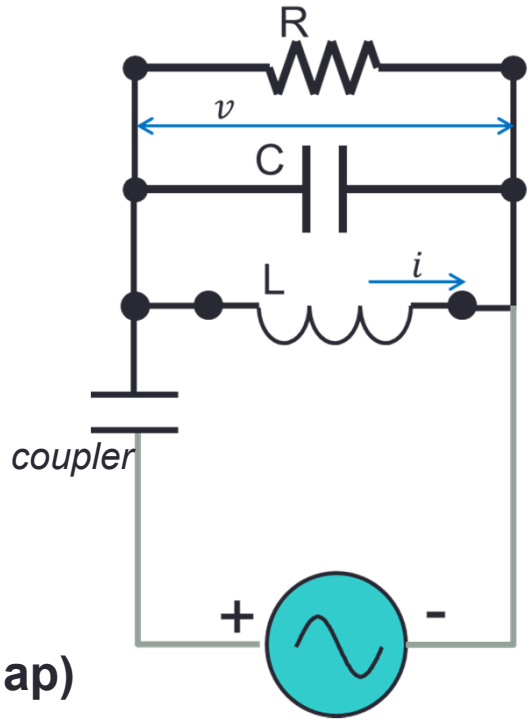


$if\ Z_L = 0\ SPECIAL\ CASE$

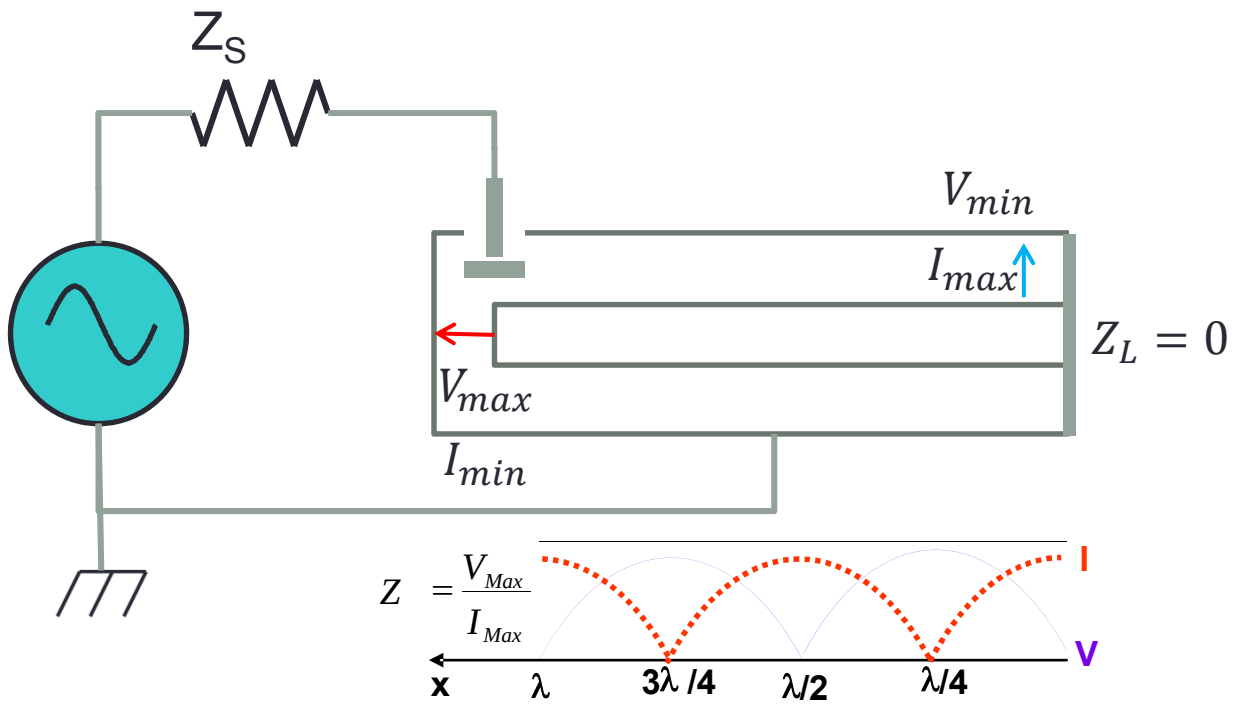


The coax transmission line can be seen as a closed structure terminated on a short circuit





We want Vmax = Vdee (acceleration, in the gap)



Quarter Wave Resonator

$$\boldsymbol{lenght} \cong \boldsymbol{n}\frac{\boldsymbol{\lambda}}{\mathbf{2}} + \frac{\boldsymbol{\lambda}}{\mathbf{4}}$$

Geometry of the structure

$$\lambda = \frac{c}{f} \ (wave\ lenght)$$

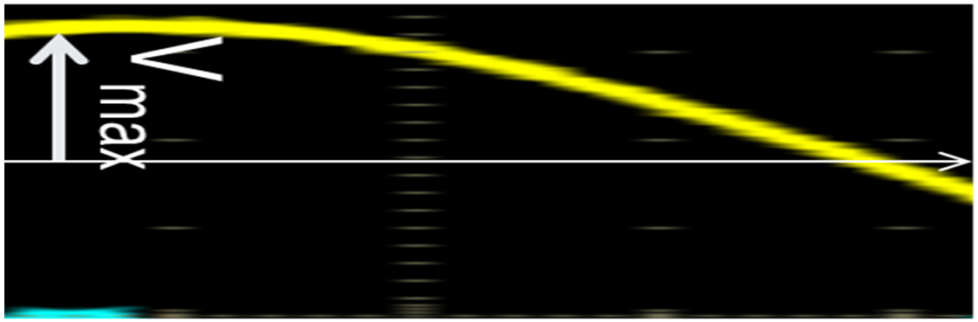
$$\omega = 2\pi f$$

MHz	λ/4 (m)
5	15
10	7,5
50	1,5
100	0,75

In a resonator **standing waves** occur during the phenomenon known as resonance. At the resonance frequency the cavity behavior is like an R-L-C circuit. But we have:

$$(R - L - C)_{equivalent}$$

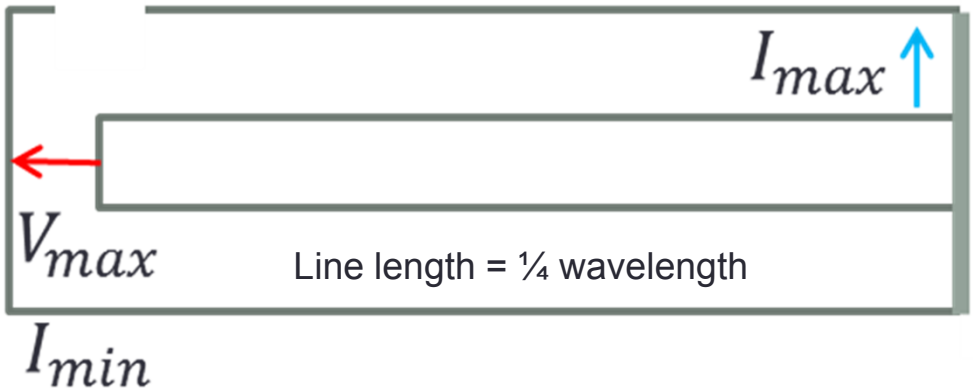
$$\frac{1}{j\omega C} = j\omega L \Rightarrow \omega^2 = 1/\sqrt{LC} \Rightarrow \boldsymbol{f = 1/2\pi\sqrt{LC}}$$



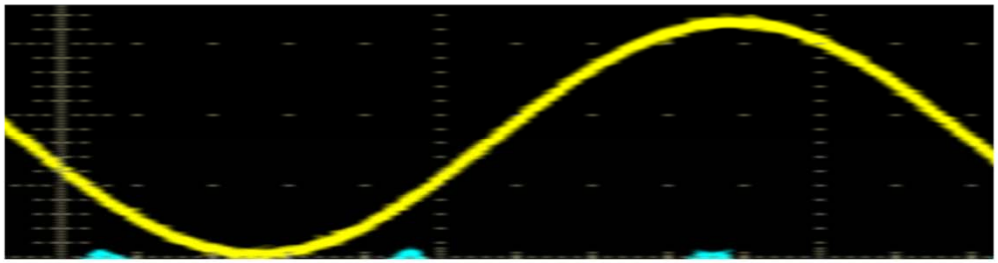
Quarter wave length ¼ λ

V_{max} accelerating voltage GAP

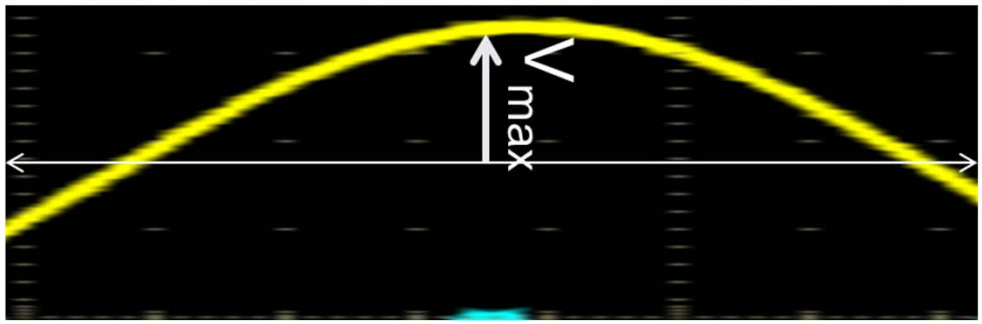
Resonance condition, Standing Waves



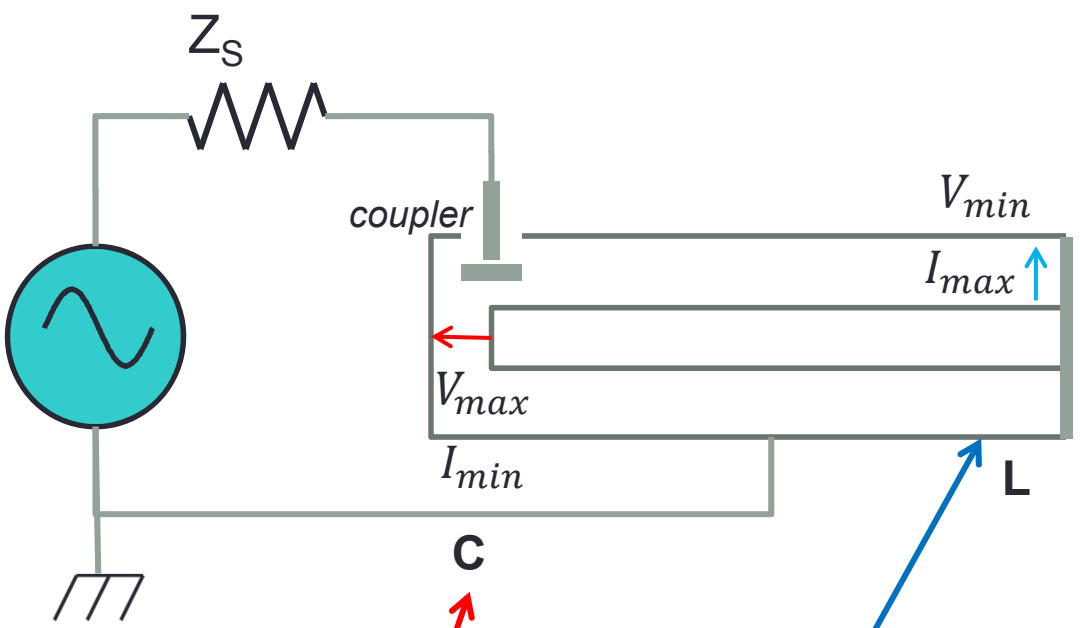
$Z_L = 0$ Quarter wave Resonator

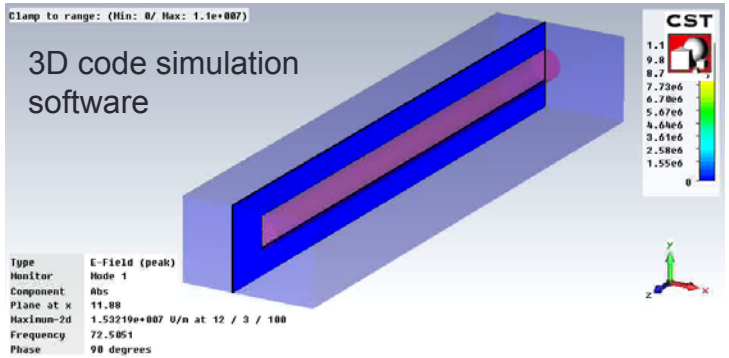


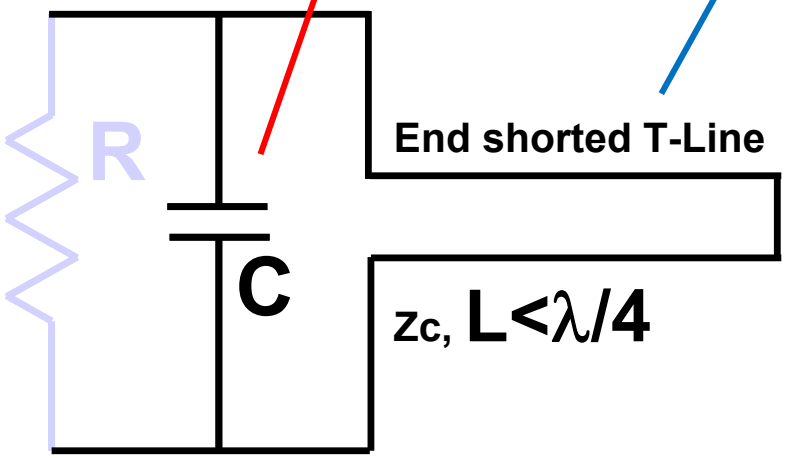
One entire wave length λ

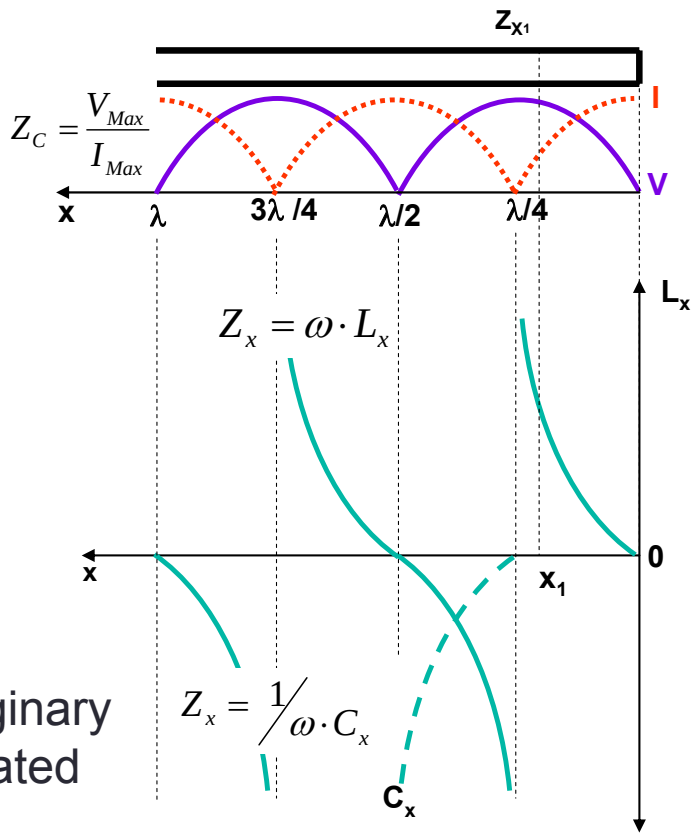


Half wave length ½ λ



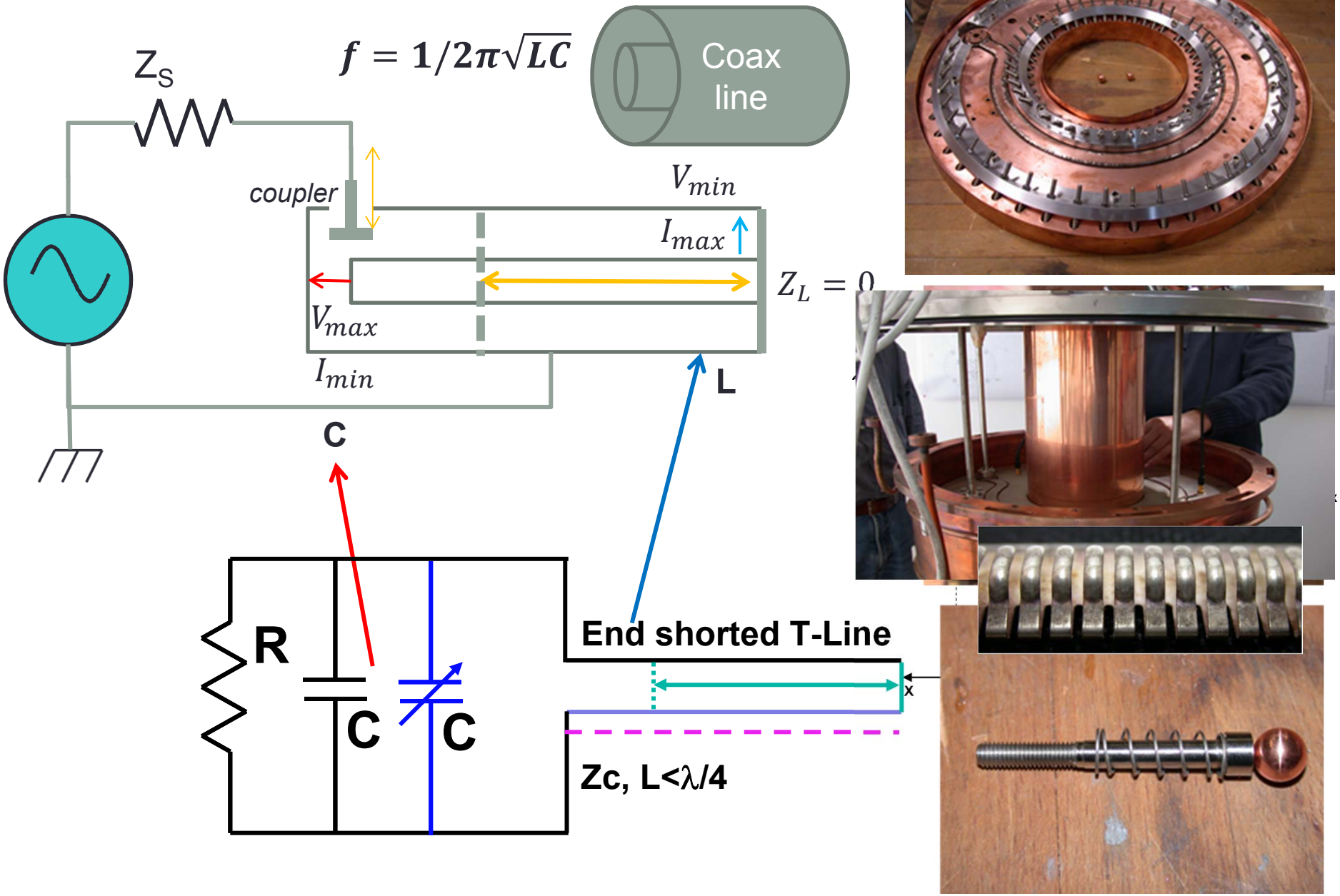


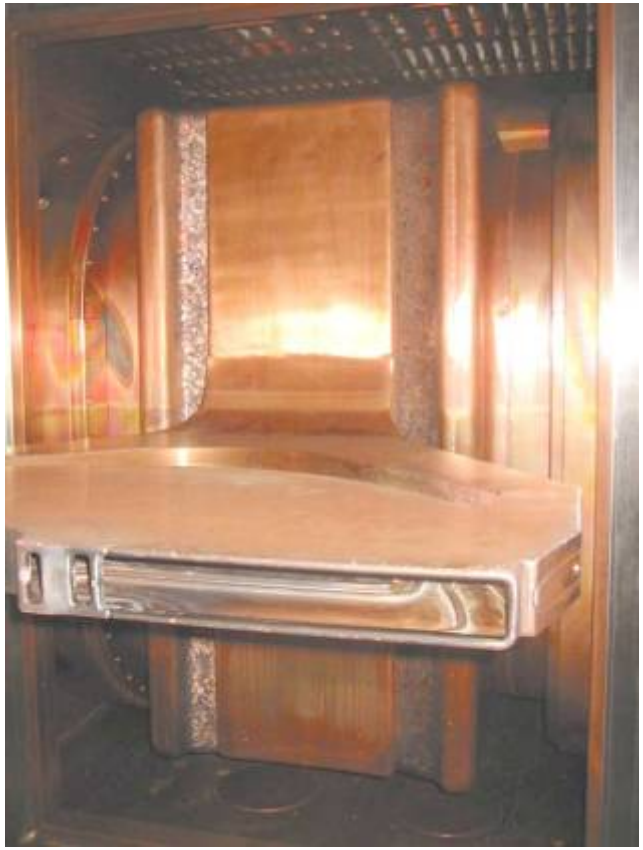


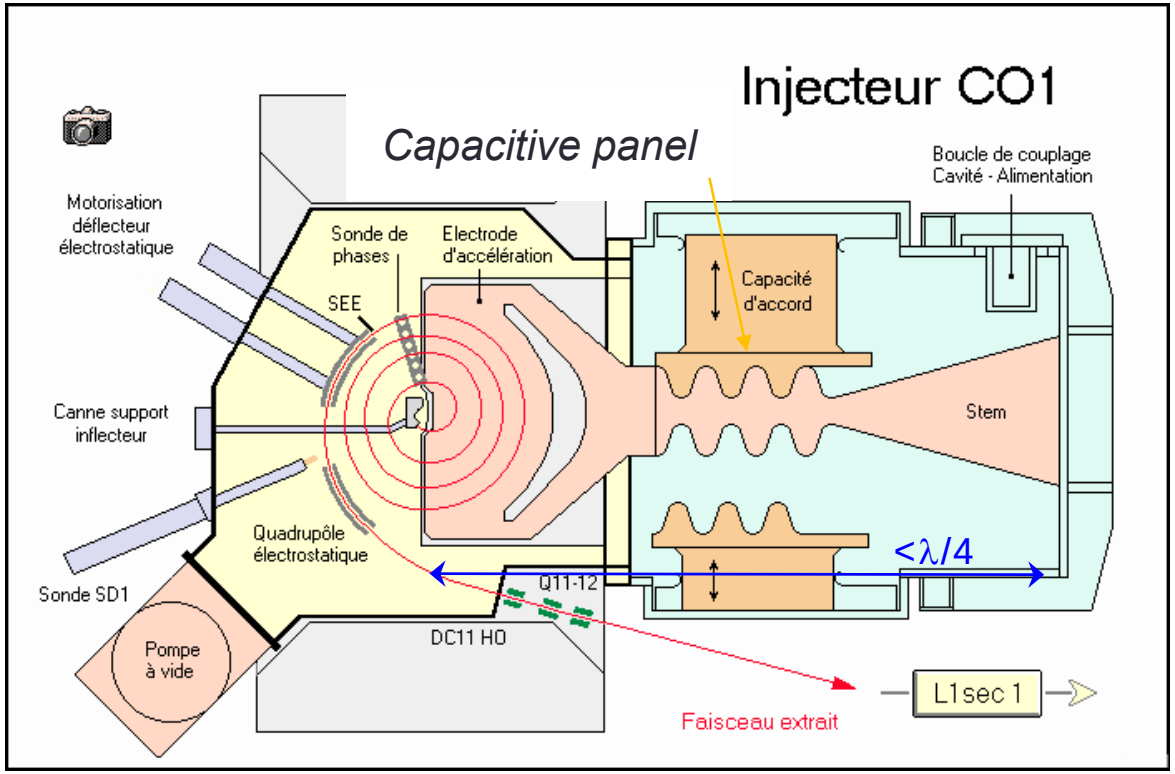


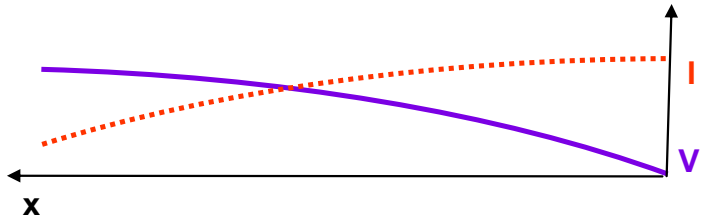
Purely imaginary
C and L related

Change and adjust the resonance frequency





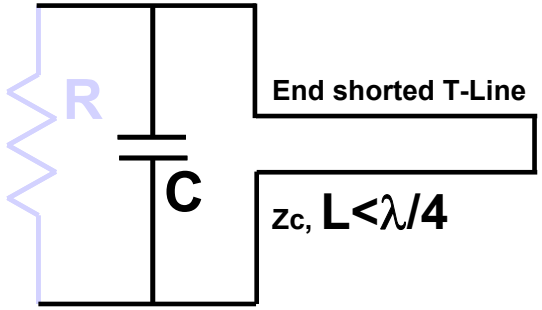




Ganil C01

C01
7÷14 MHz
50÷30 kW @ 50÷30 kV
Q=4000÷6000

Courtesy of M. Di Giacomo



Dee stems (balanced shielded **line, 1/4 wave)** 5.2 feet

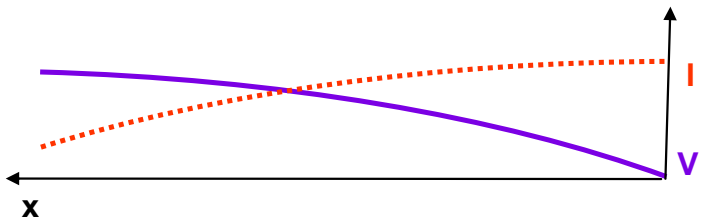
Radiofrequency 13.5 MHz

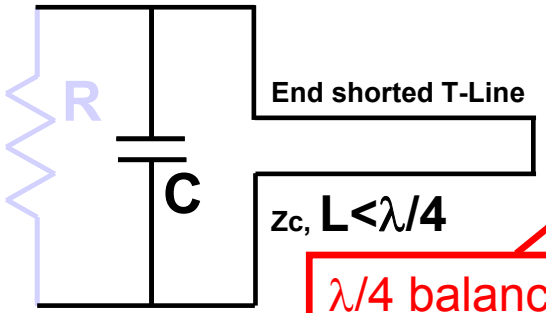
Q of resonant system, unloaded 12300

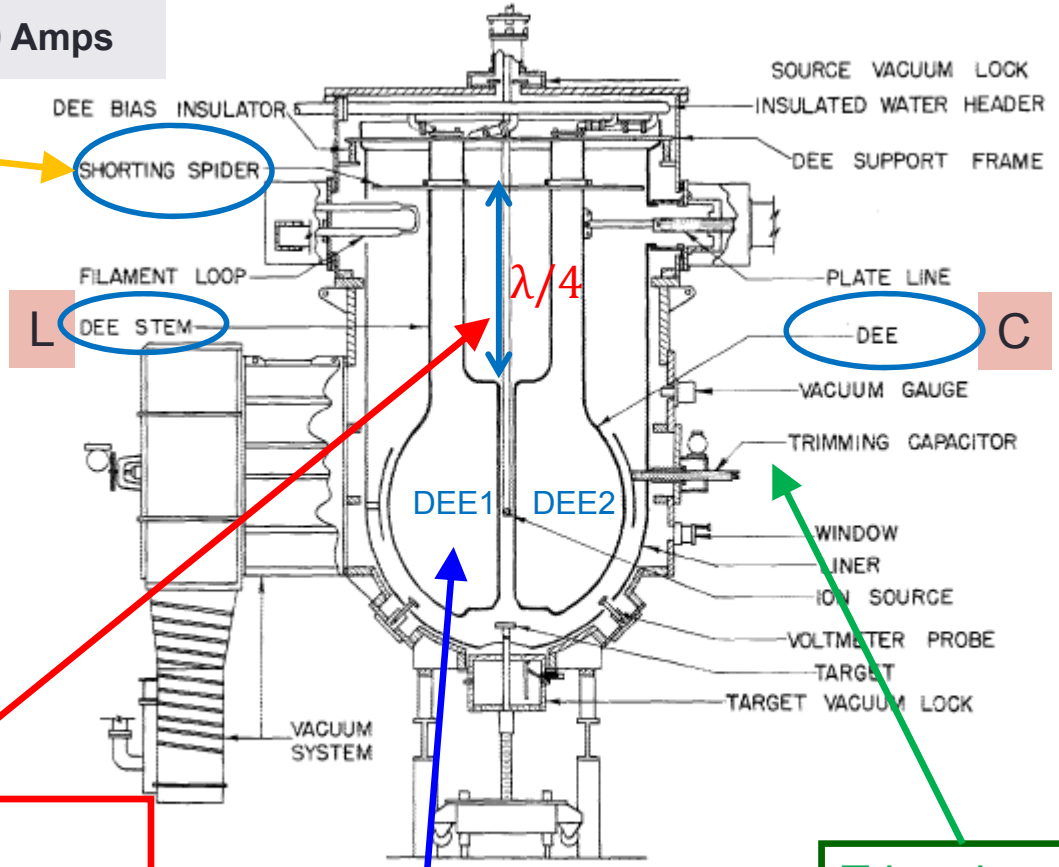
Maximum RMS current at shorting spider **5600 Amps**

Old real classic cyclotron (86” Oak Ridge, 1952)

shorting plate







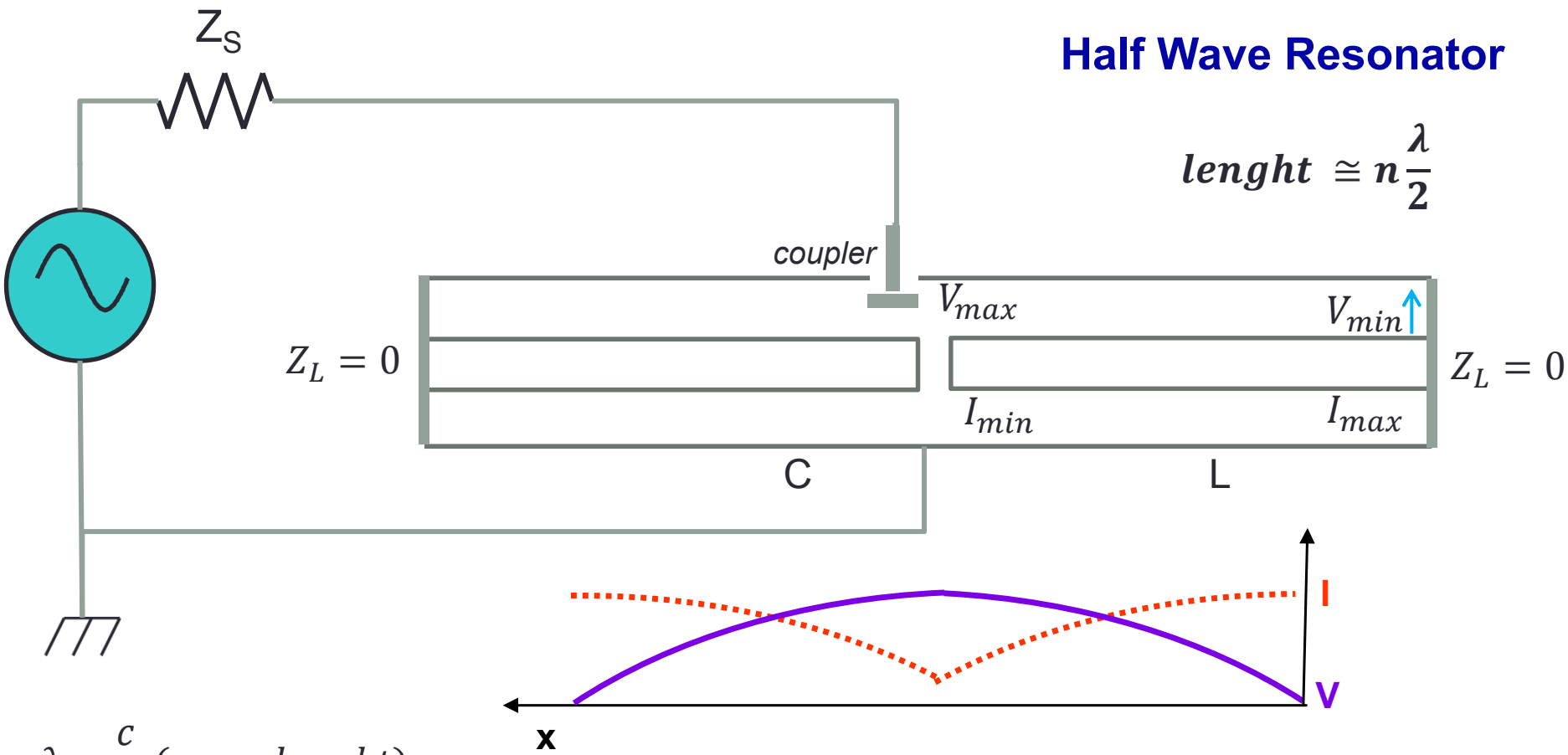
λ/4 balanced transmission line

180° acceleration electrode (Dee) 2 gaps per turn

Trimming capacitor Frequency adjustment

Half Wave Resonator

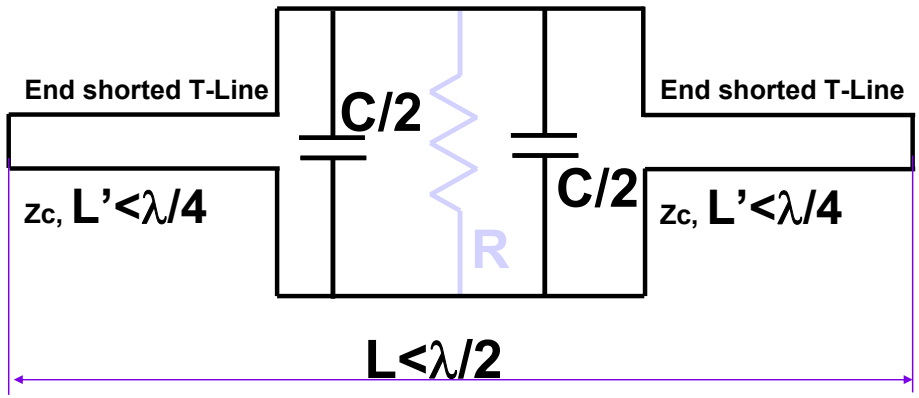
$$lenght \cong n\frac{\lambda}{2}$$



$$\lambda = \frac{c}{f} \ (wave\ lenght)$$

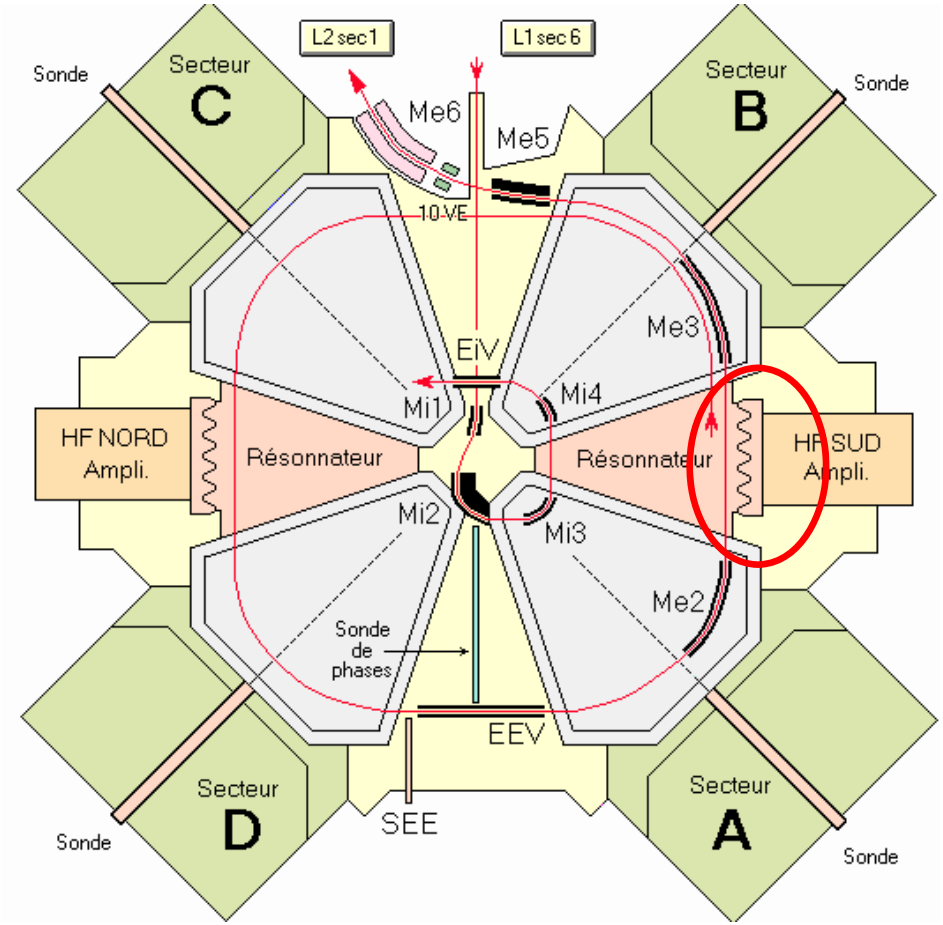
$$\omega = 2\pi f$$

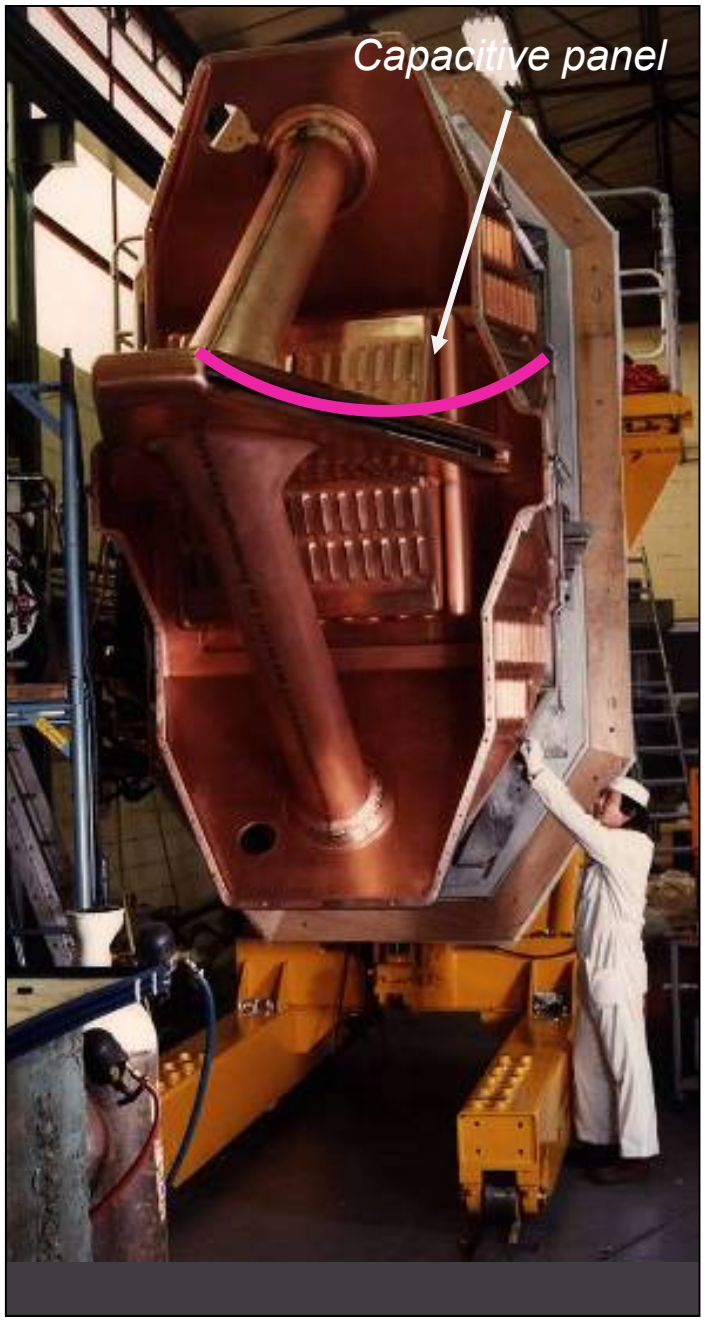
$$f = 1/2\pi\sqrt{LC}$$

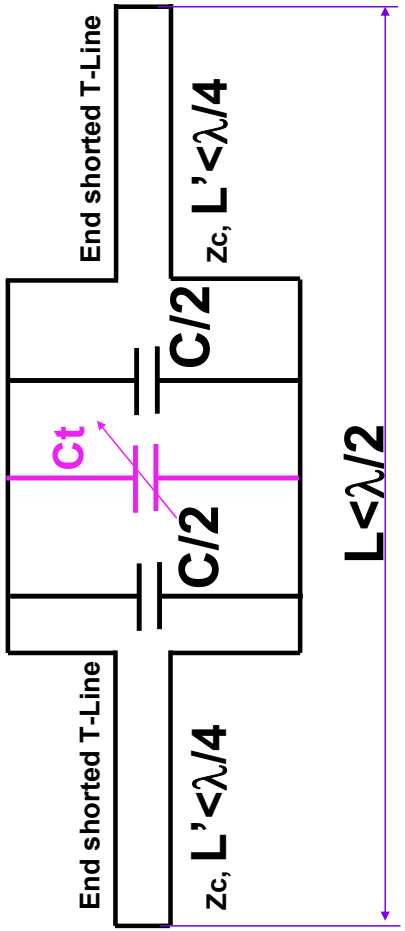


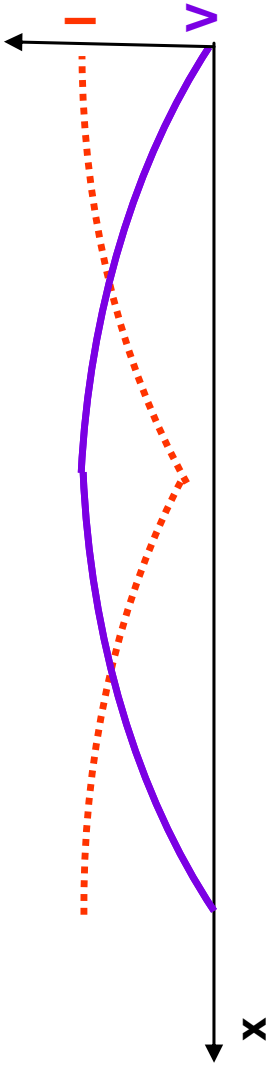
MHz	λ/2 (m)
10	15
50	3
100	1,5

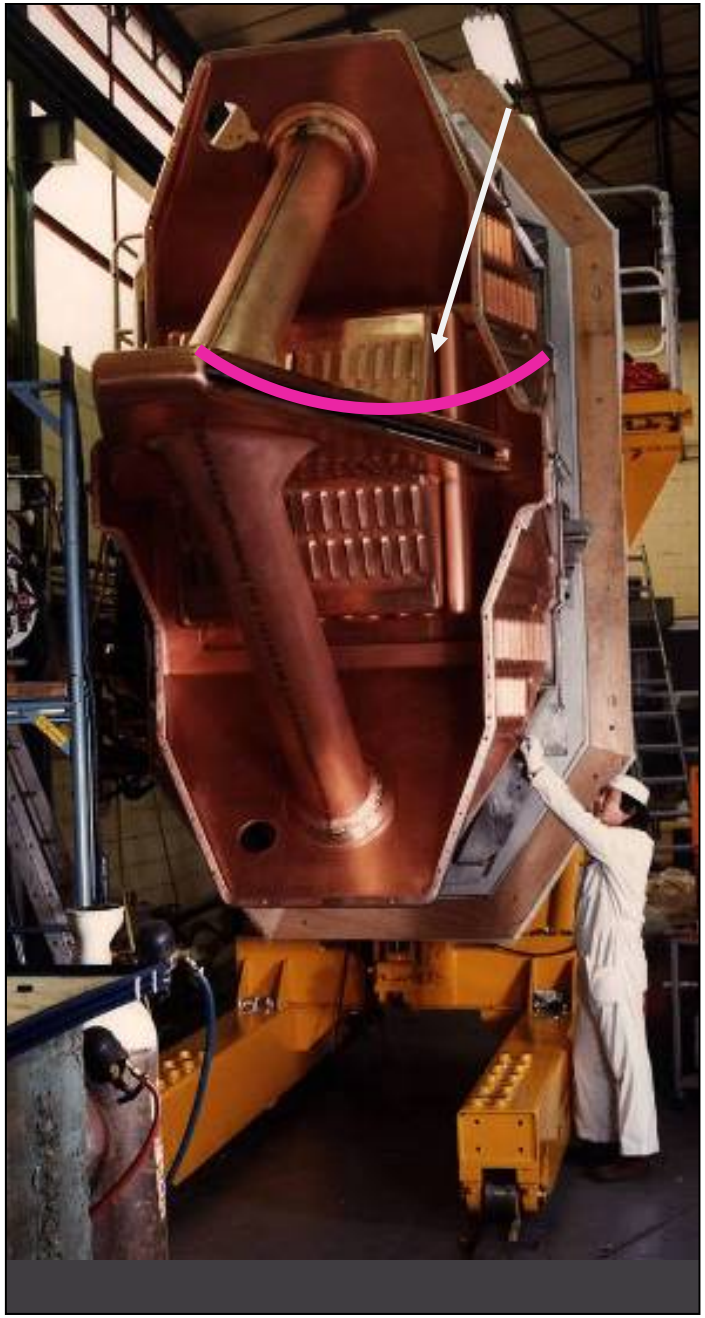
Ganil CSS Cavity (main cyclotron)
7÷14 MHz
100 kW @250 kV
Q = 6000 - 10000

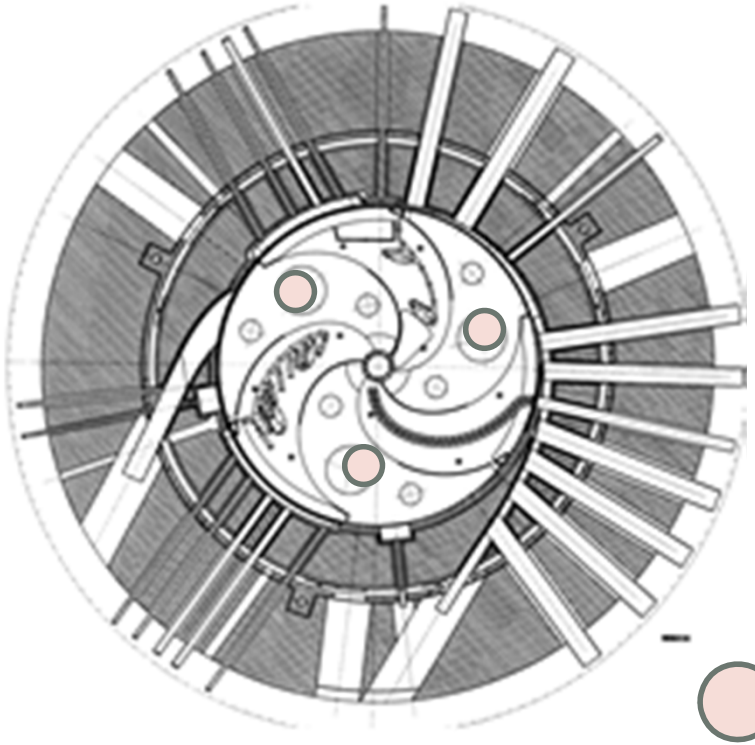





End shorted T-Line
Zc, L'<λ/4
C/2
Ct
C/2
Zc, L'<λ/4
End shorted T-Line
L<λ/2


I
V
x





INFN - LNS

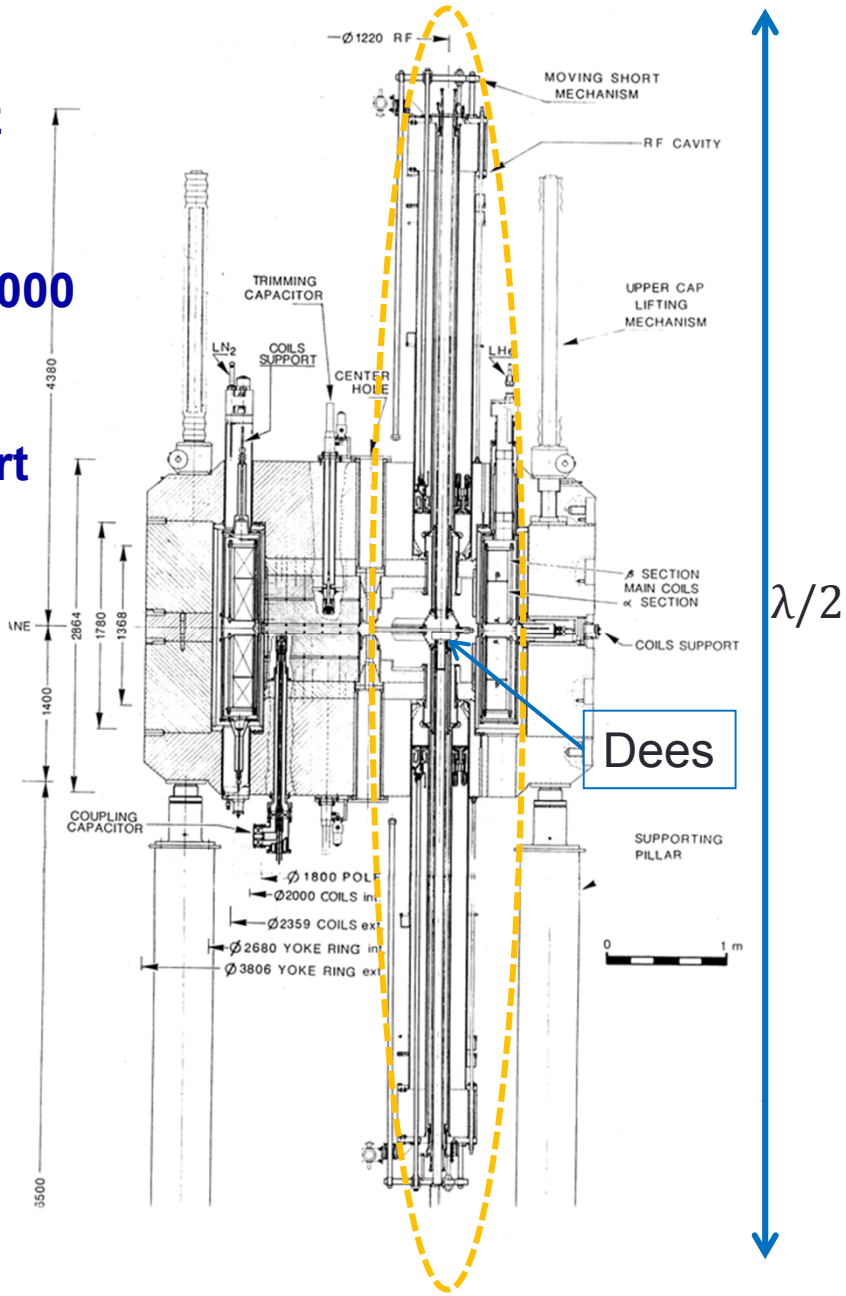
15 - 50 MHz

100 kV

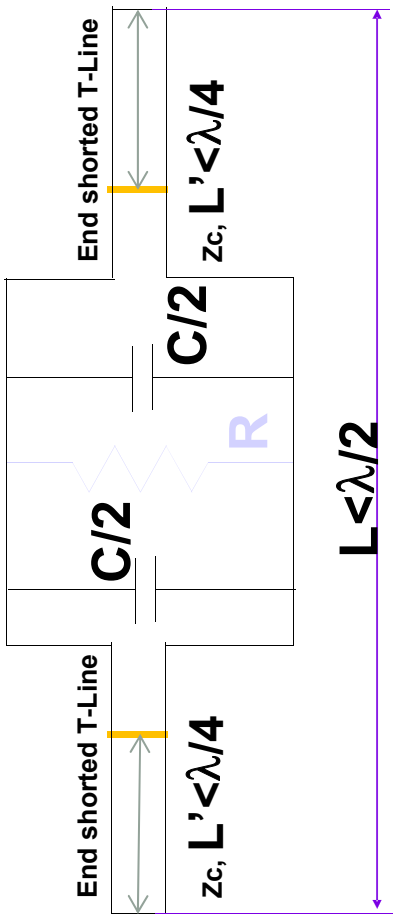
Q= 2000 - 6000

Tuning by sliding short

RF cavities



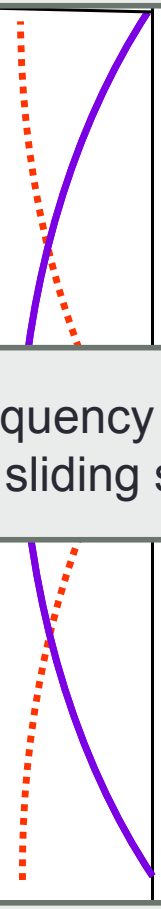
$$f = 1/2\pi\sqrt{LC}$$

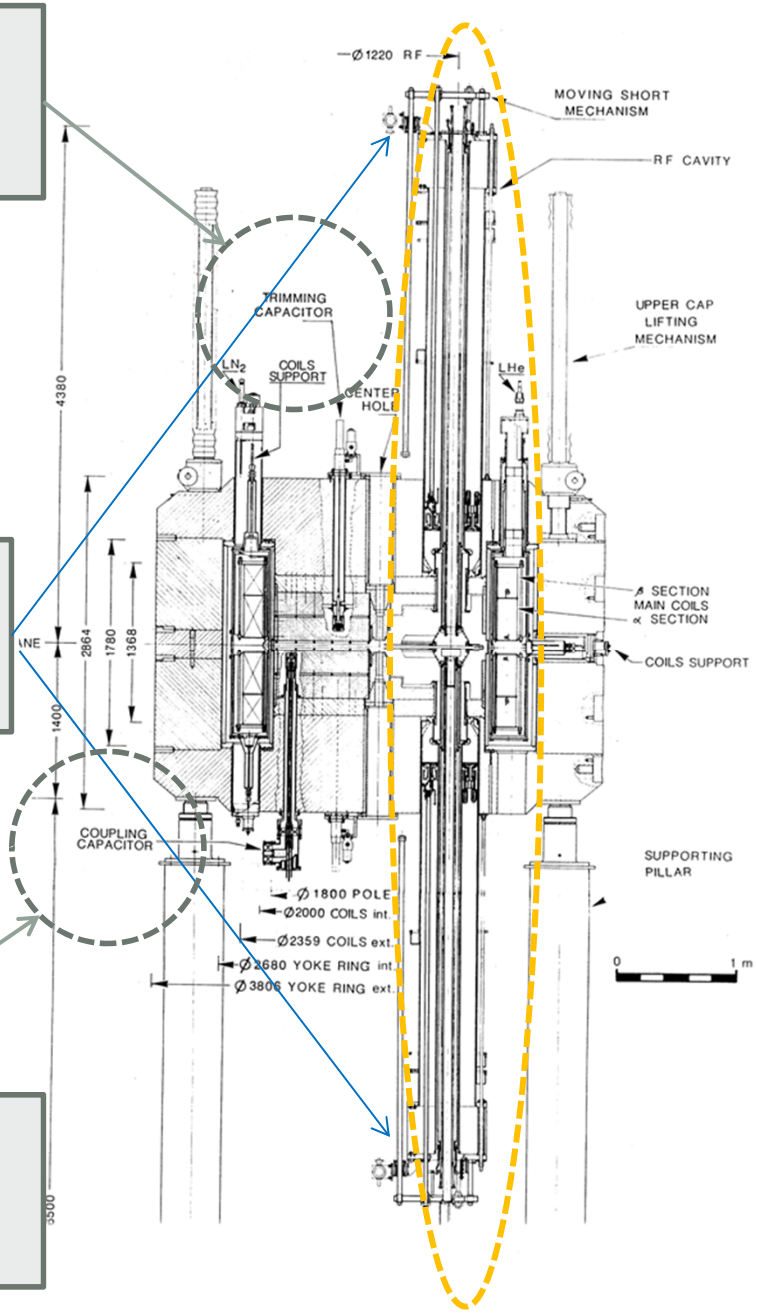


Fine tuning by trimming capacitor

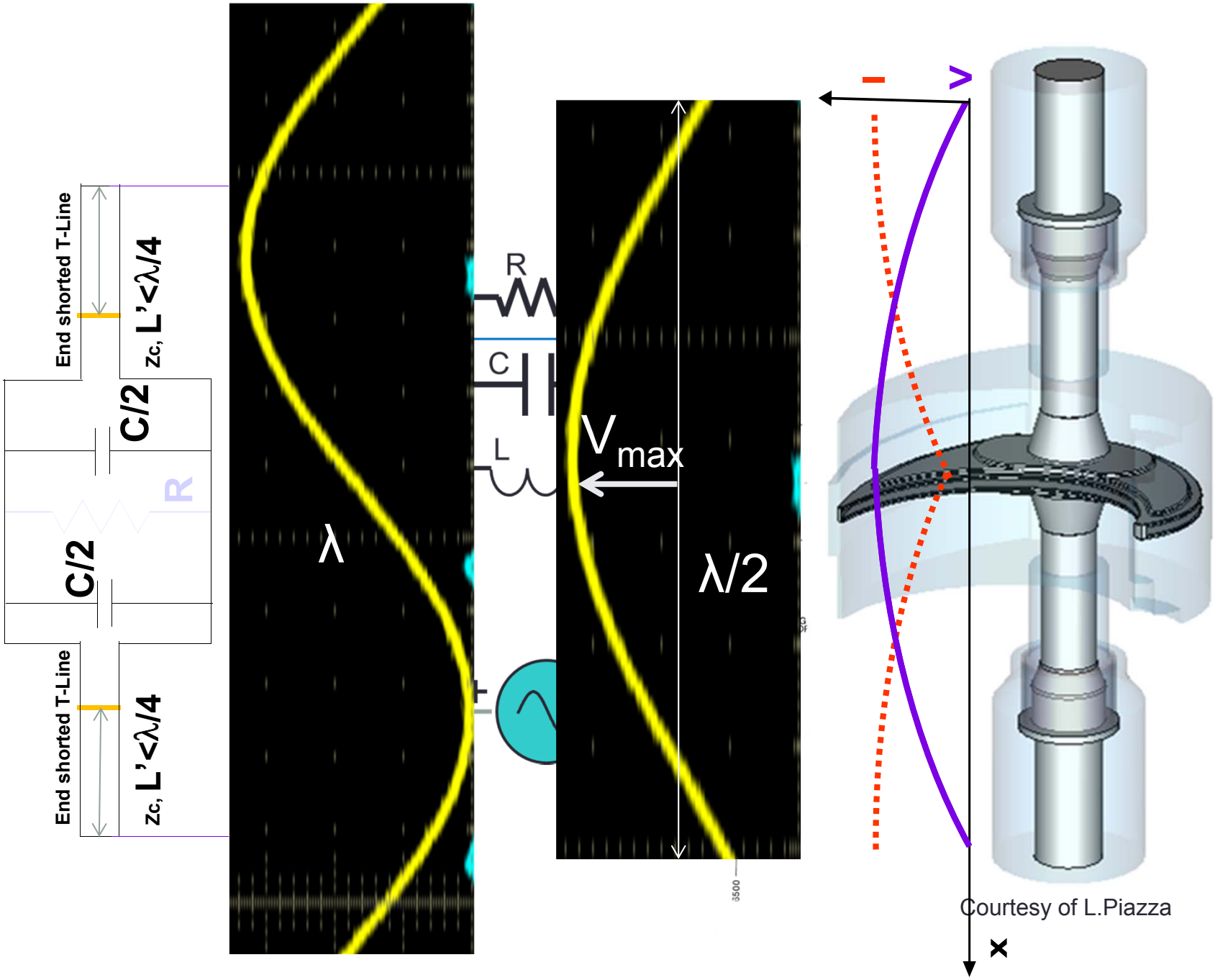
Frequency tuning by sliding shorts

Coupling capacitor

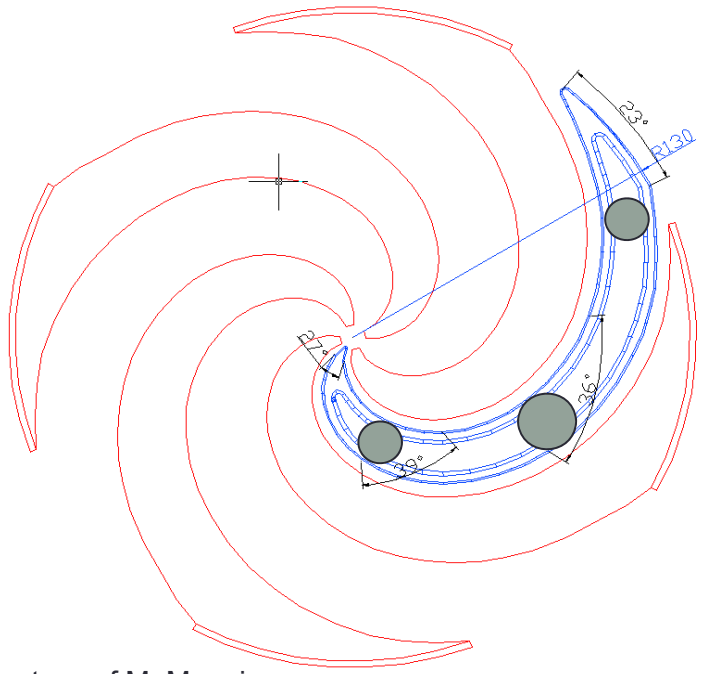




λ/2



Courtesy of L.Piazza



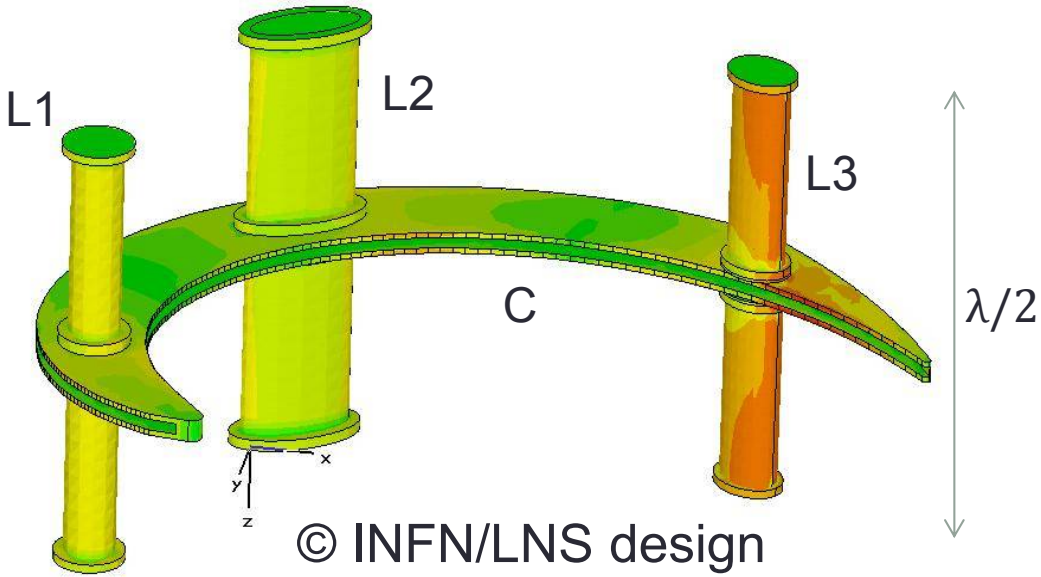
Courtesy of M. Maggiore

Multi stem Half Wave Cavity

$$f_o = \frac{1}{2\pi \cdot \sqrt{L \cdot C}}$$

$$length_{DEE} = 2.5\,\mathrm{m} \rightarrow C \approx 230\,pF$$

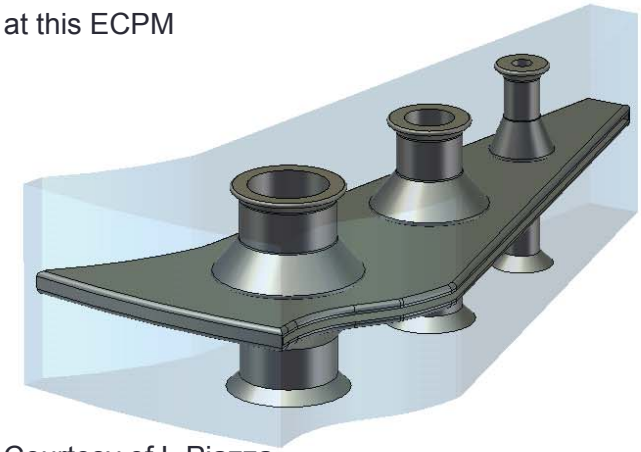
Working frequency	97.5 MHz
Q value	~ 9000
Power loss	~ 42 kW
Voltage range	30-160 kV
Trimmer ΔF	> ± 50 kHz



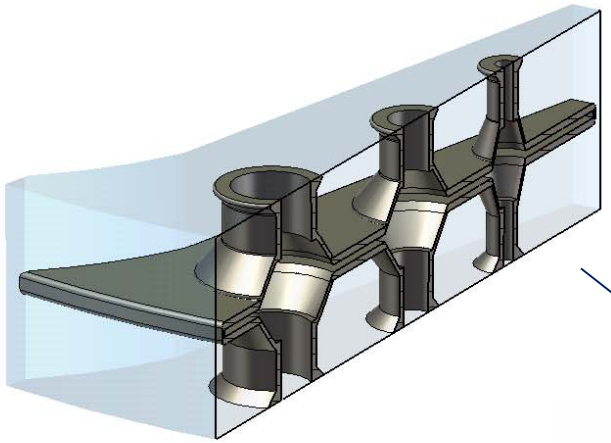
From ”Daedalus
Multi Mega Watt Cyclotron”

Multi stem Half Wave Cavity

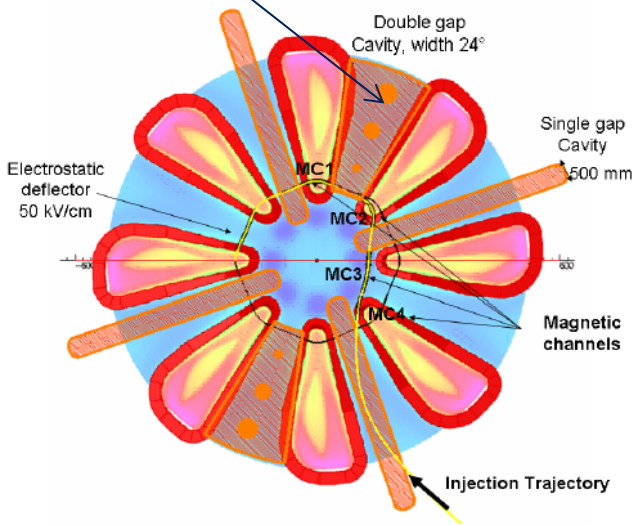
Talk of A. Calanna and L.Calabretta
at this ECPM



Courtesy of L.Piazza



$$f = 1/2\pi\sqrt{LC}$$

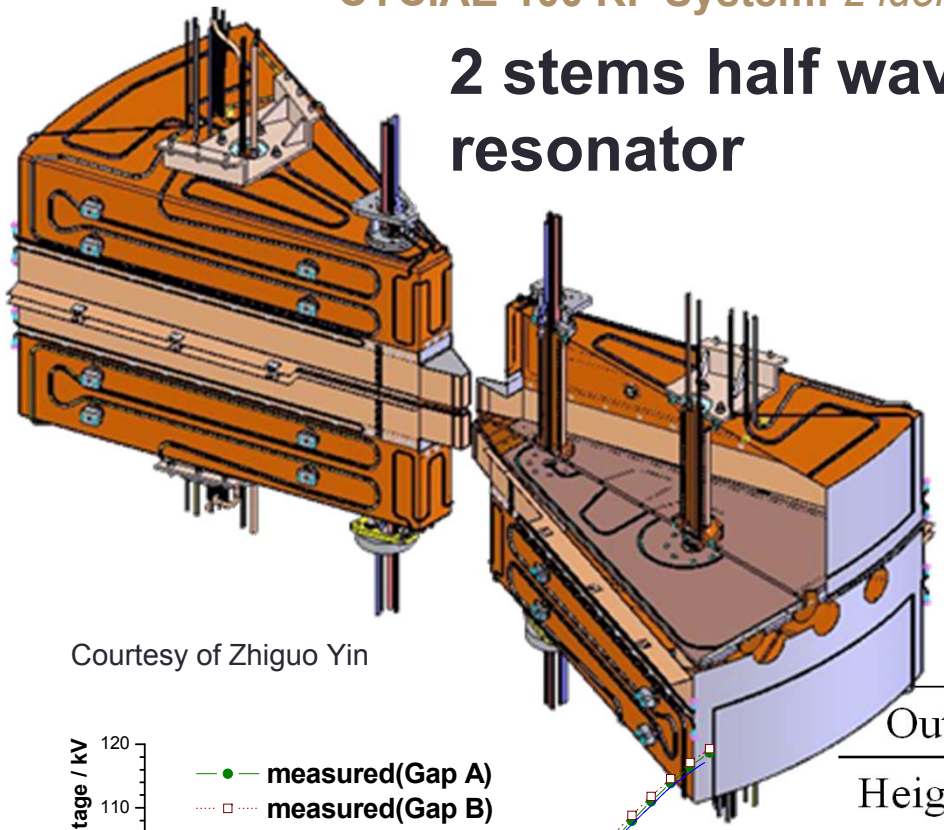


Courtesy of A. Calanna

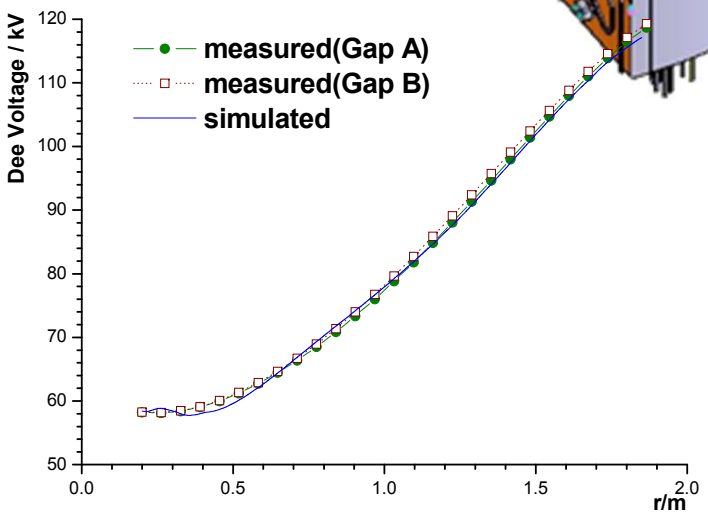
RF Specifications	
Resonant Frequency	≈ 50 MHz
Effective Accelerating Voltage per Cavity	≈ 500 kV
Power Dissipation per Cavity	< 500 kW
Number of Cavities	= 8
Harmonic Number	= 4
Material	OFHC Copper

CYCIAE-100 RF System: *2 identical cavities in the valleys*

2 stems half wave resonator



Courtesy of Zhiguo Yin

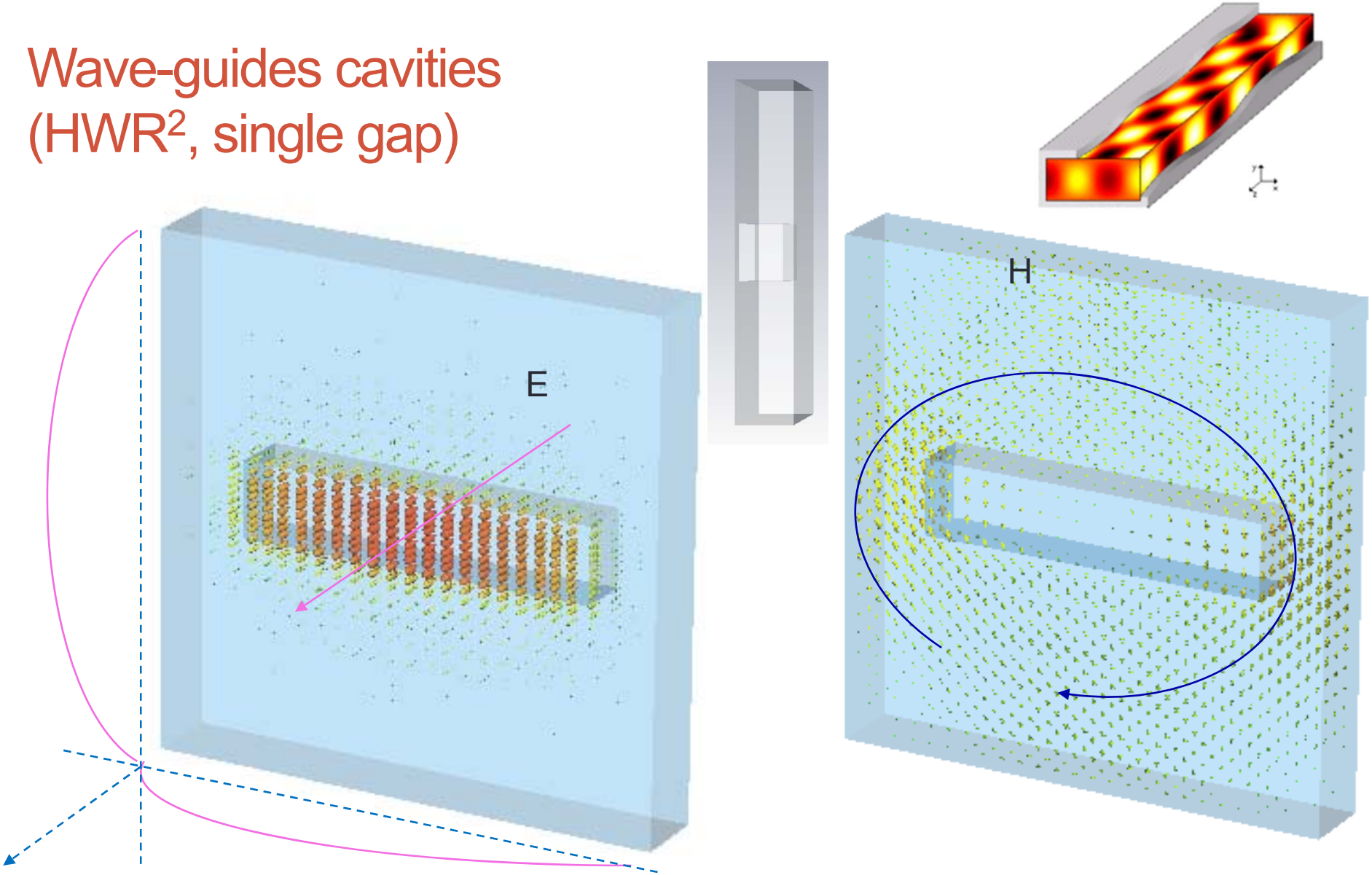


Frequency:**44.32 MHz**
Q value: **10300**
Cavity Dissipations: **57kW**
Material: **OFHC**
Beam Loading: **20~50kW**
Dee voltage: **60kV~120kV**

RF Cavity Dimensions

Outer conductor		Inner conductor	
Height of the Cavity	1.26m	Radius of Stem 1	6.4cm
		Radius of Stem 2	7cm
Outer Radius	1.98m	Length of Dee along its symmetric axis	1.86m
Angle	36.6Deg.	Dee Angle	34.4Deg.

Wave-guides cavities (HWR^2, single gap)



PSI

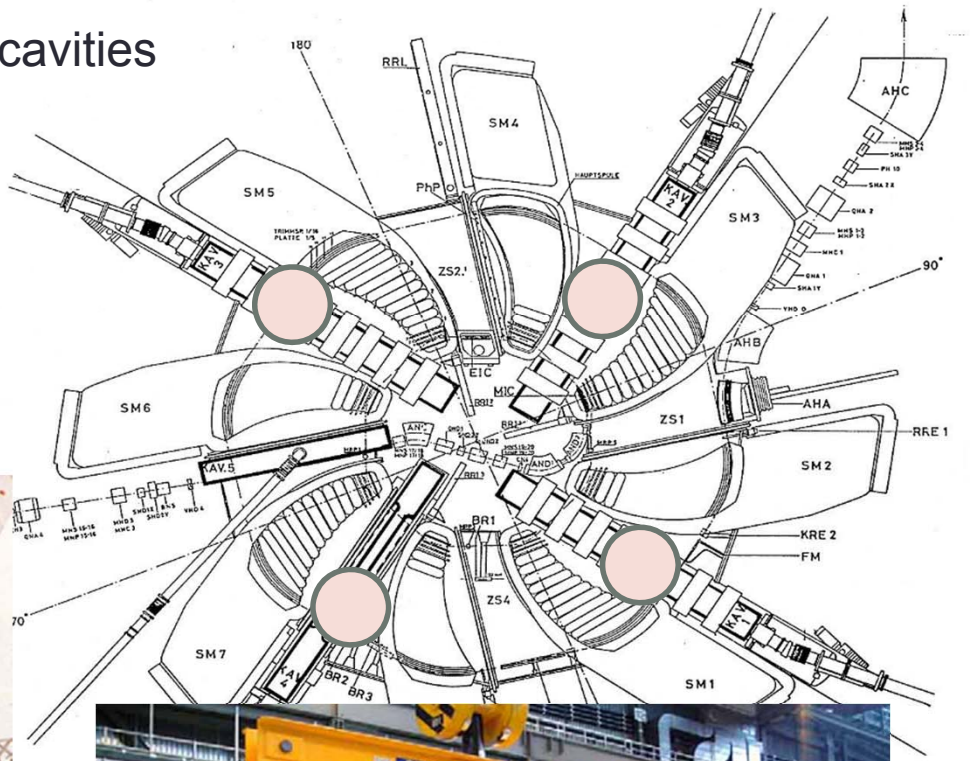
50 MHz,

600 kW @1 MV

Q=45000

Tuning by deformation

RF cavities



PSI

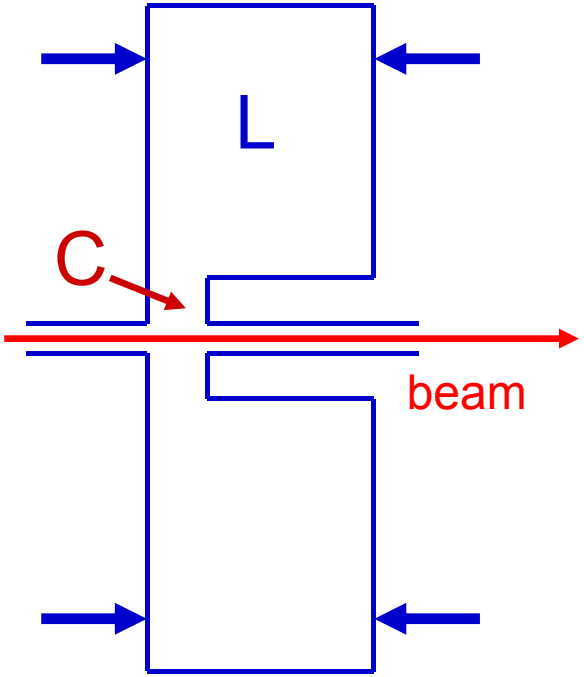
50 MHz,

600 kW @1 MV

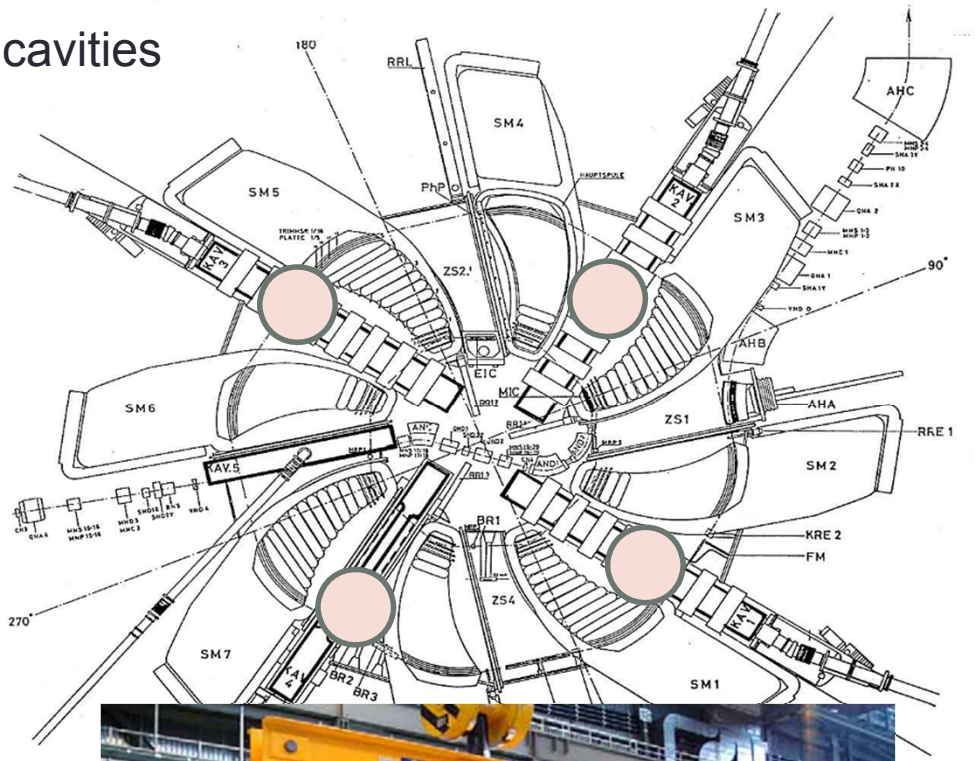
Q=45000

Tuning by deformation:

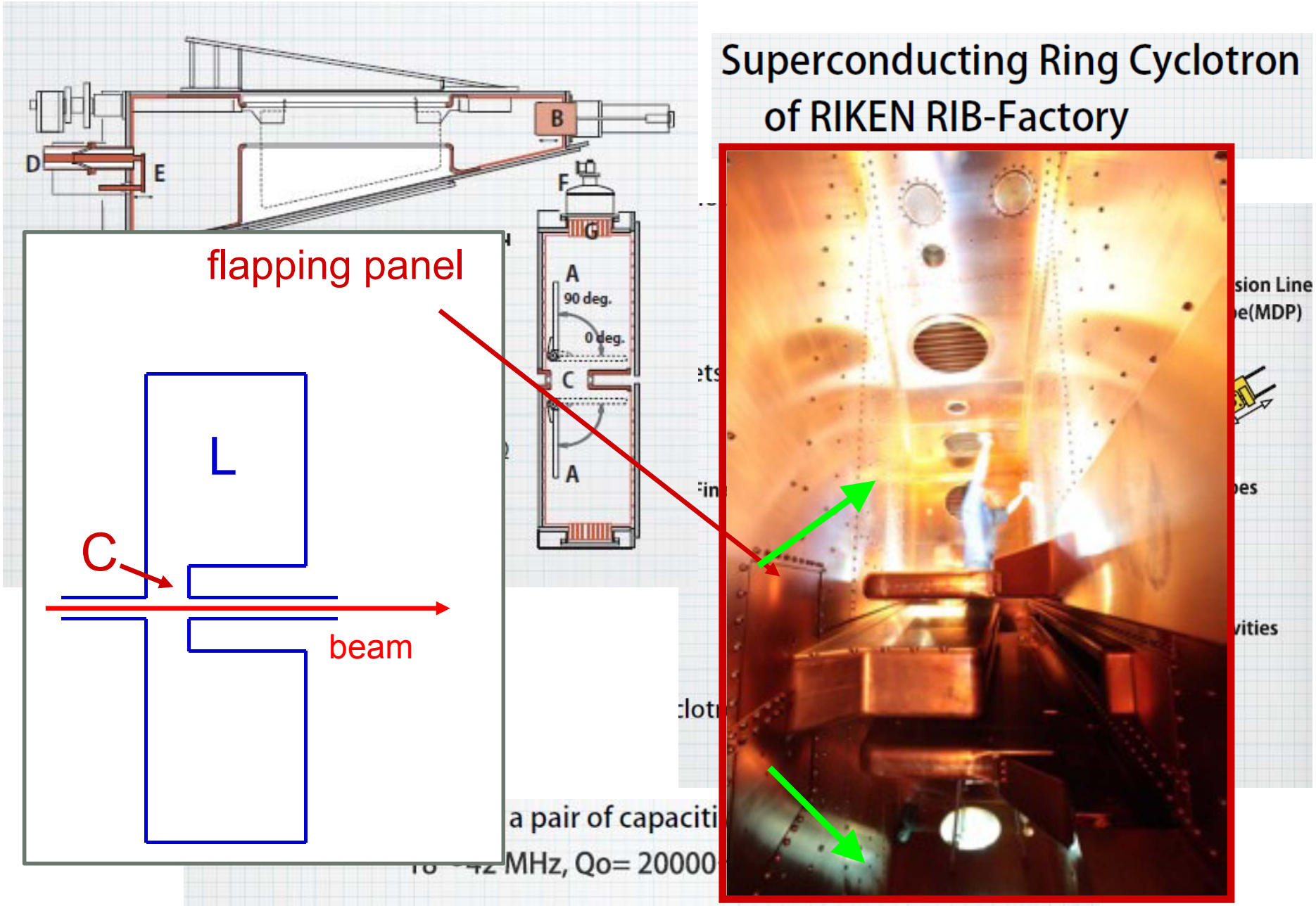
- **Gap capacitance**
- **Chamber inductance**



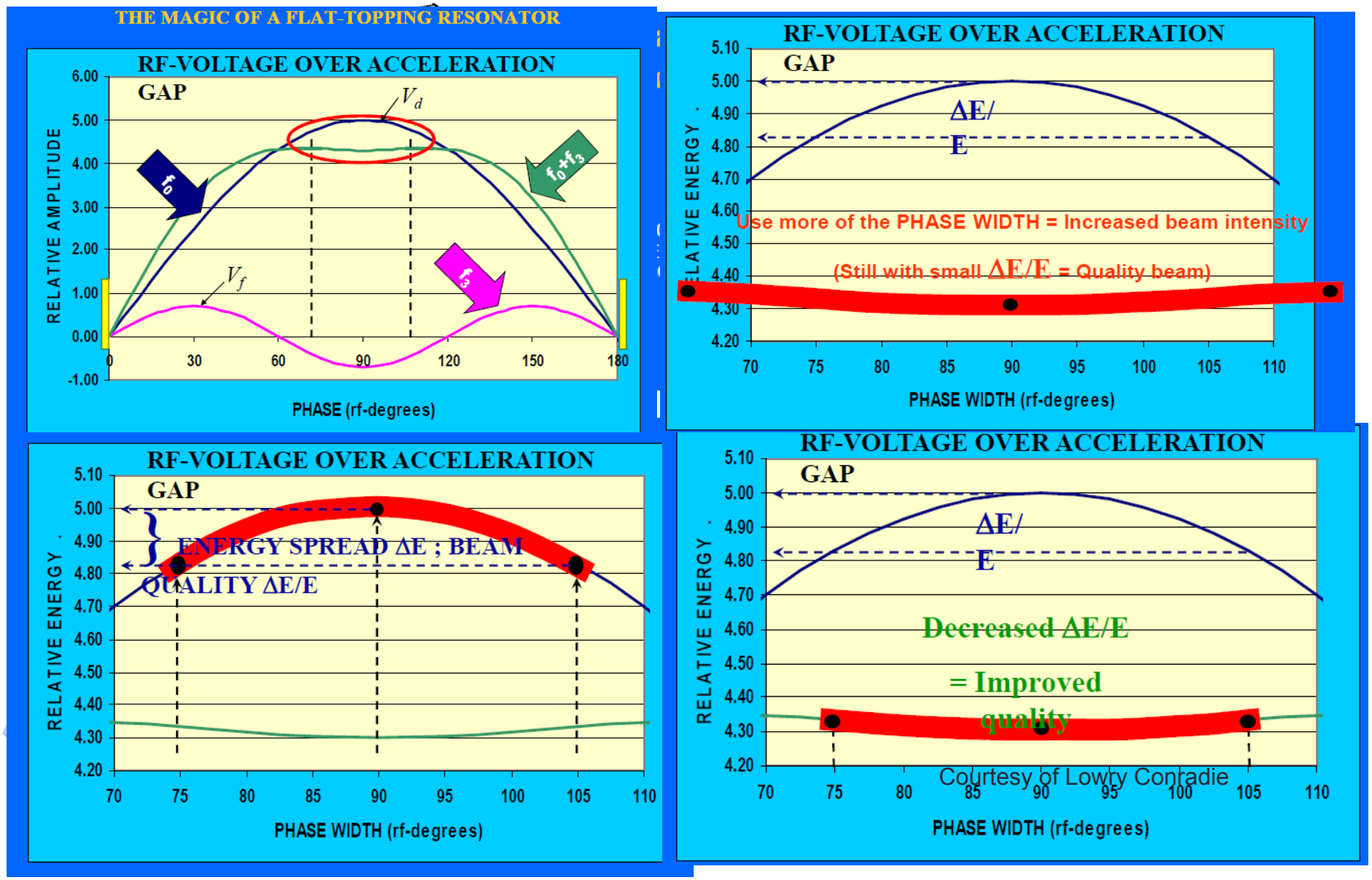
RF cavities



Superconducting Ring Cyclotron of RIKEN RIB-Factory

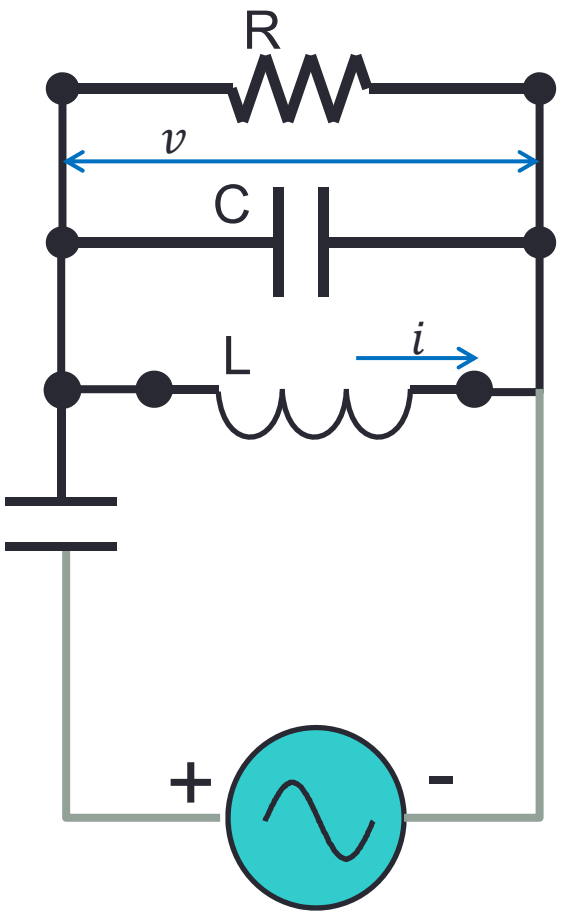


High harmonic frequency Flat top cavity



Courtesy of Lowry Conradie

Capacitive coupling



$$Q = \omega RC$$

How to feed the power into the cavity resonator?

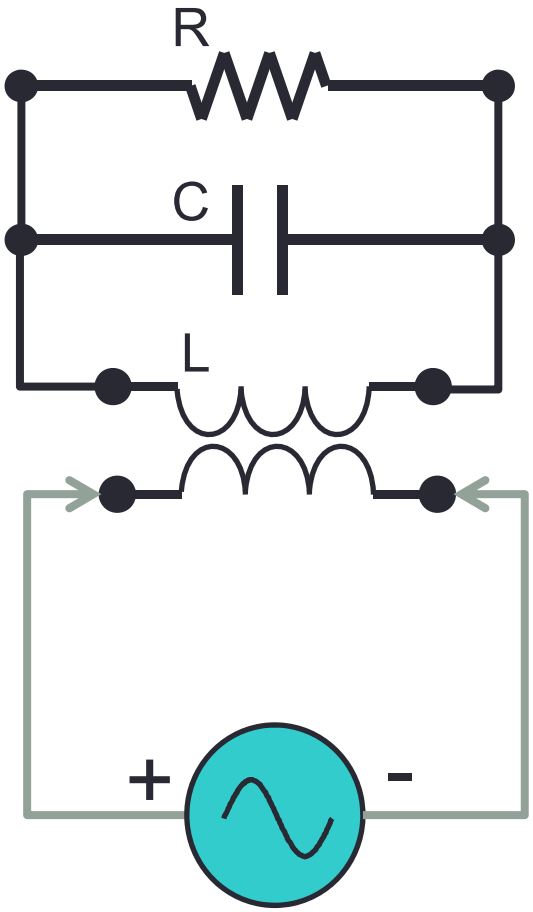
- Capacitive
- Inductive

$$R = \frac{2P}{V^2}$$

$$C = \frac{Q_0}{\omega_0 R} \qquad L = \frac{R}{\omega_0 Q_0}$$

AROUND THE RESONANCE FREQUENCY YOU CAN SEE THE CAVITY AS A CIRCUIT R-L-C

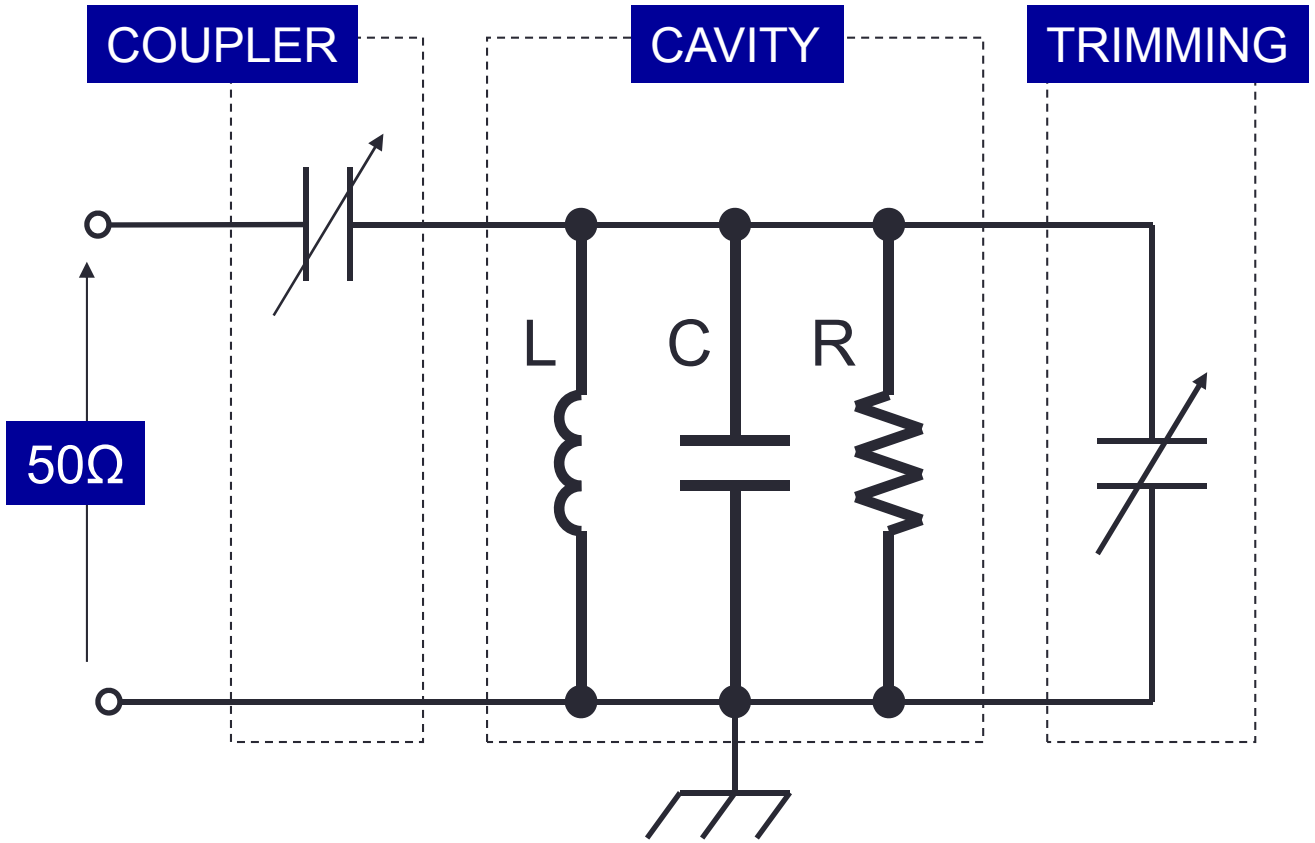
Inductive coupling



$$Q = \frac{R}{\omega L}$$

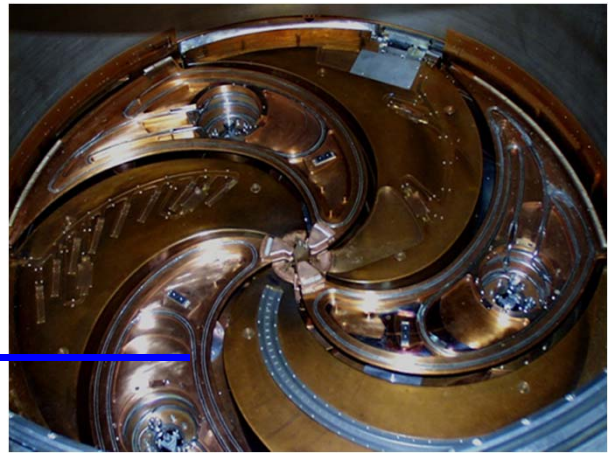
COUPLING CAPACITOR SCHEMATIC

Matching please

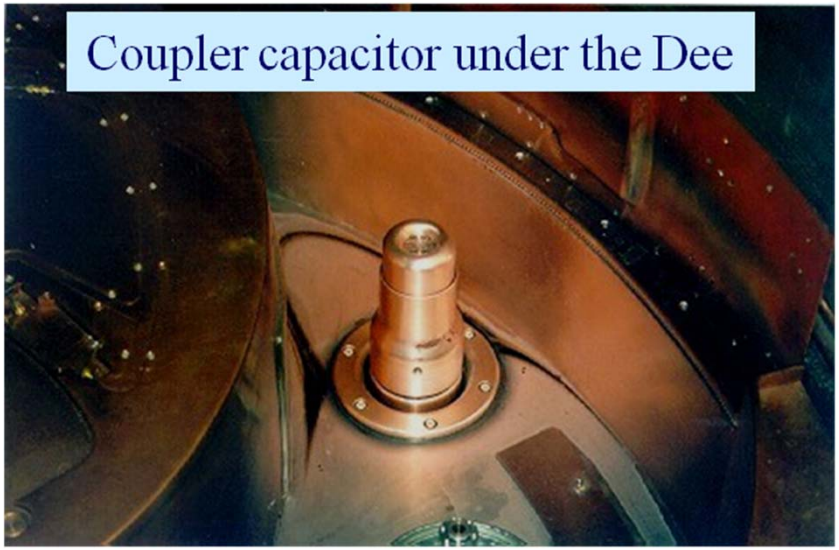


Coupling Capacitor

- simple mechanics
- also applicable for tuning control
- high voltage
  - insulator
  - discharge

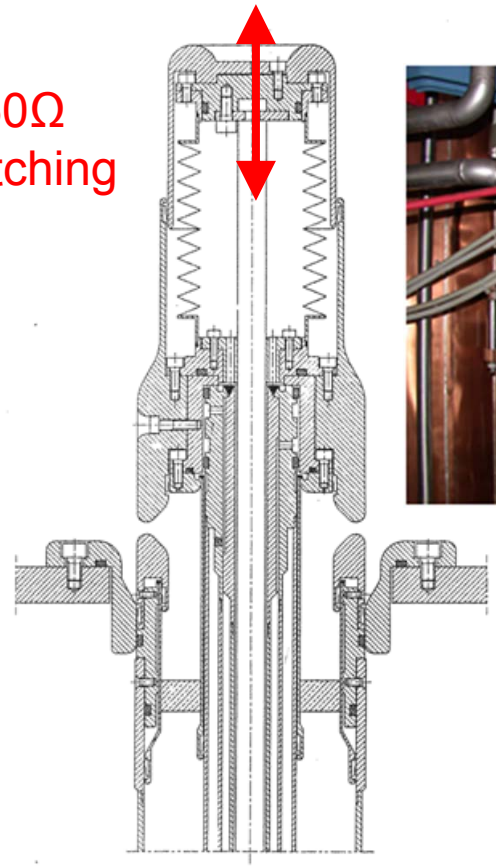


Dee



INFN-LNS, Catania

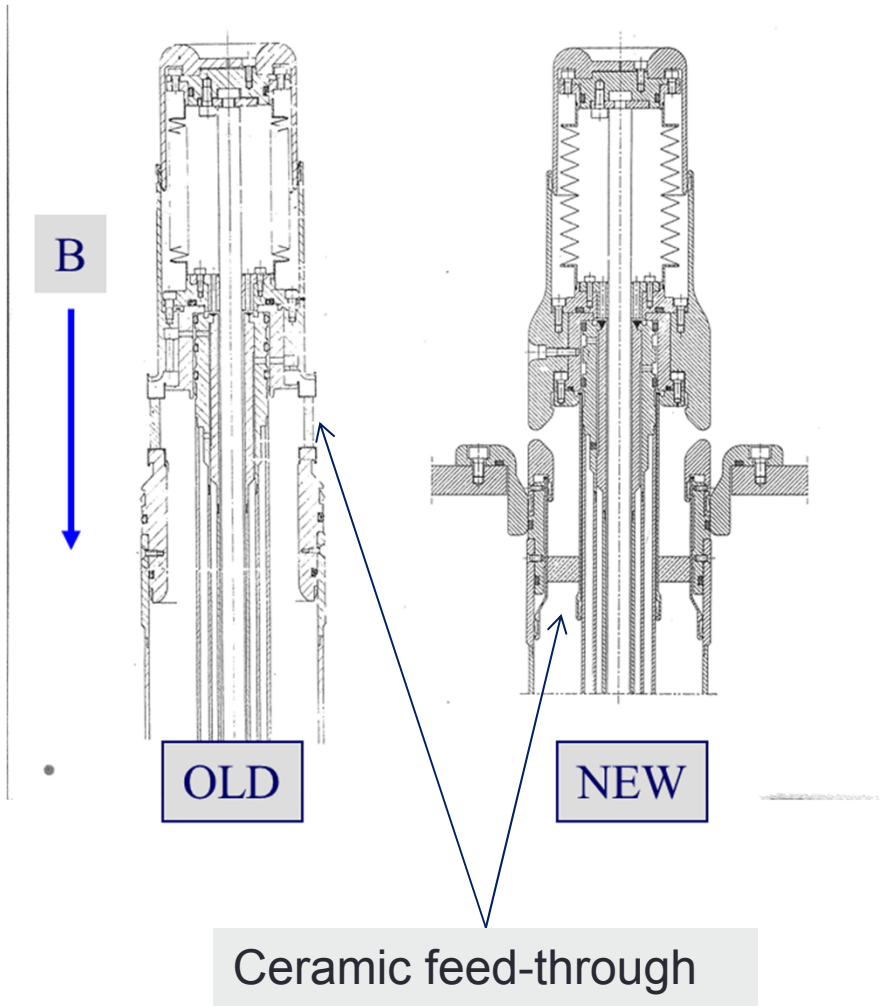
50Ω matching



Standard
6”1/8 coaxial rigid
transmission line

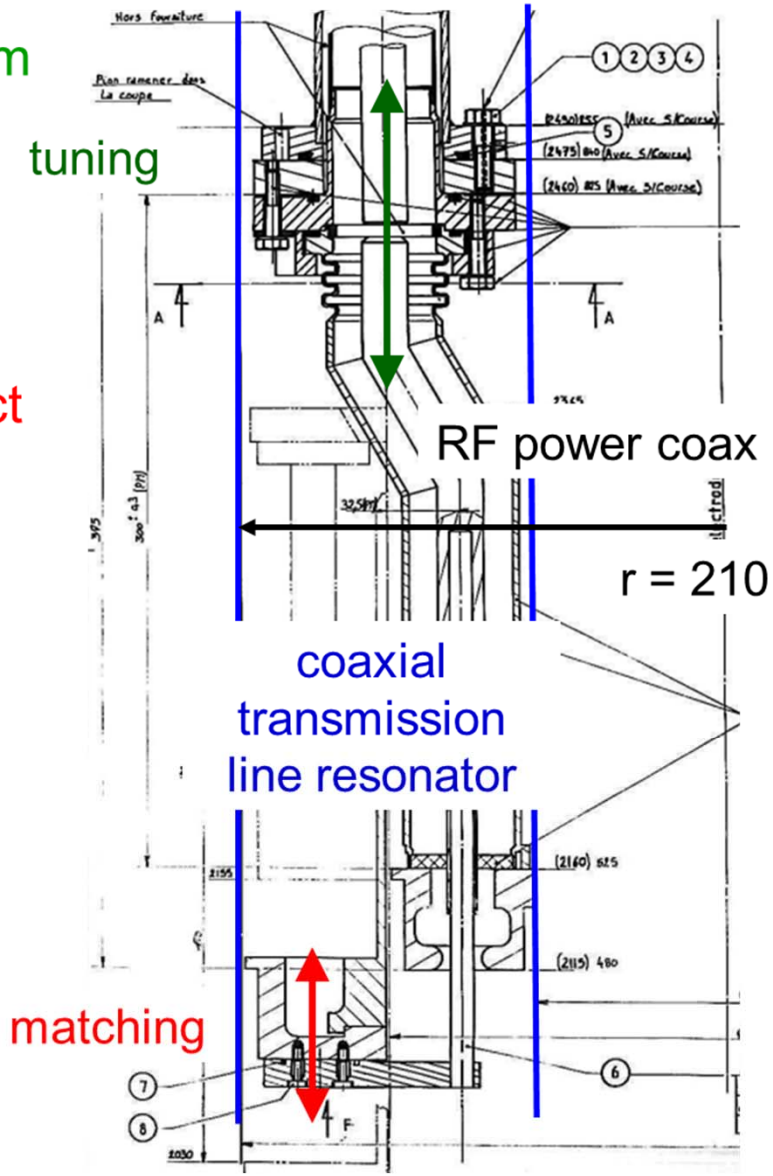
Something to strongly avoid

avoid ceramic insulator
parallel to magnetic field

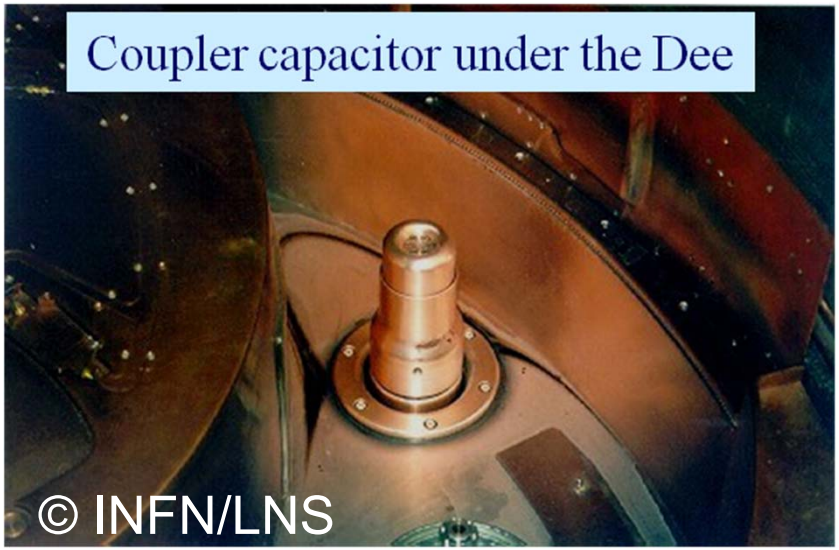


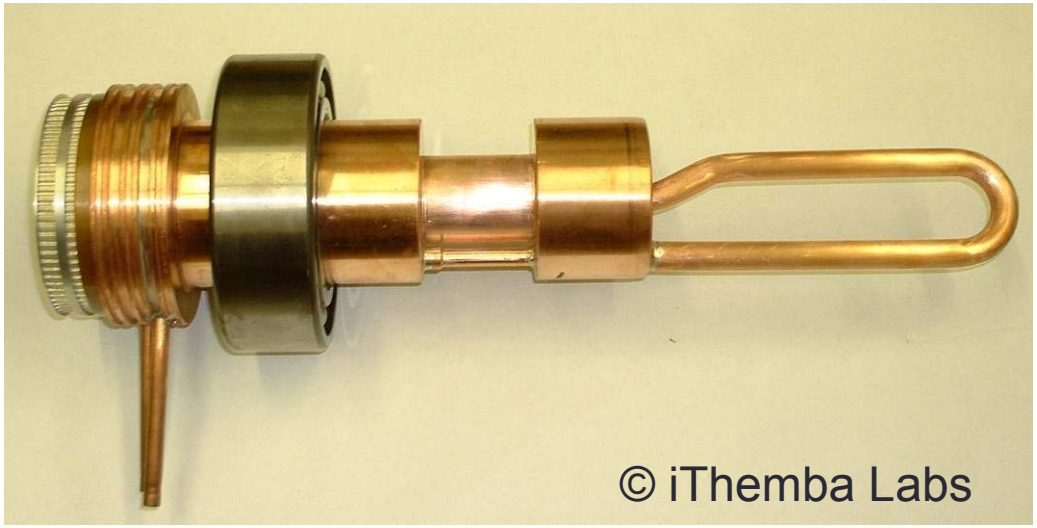
power coupling: inductive

- low voltage ➔ insulator no problem
- multipactor
- variable frequency resonator: complex mechanics
- high current rotating/sliding contact

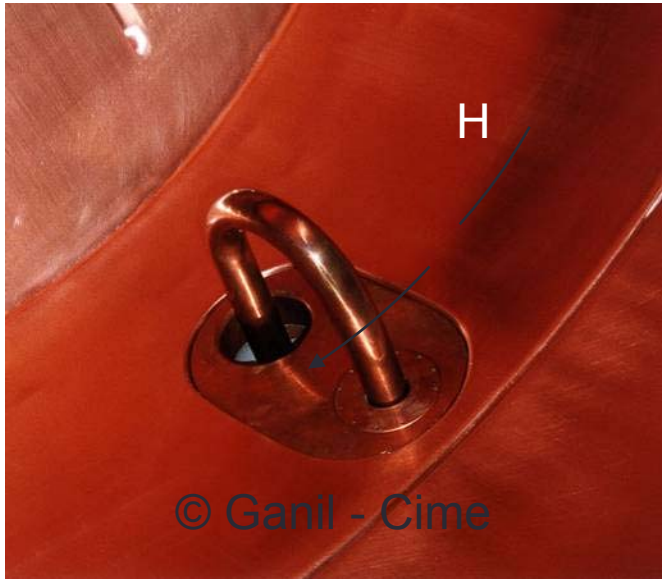


Courtesy of Sytze Brandenburg



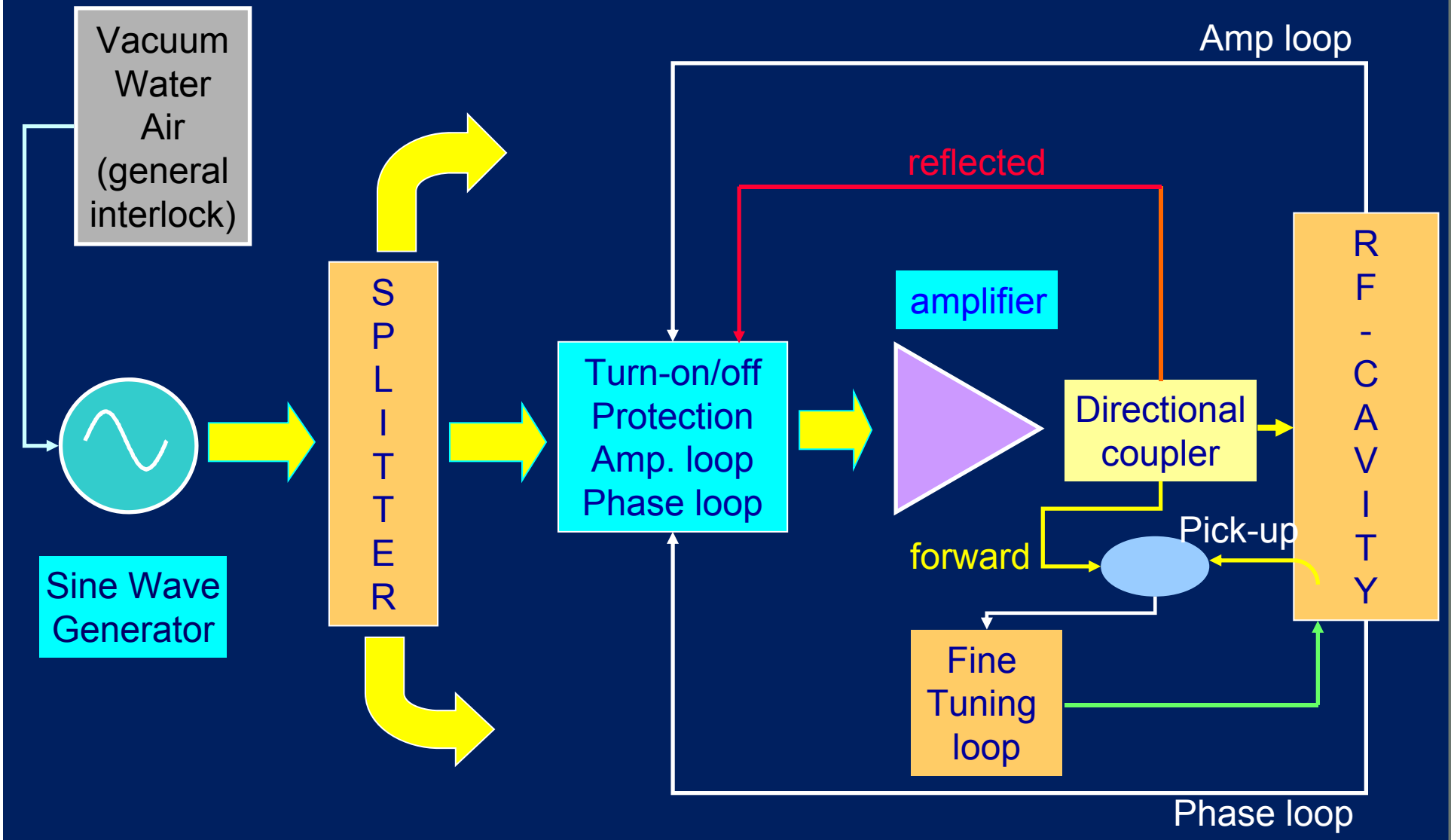


Couplers selection



- Protects the system from sparks, multipactoring, reflected power
- *Vacuum level, water cooling, temperature*
- Turns the system on/off
- Change and check the tuning at the resonance frequency
- Stabilize the accelerating voltage in amplitude and phase

The most important blocks



RF Control System (LLRF)

$$\Delta E = 2qV_D(\sin\varphi)$$

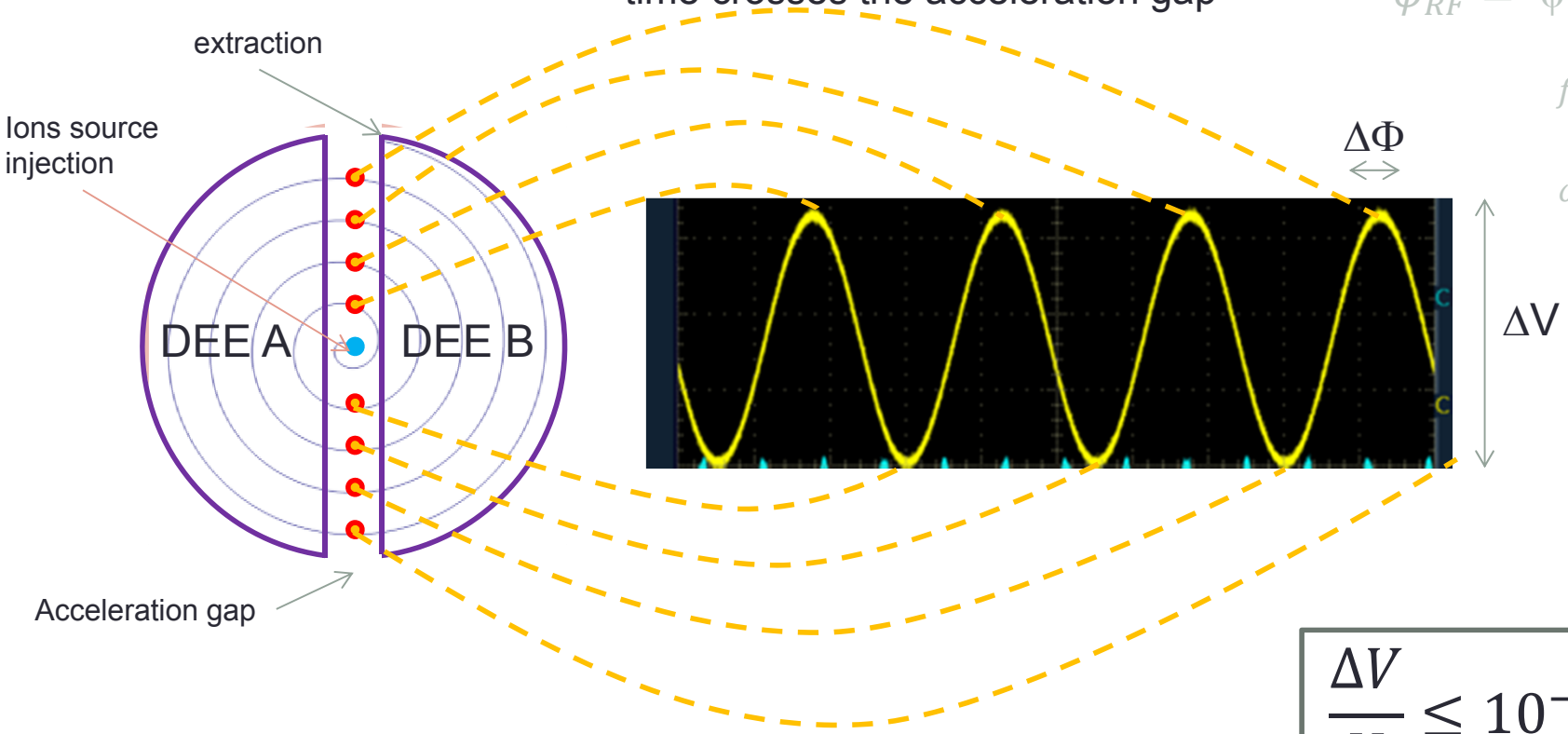
Maximum energy gain for ions each time crosses the acceleration gap

$$\varphi = \varphi_{ion} - \varphi_{RF}$$

$$\varphi_{RF} = \psi$$

$$f = \frac{qB}{2\pi m}$$

$$\omega = 2\pi f$$



$$V_D(t) = V_D\cos(\omega_{RF}t + ?)$$ Accelerating voltage

$$\frac{\Delta E}{E} = 10^{-3}\ energy\ stability\ of\ accelerating\ beam$$

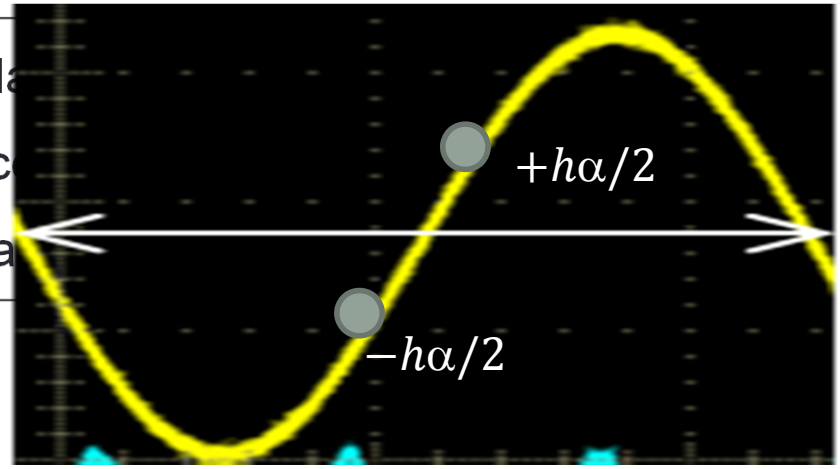
$$\frac{\Delta V}{V} \leq 10^{-5}$$

$$\Delta\Phi = \pm 0.1°$$

Maximum energy gain for ions crossing the valley centre as the RF voltage changes sign

$$\Delta T = 2qV_D\left(\sin\mathrm{h}\frac{\alpha_v}{2}\right)$$

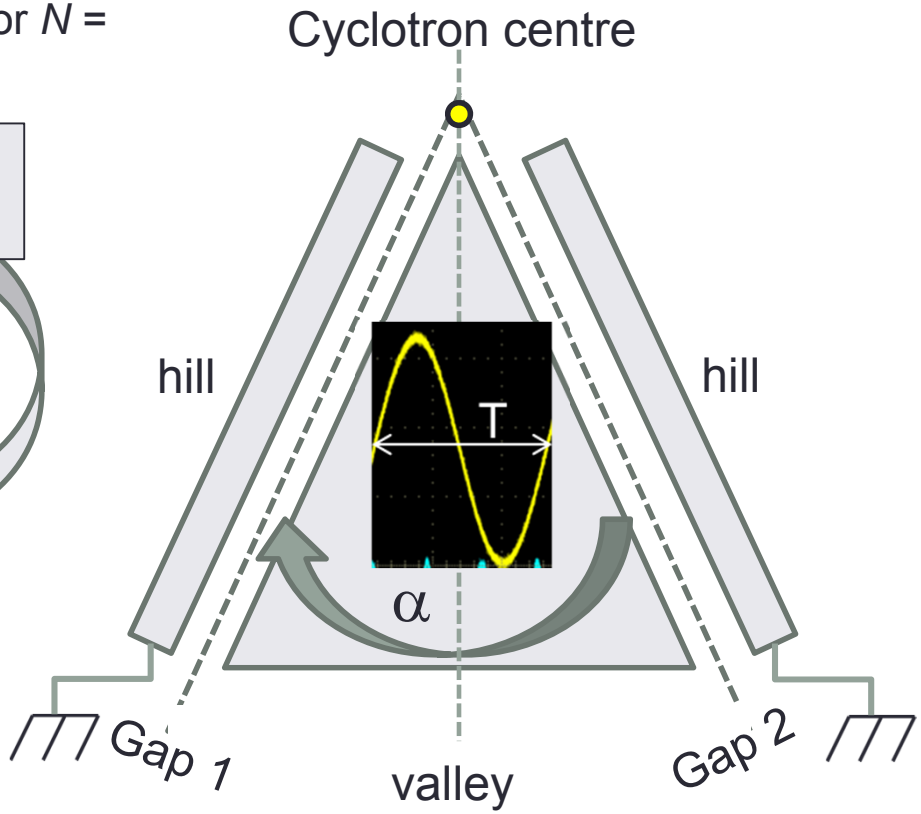
Nowada
the acc
to a tria



To optimize this, one should choose $\frac{h\alpha_v}{2} = \pi$

If $\alpha_v = \alpha_h$ this becomes just $h = N$, e.g. $h = 4$ for $N = 4$ and $\alpha_v = 45°$.

K-130 Cyclotron, Jyväskylä, Finland

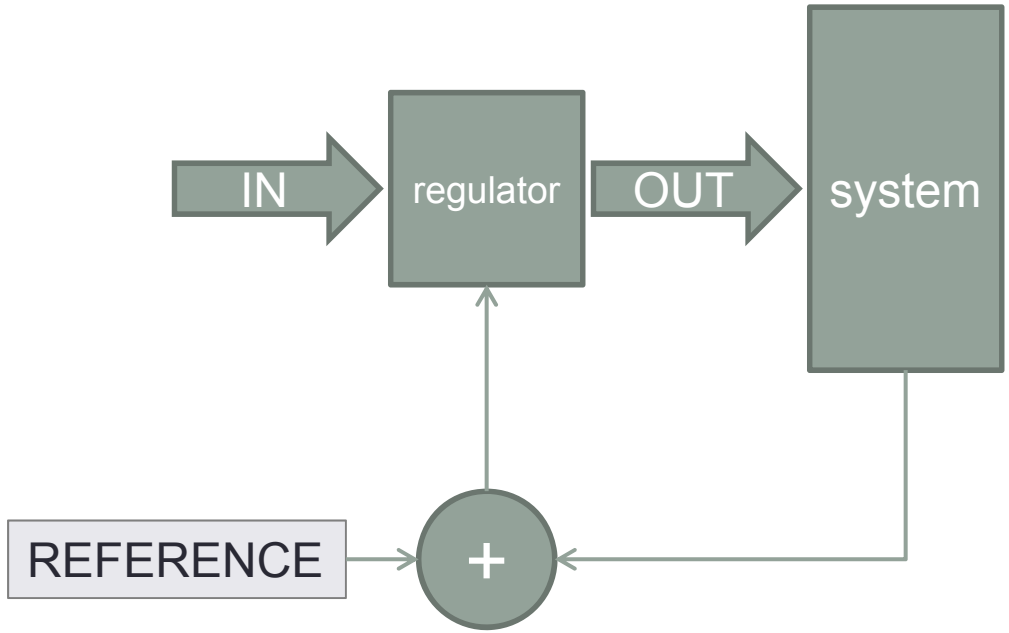


Feedback rules of thumb

$$\frac{\Delta V}{V} \leq 10^{-5}$$

$$\Delta\Phi = \pm 0.1°$$

Main Goal



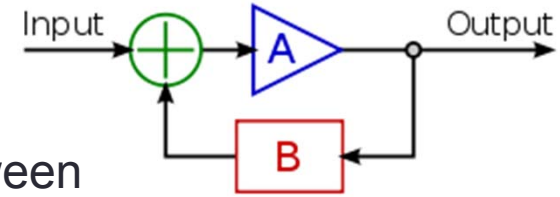
Automatic feedback system is carried out along this following lines:

- the magnitude that needs to be regulated is continually measured and compared with the required value
- the error signal (the difference between the real value and the required value) is used to automatically vary the magnitude itself so as to bring it up to the desired value (+).
- the system behaves in such a way as to minimize the error signal

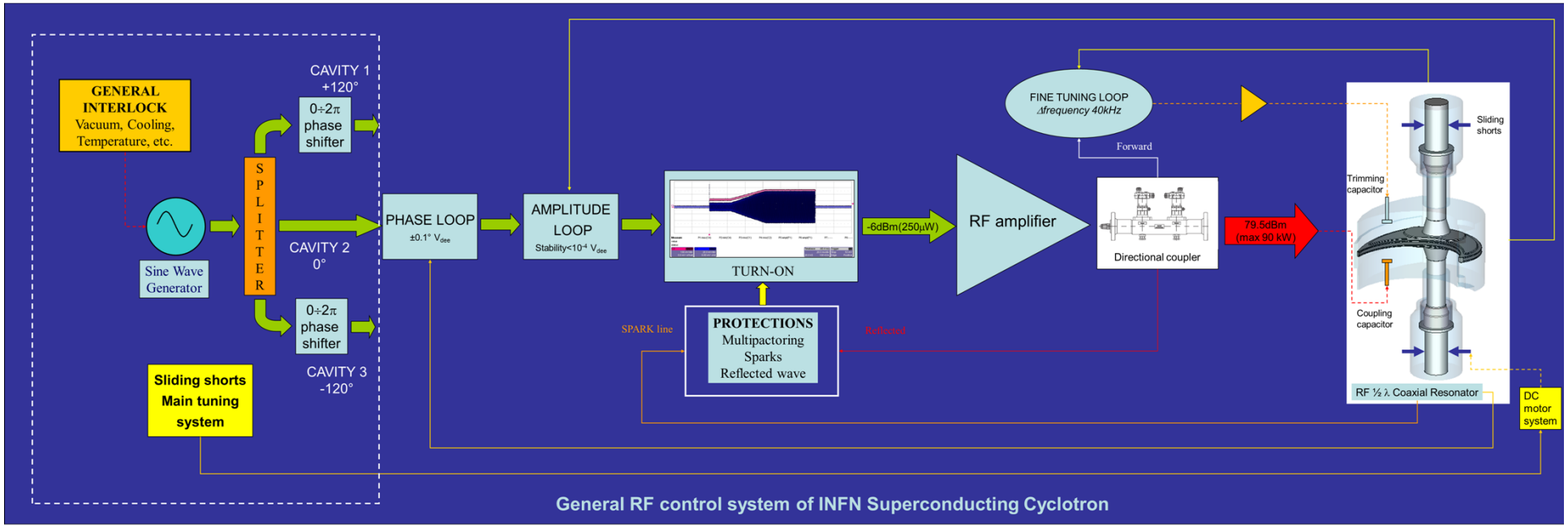
- controlled parameters
  - amplitude acceleration voltage
  - phase acceleration voltage
  - resonator tuning

- measured parameters
  - amplitude acceleration voltage
  - phase acceleration voltage
  - phase incident wave – acceleration voltage
  - reflected power

Automatic feedback system

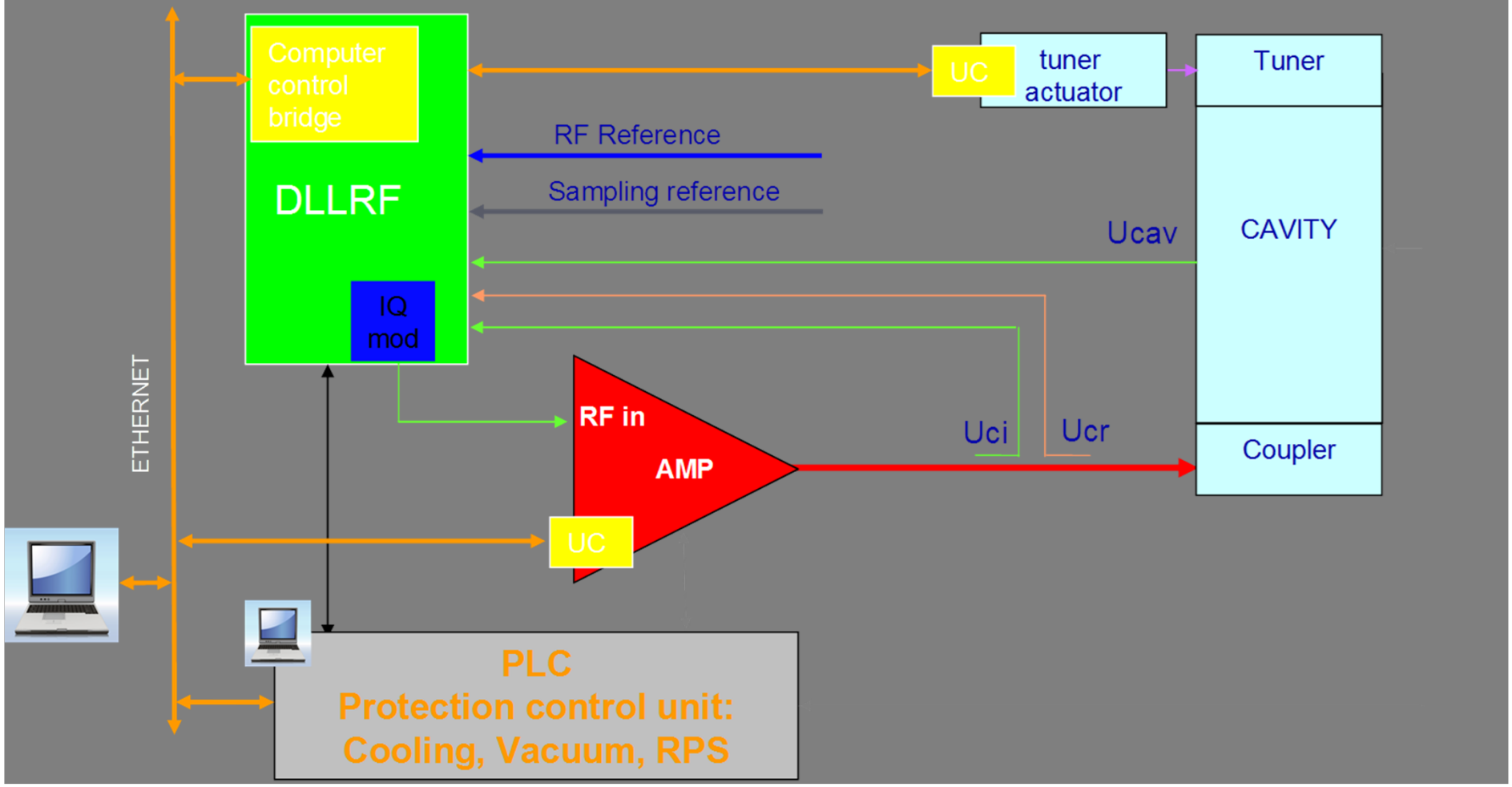


Analog approach or mixed between digital and analog LLRF system

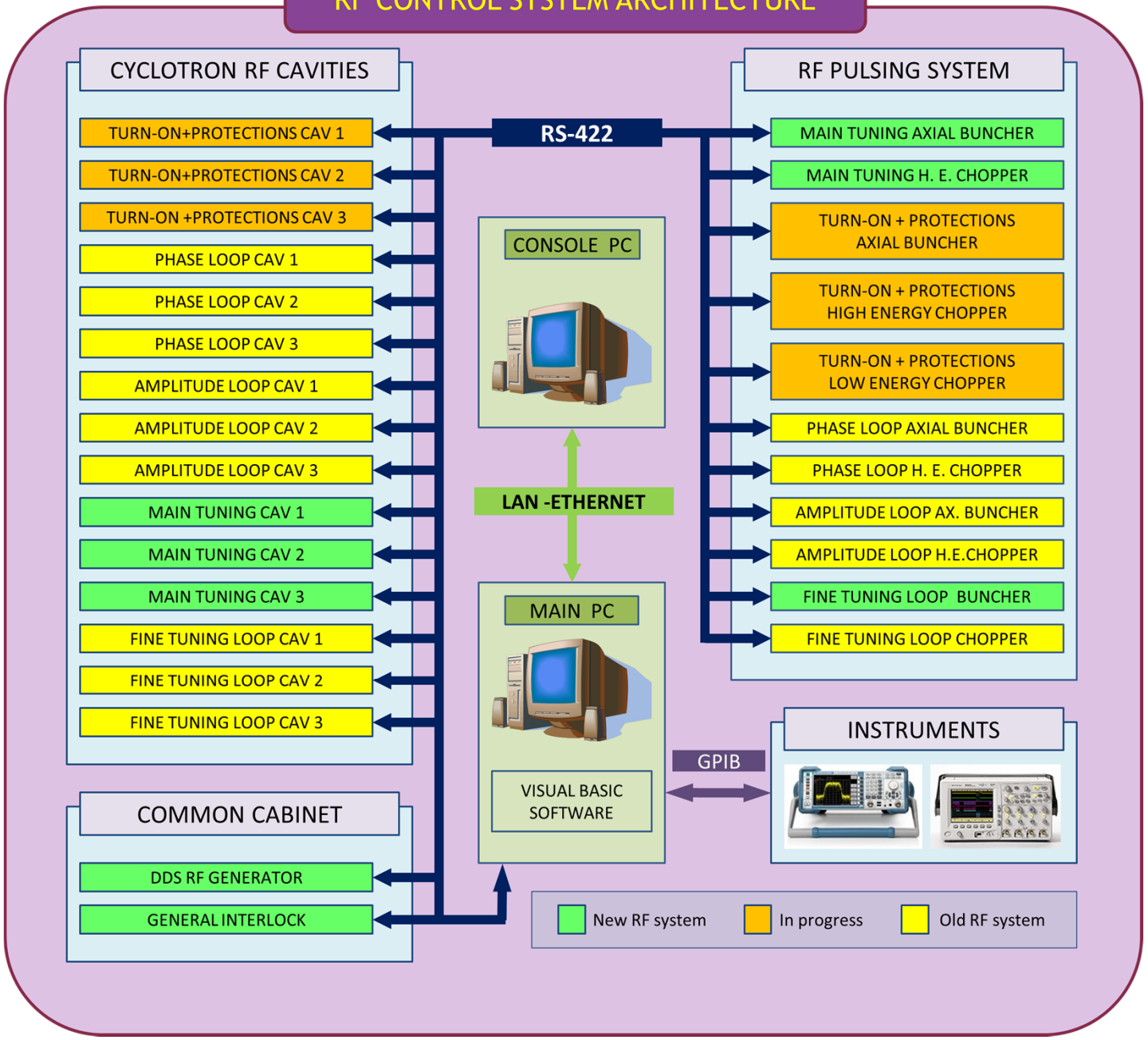


General RF control system of the LNS superconducting cyclotron

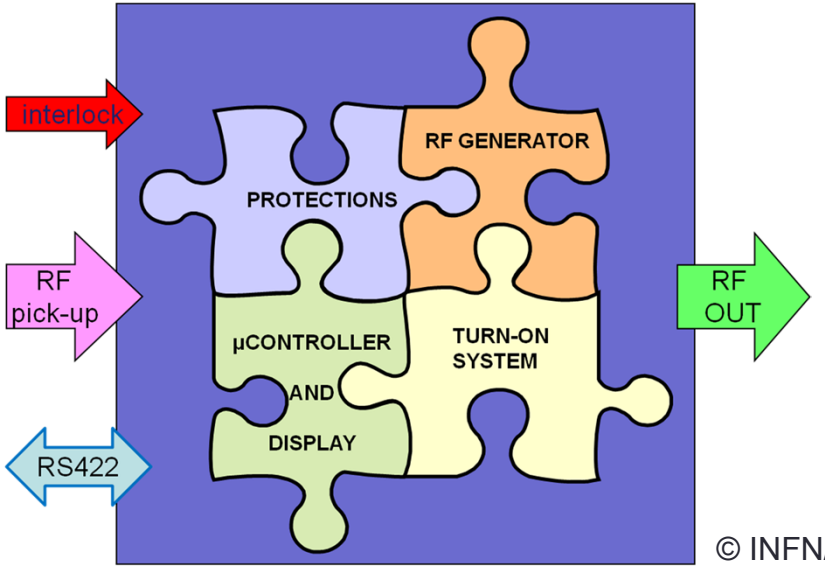
LLRF : RF system scheme with digital LLRF

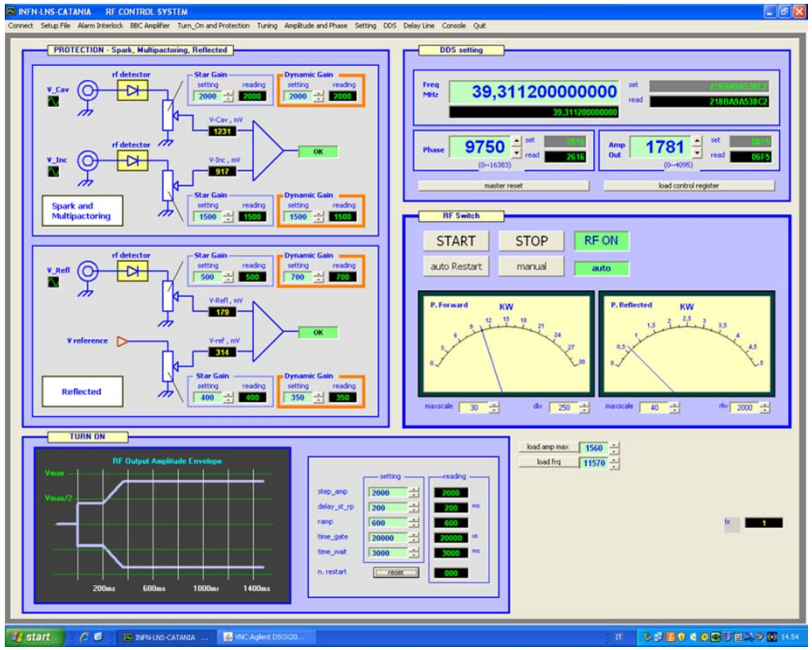


RF CONTROL SYSTEM ARCHITECTURE



Digital LLRF
(synthesizer, turn-on, protection)





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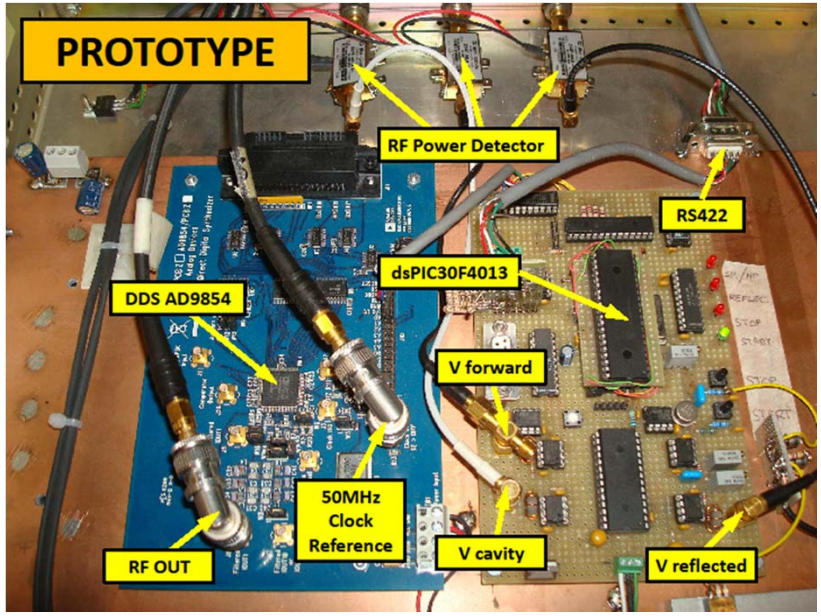
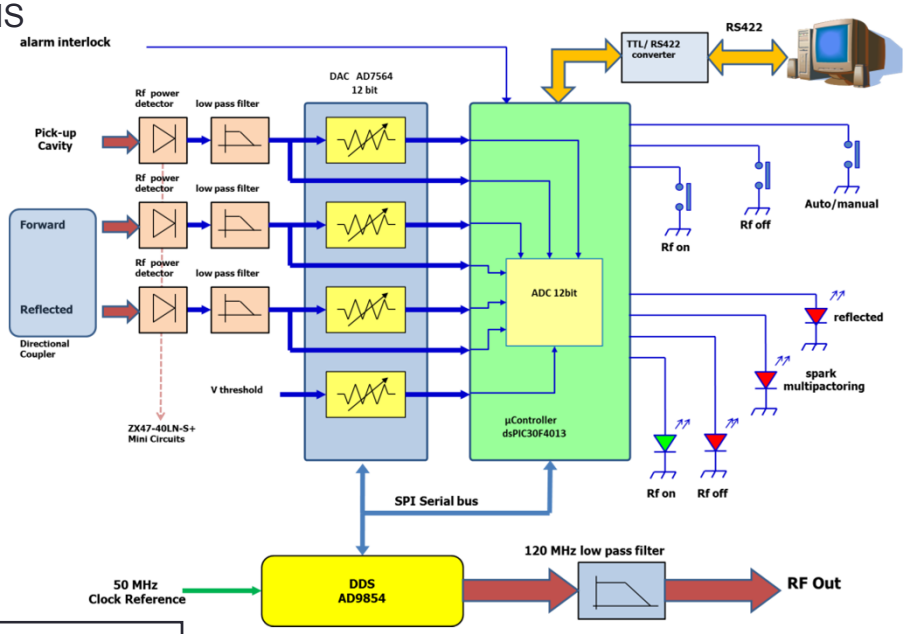
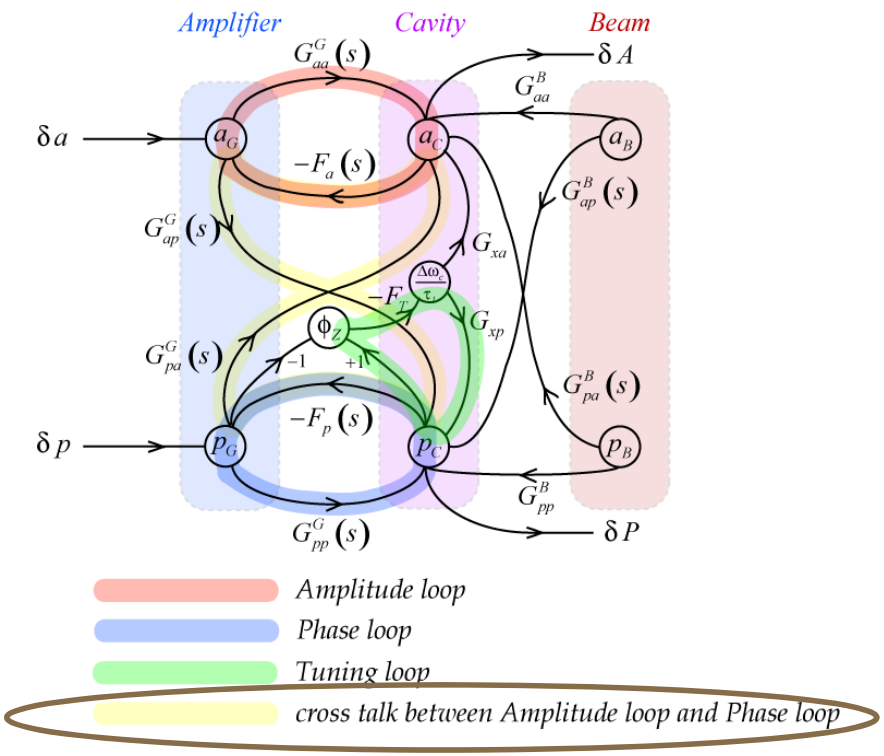




DDS based



From

Analog to Digital

Courtesy of Zhiguo Yin

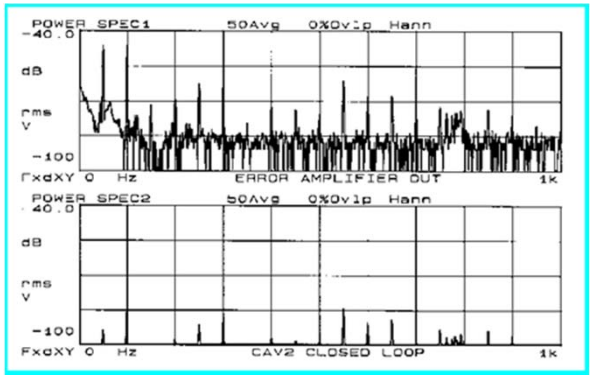
Stable voltages: VNoise/Vdee better than 10^{-4}, phase error < 0.1°

Fine Tuning: Frequency drift (slow but large (f_0*10^{-3})

- Thermal frequency drift: water input temperature (hours)
- RF power (100 ms to 10 s)

Amplitude loop

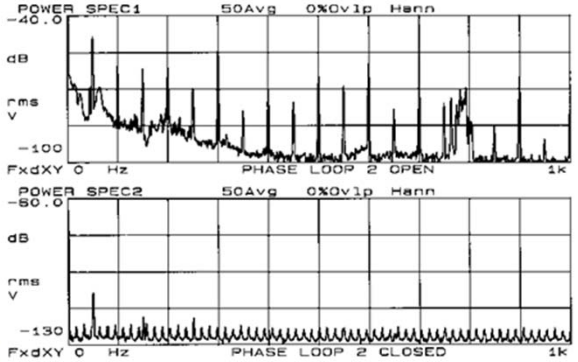
- Residual amplitude error from fine tuning (few %, slow)
- 50 Hz from the tube filament (1%)
- 100 ÷ 500 Hz from HV ripple (0.2%)
- Amplifier gain stability (% but very slow)



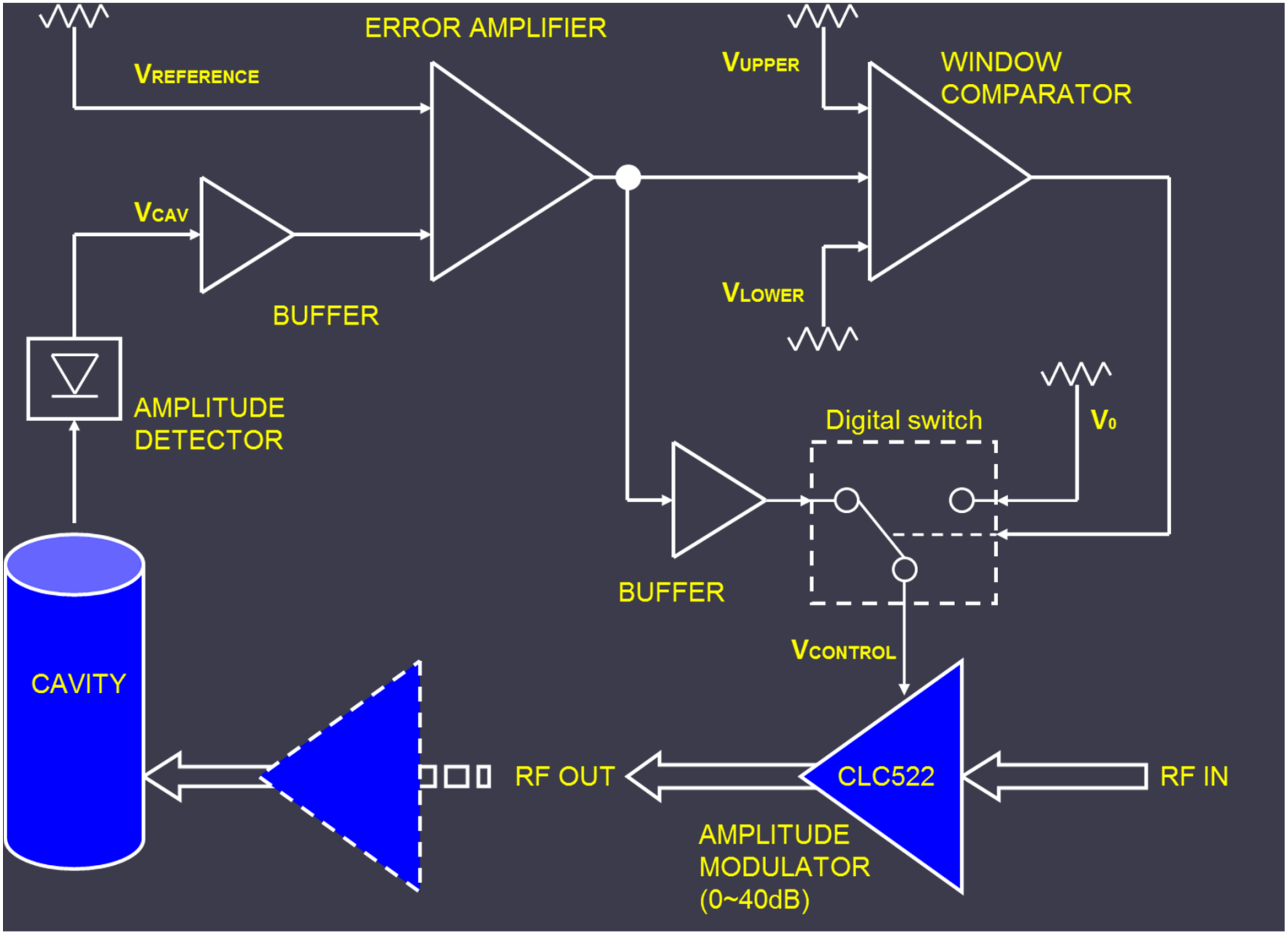
Residual noise of phase and amplitude loop

Phase loop

- Residual phase error from fine tuning (±10°)
- Phase modulation of the amplitude modulator
- Phase drifts in the amplifier, T-lines, etc with pov



Amplitude LOOP



Multipactoring

Can be dangerous,
can increases a lot the time
to “condition” the cavity

The **multipactoring** is a phenomenon of electrons multiplication.

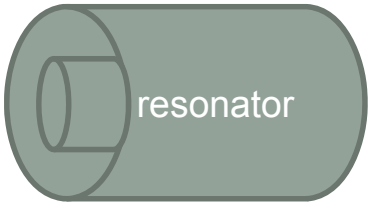
$$f \cdot d = \frac{(k-1)G}{k\pi\cos\varphi} \cdot \sqrt{\frac{eW_f}{8m}}$$

Where f is the radiofrequency, d is the distance between the two copper surfaces, k is a constant, φ is the initial phase of the electron motion, eW_f is the impact energy of the electron, m is the electron mass, G is

$$G = \left(\frac{K+1}{K-1}\right)\pi\cos\varphi + 2\,\mathrm{sen}\,\varphi$$

Conditions for the multipactoring between two surfaces of the resonator

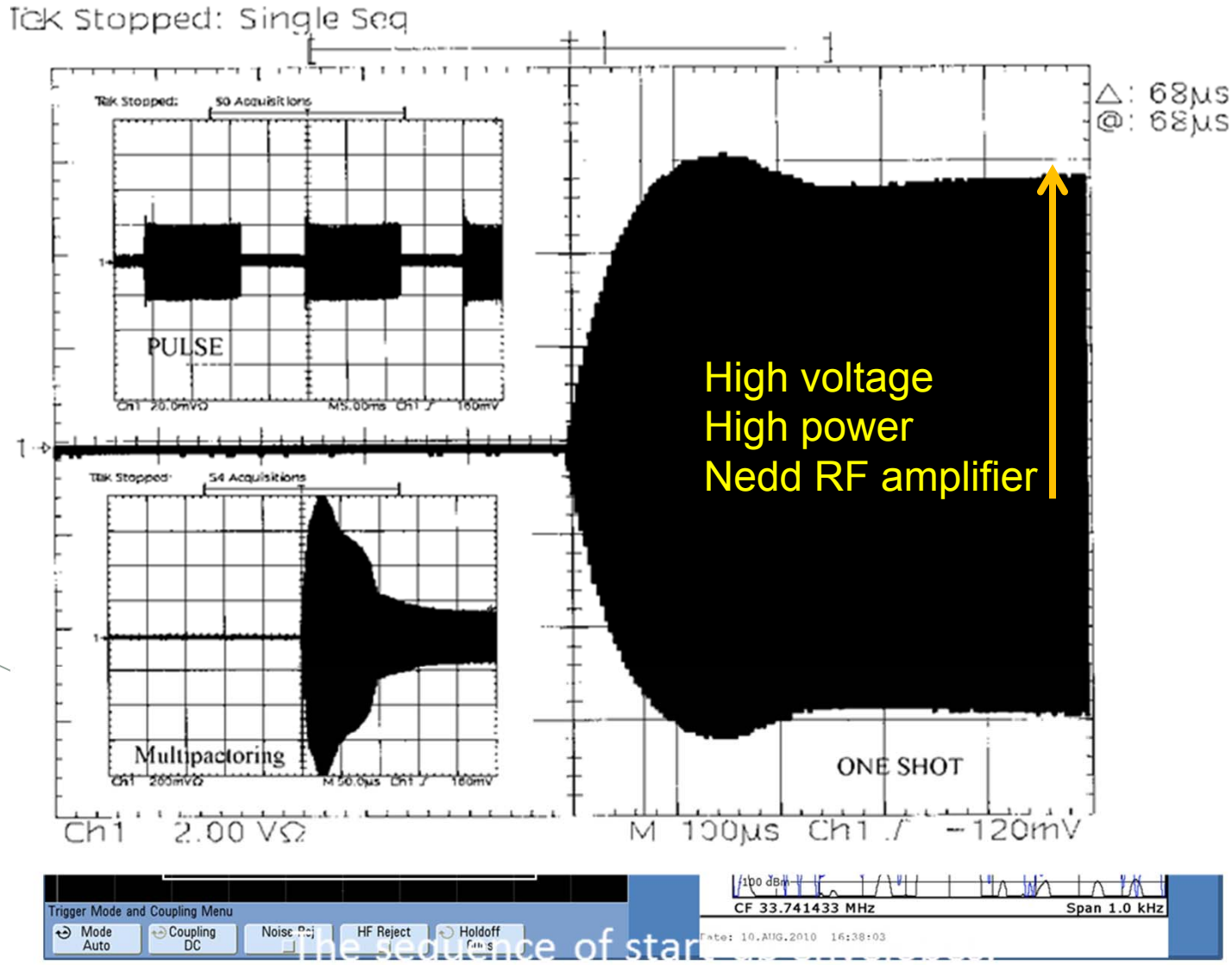
- distance between the electrodes > λ
- secondary emission coefficient $\delta > 1$
- electrons transit time between the electrodes equals (2n+1)T/2
- frequency and intensity field confined in a certain range.



Typical sequence of turn-on

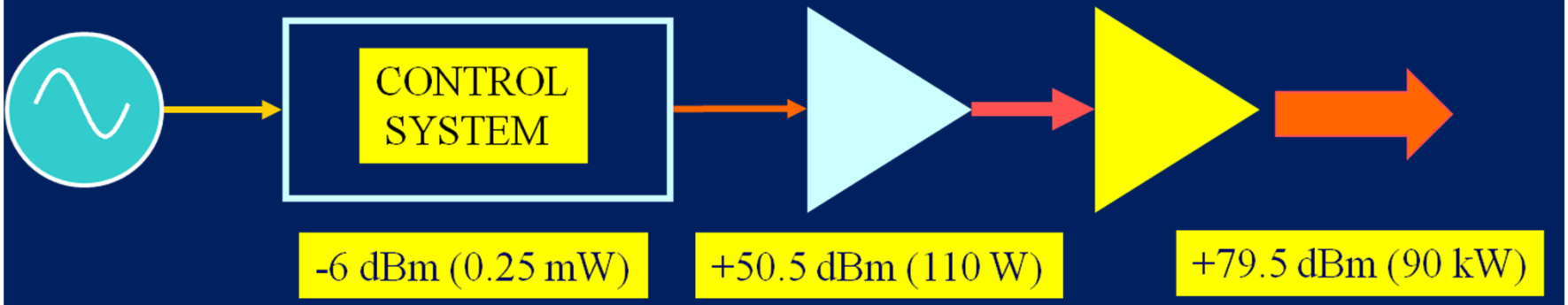
Amplitude, duty cycle, frequency of pulse mode

Fast and variable Step size. Variable ramp To reach the accelerating voltage



The sequence of star

RF Amplifiers

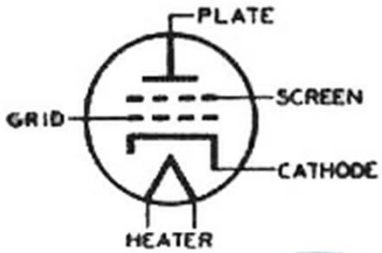


RF control electronic system

Driver Amplifier (ENI)
P_{max} 200 W

RF power amplifier BBC
P_{max} 90 kW CW,
Frequency range 15-50 MHz

Active device: transforms DC power into RF power

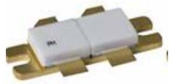


Grid or vacuum tubes:

- Triodes and Tetrodes (more linear)
- 1 or 2 devices cascaded
- Require high DC voltages (1 to 15 kV)
- Limited life-time (5000 hours guaranteed,10k-20k Typ.)
- Require hand-manufacture
- Increasing costs

Solid state

- RF Mosfets
- $N_{(big)}$ devices combined and cascaded
- 50 V DC bias
- Long life-time
- Power/mosfet increasing
- Decreasing costs (lots of applications)

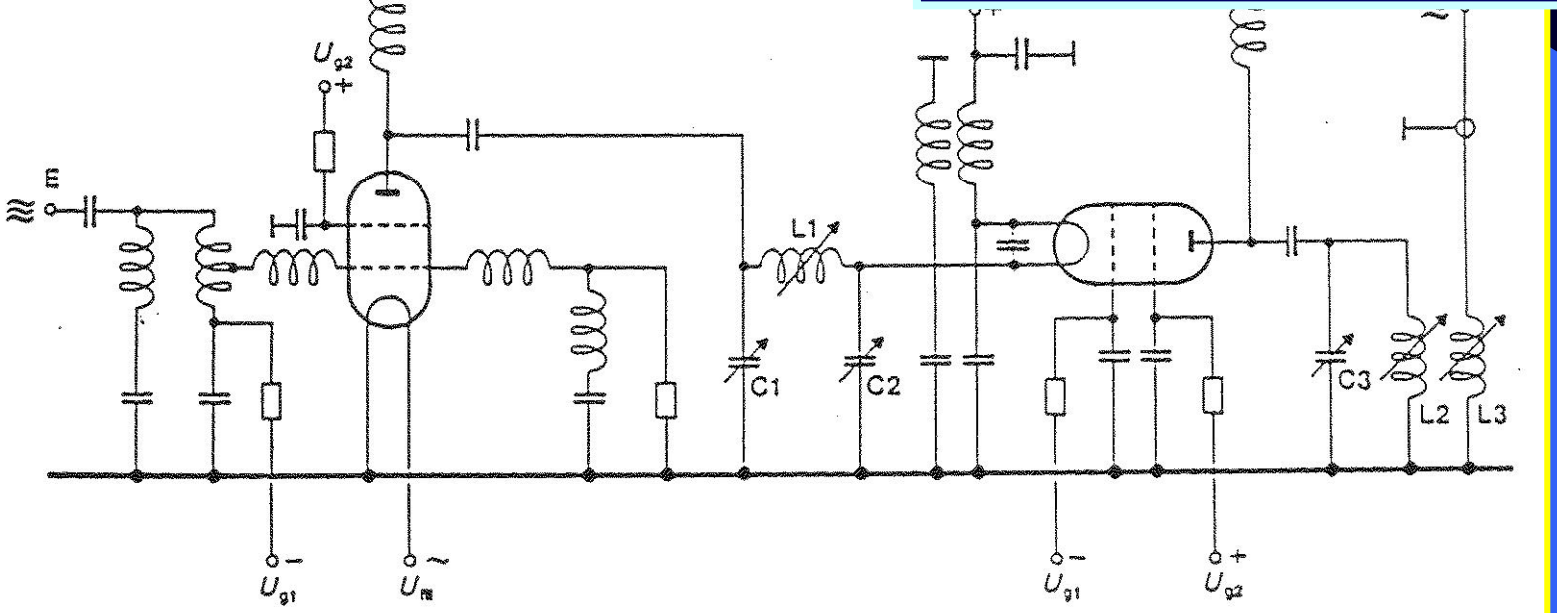


Input filter stag
• wide band
• adapts from 2
tetrode and EN
•The RF power
dissipated on t
•No tuning is r

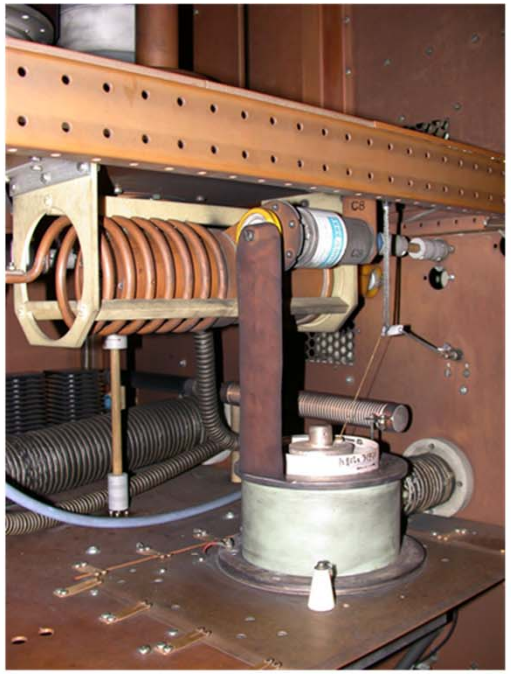
The 2nd stage (4CW100000):
common-grid configuration,
high isolation between the
in/out sections.
Filament input. Water cooled.
The load is a ¼ λ cavity plus a
capacity.

the two stages is
he 1st stage and
edance of the
ime. All the
e and capacitive

stage is a ground-cathode
ration. In general this
ration is very reliable, shows
w technical problem and a
rably low number of
ents.
Grid-control input.
Class AB.
Forced air cooled.
P_{OUT} 5 kW
T1 Siemens RS1054

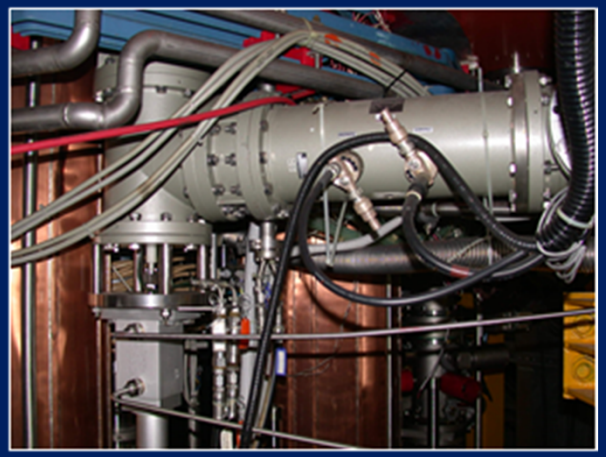


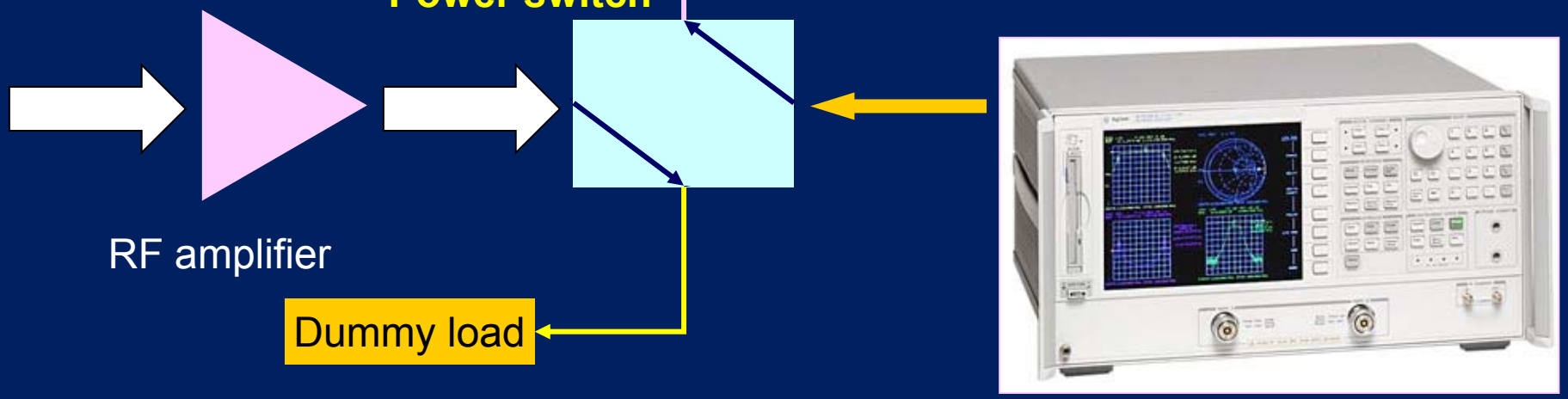
Inside the power amplifier

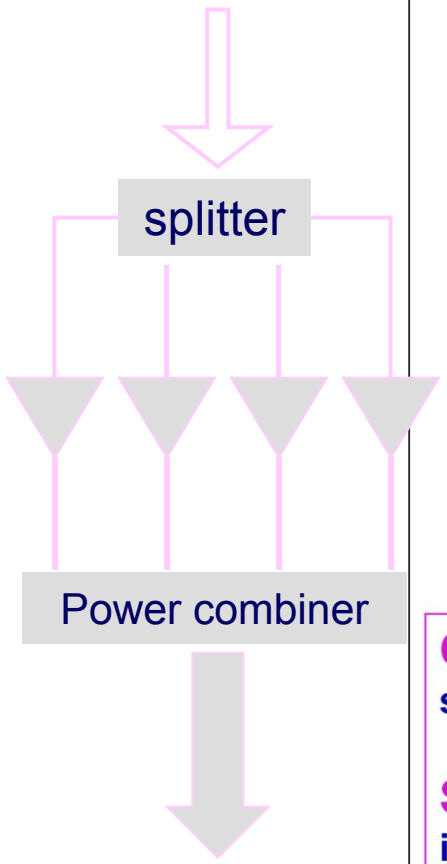


15 – 50 MHz
Max Power 90 kW

AN USEFUL TOOL







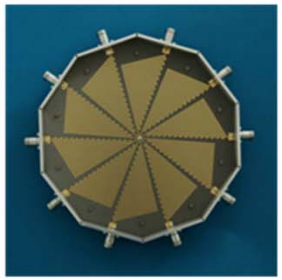
Solid state amplifiers: architecture

© Cryoelectra GmbH

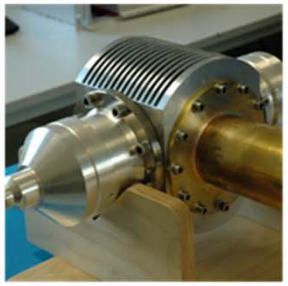
1.4 kW module

Combining: adding several parallel signals

Splitting: dividing into several parallel signals



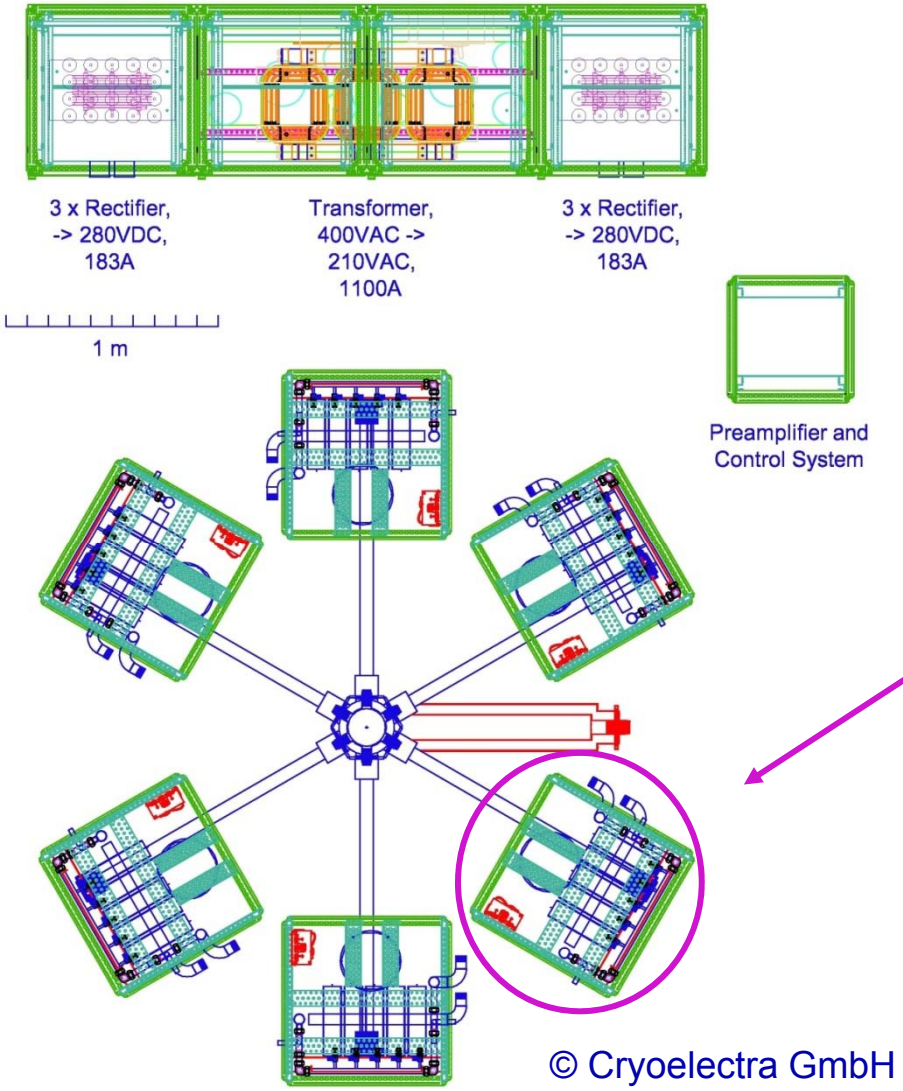
10-way micro-strip Wilkinson splitter



Quarter-wavelength coaxial combiners

Courtesy of M.DiGiacomo

Final combination up to 150 kW

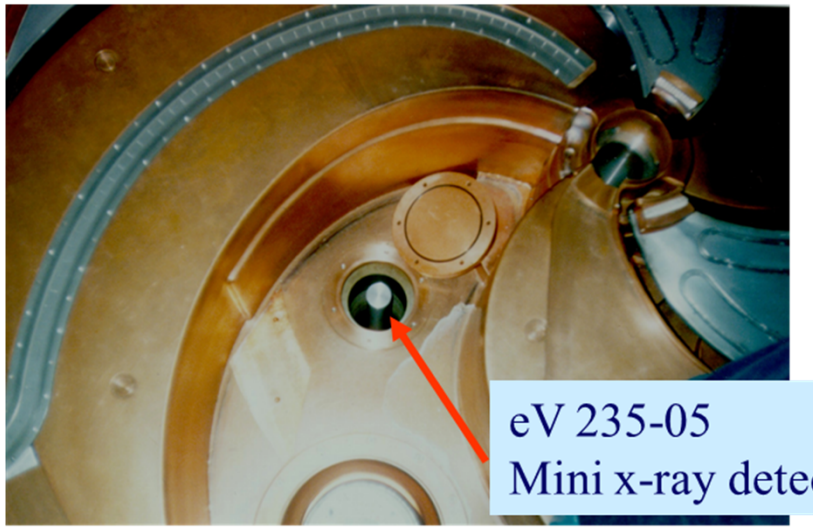


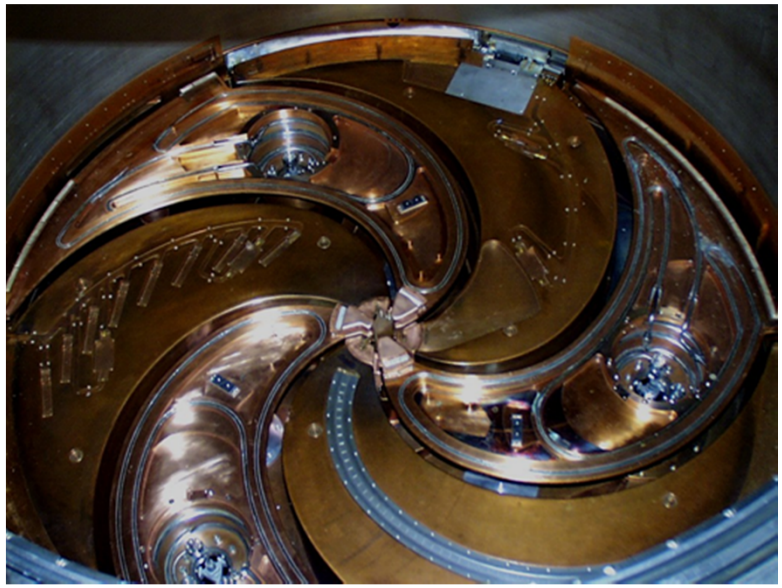
X-rays V_{dee} calibration

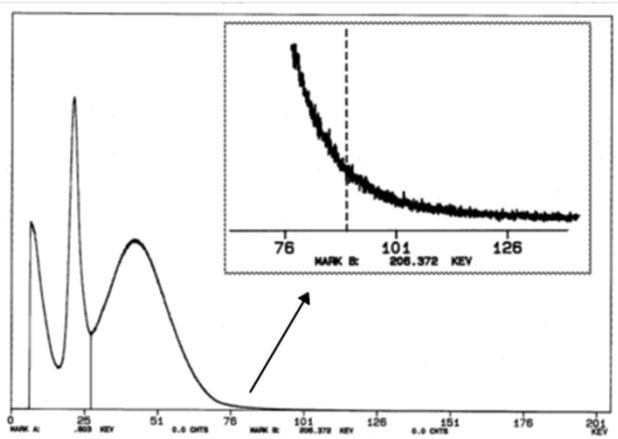
$V_{dee} = (2R_{shunt} P_{loss})^{1/2}$

$R_{SHUNT} = Q/\omega C_{eq}$

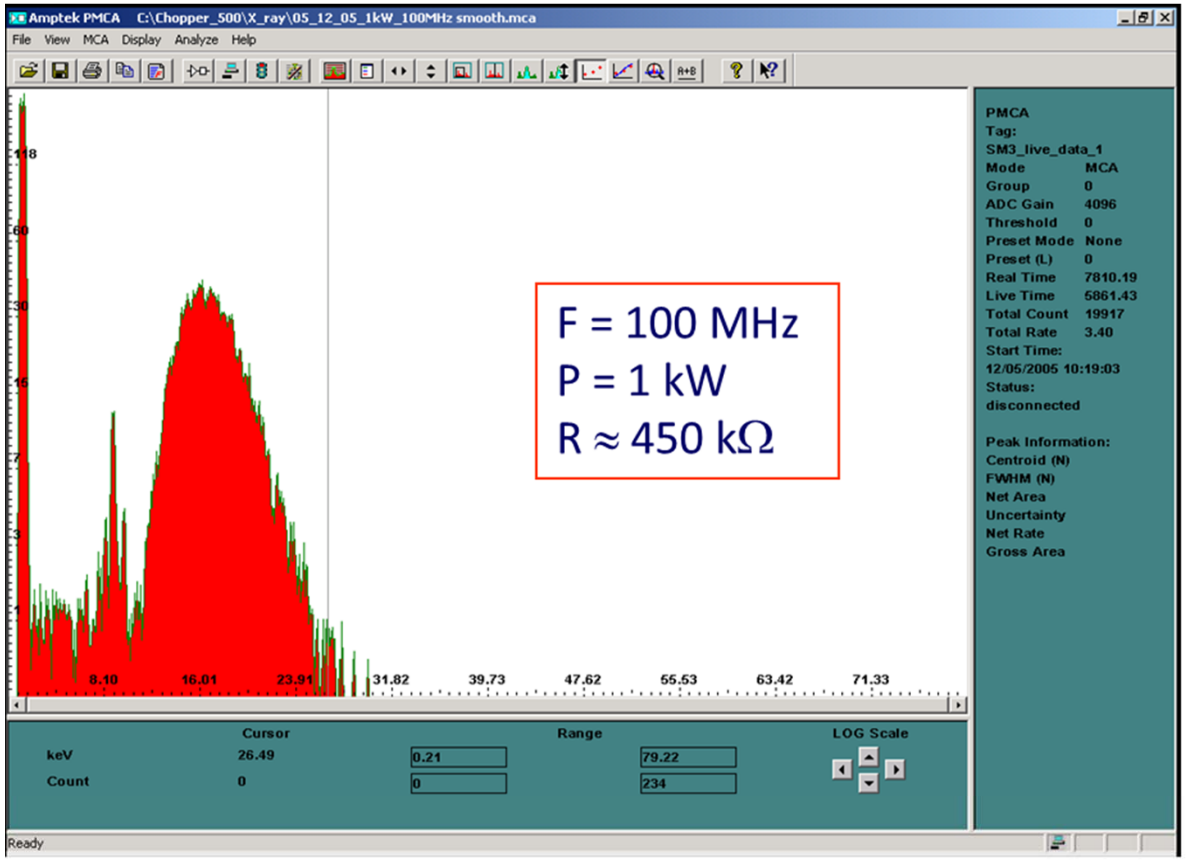
$R_{SHUNT} = Q \omega L_{eq}$







$$R_{shunt} = \frac{V_{xray}^2}{2 \cdot P}$$



F = 100 MHz
P = 1 kW
R ≈ 450 kΩ

Perturbation method

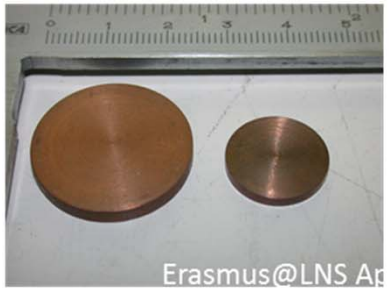
$$R_{shunt} = \frac{2}{\varepsilon_0}\left(\frac{g}{\pi \cdot D}\right)^2 \frac{1}{\Delta g} \cdot \frac{\Delta f \cdot Q_0}{f_0^2}$$

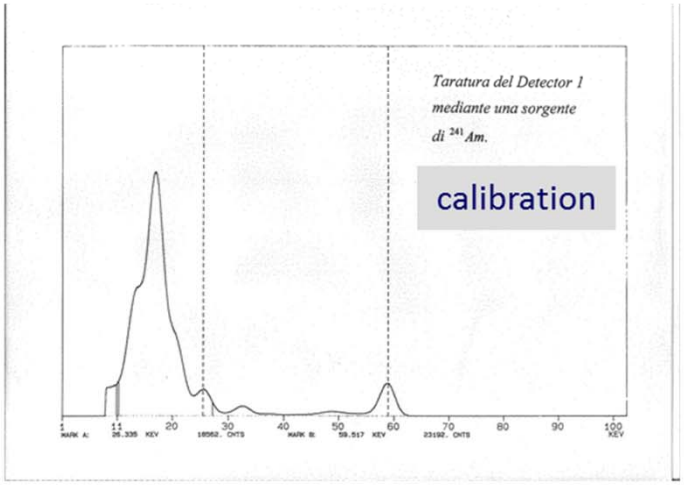
$$\varepsilon_0 \approx 8.85 \cdot 10^{-12}$$

g: gap between the electrodes
D: diameter of the perturbation element
Δg: thickness of the perturbation element
f_0: resonance frequency without perturbation
Q_0: unloaded Q factor

X-Rays method

$$R_{shunt} = \frac{V^2}{2 \cdot P}$$





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Michel Abs (IBA)

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Sumit Som (VECC)

Particle Physics - The High Energy Frontier by M Stanley Livingston editor McGraw- Hill

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Principles of Cyclic Particle Accelerators by John J Liningood editor D. Van Nostrand Company, Inc.

J. Millman, Microelectronics, Mc Graw Hill

Publications from cyclotron conferences available on JACoW site

Extra slides

Relativity – in brief.

$$\mathcal{E} = \mathcal{E}_0 + T = m_0 c^2 + T = m c^2$$

$$\begin{matrix} v \ll c \\ T \ll \mathcal{E}_0 \end{matrix} \Rightarrow T = \frac{1}{2} m_0 v^2$$

$$\begin{matrix} T \gg \mathcal{E}_0 \\ v \simeq c \end{matrix} \Rightarrow T = (m - m_0) c^2 = (\gamma - 1) m_0 c^2$$

$$m = m_0 \gamma \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\beta = \frac{v}{c}$$

$$\mathcal{E}_0 = m_0 c^2 \simeq \begin{cases} 0.5\ \text{MeV} & \text{elettrone} \\ 1\ \text{GeV} & \text{nucleone} \end{cases}$$

T=kinetic energy

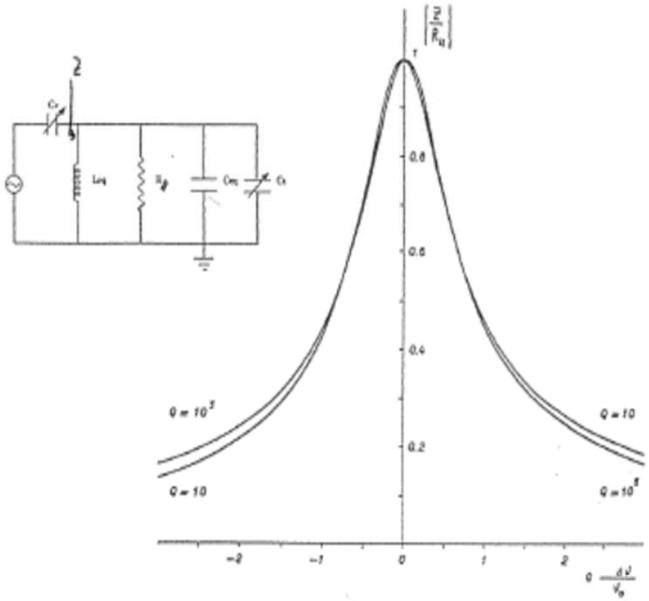
m_0= mass ($v \ll c$)

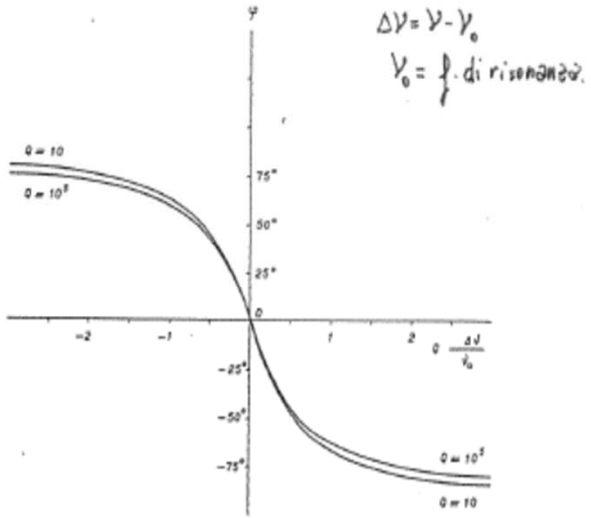
m = mass ($v \cong c$)

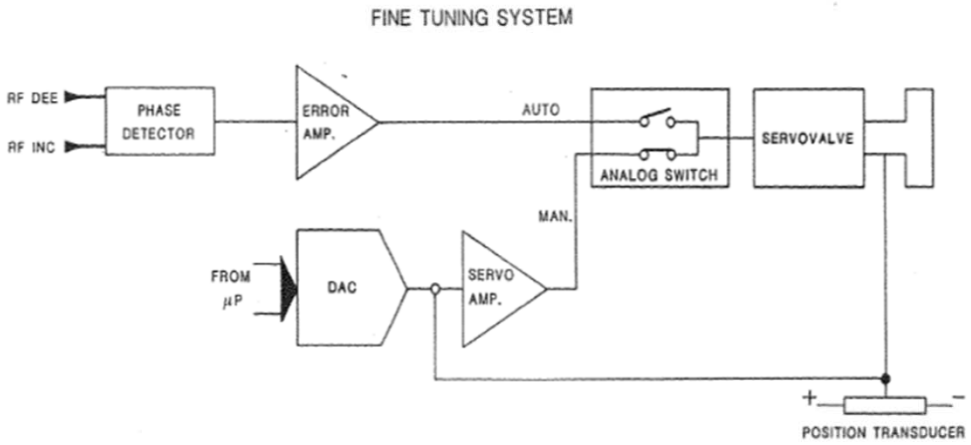
$$\boldsymbol{\omega = qB/m}$$

(cyclotron frequency)

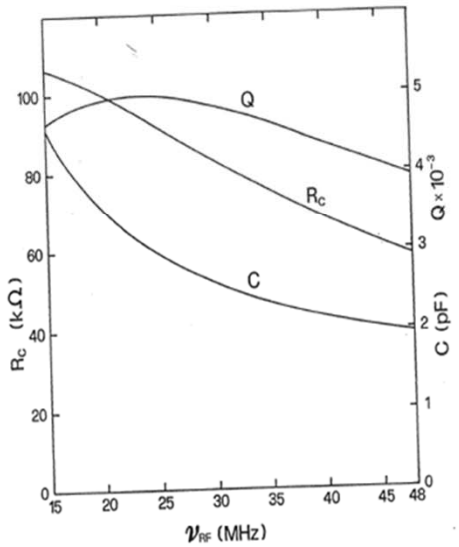
Tuning loop





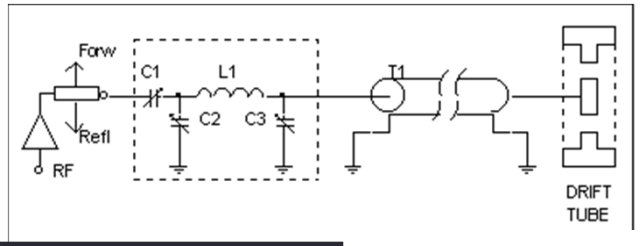


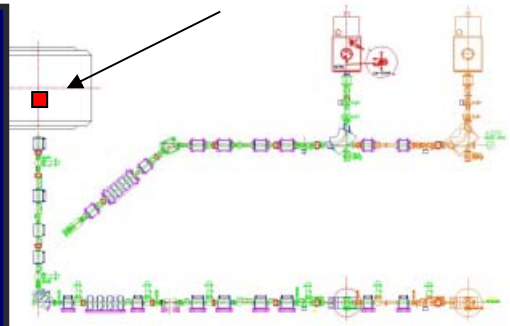
$\Delta f = 40\ kHz$



Axial buncher system

- Drift tube solution inside the CS yoke
- ½ meter from median plane
- Frequency range 15-50 MHz
- Electrode length 41 mm $L=2\pi R_i/2h$
- Efficiency measured 3.5-4.5
- Extracted beam bunch < 1ns FWHM
- V_{pick} 1500 V – P_{max} 150 W
- Vacuum enviroment.





Main components:
- RF amplifier
- The matching box
- The 1”5/8 coaxial line
- The electrode
- The control system

WORKING PRINCIPLE

The drift tube with the coaxial line could be considered as a fixed frequency resonator. A resonance of **76 MHz** was found with a **Q-factor of about 600**. With the help of the **matching box**, we are able to reduce the resonant **frequency down to our range, 15÷50 MHz**. At the same time **the 50 Ohms matching** for the output stage of the RF amplifier is achieved. Therefore, the combination of the matching box, the coaxial line and the drift tube is a sort of **variable resonator** with the voltage **antinode** localised **on the electrode**.

How to fit a resonant circuit in a cyclotron?

Old real classic cyclotron

CLASSIC CYCLOTRON

$$\omega = qB/m$$

Non relativistic ions

B decreases while m increases

Defocusing problem

Limit highest velocity of ions

Record is $\beta = 0.22$ (86" Oak Ridge, 1952)

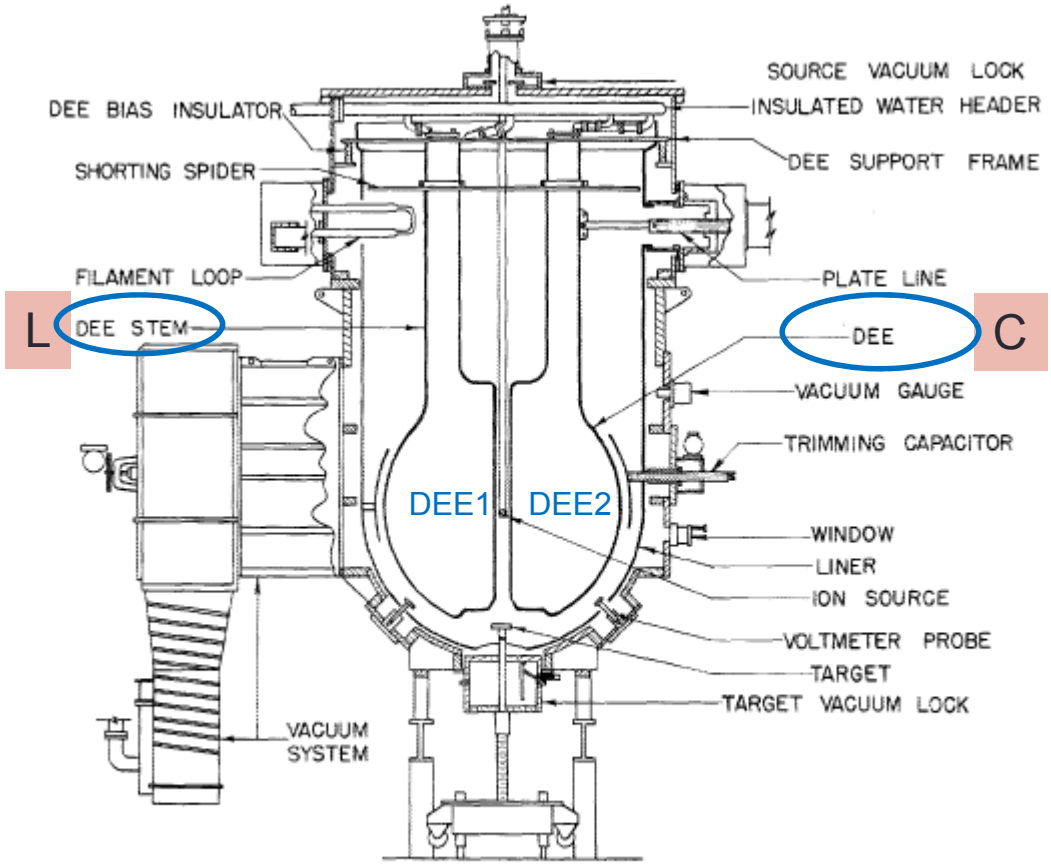


FIGURE 2. CROSS SECTION OF CYCLOTRON

Robert S. Livingston
Alfred L. Boch

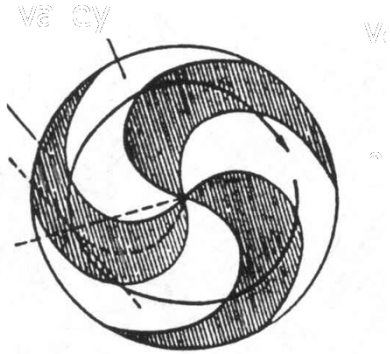
$$f = 1/2\pi\sqrt{LC}$$

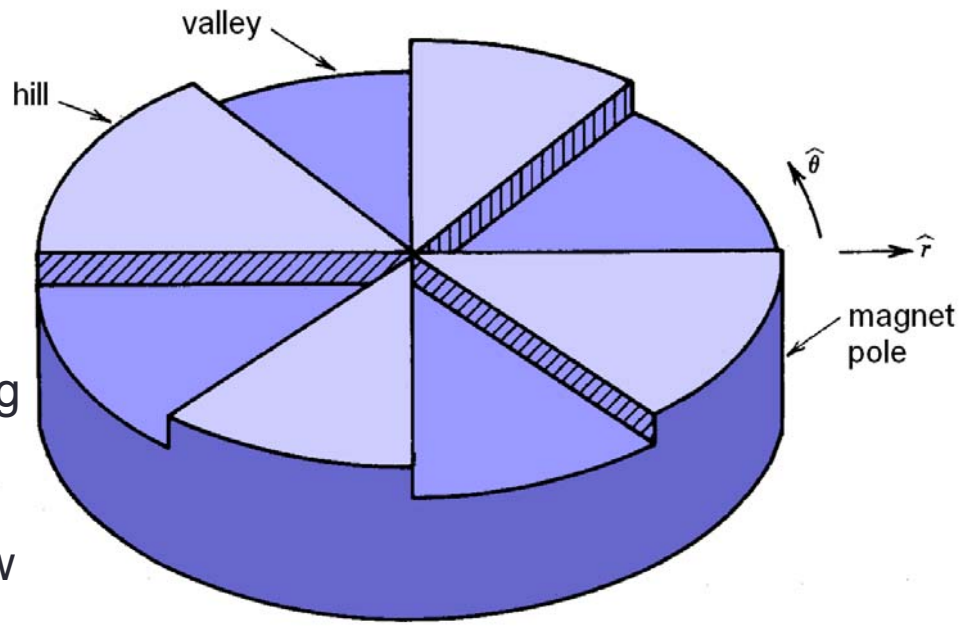
Classic Cyclotron, rare today

FROM CLASSIC TO ISOCHRONOUS CYCLOTRON

Thomas focusing, magnet with alternate strong and weak azimuthal regions (sectors or hills and valleys) provided an additional axial focusing which could offset the defocusing from a radially increasing magnetic field (L.H. Thomas, PR 54 (1938) 580). The average magnetic field can therefore match the mass increase of the accelerated particle with positive axial focusing provided by the azimuthal variation $(\beta = 0.5)$ 1940.

nowadays





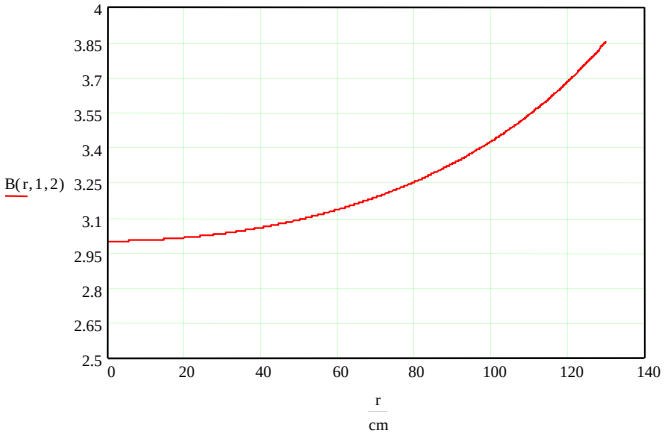
Strong focusing by **spiralling the hills** was introduced and designations “sector focusing cyclotron”, “spiral-ridged cyclotron”, “azimuthally-varying field cyclotron”, are now used largely with isochronous cyclotron

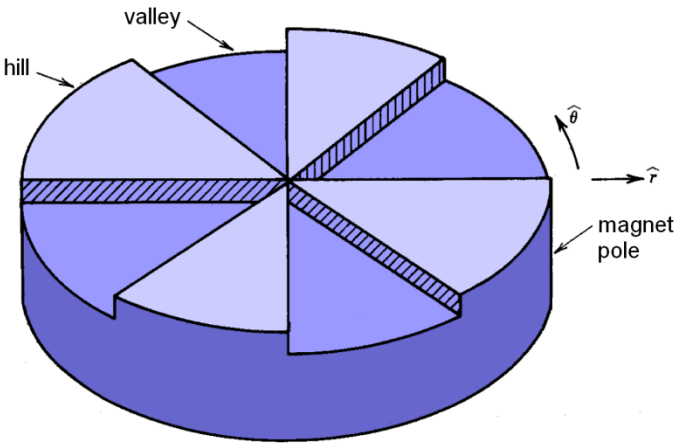
IL CICLOTRONE ISOCRONO

CONDIZIONE D'ISOCRONISMO

$$\omega = \frac{qB}{m_o \gamma(R)} = \text{cost}$$

$$B = B(R) = B_O \gamma(R)$$





LIMITI DI OPERATIVITA'

$$K_{bend} = \frac{q^2 c^2 B_{ext}^2 \cdot R_{ext}^2}{(\gamma+1)\cdot E_o} \quad [\text{MeV}]$$

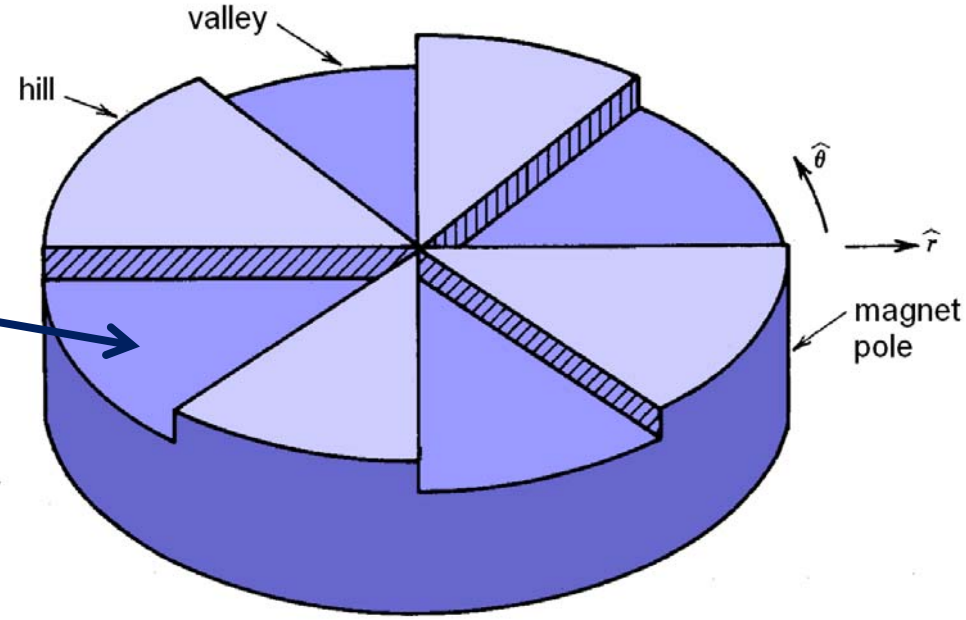
$$\frac{T_{\max}}{A} \le \left(\frac{Q}{A}\right)^2 \cdot K_{bend} \quad \text{limite in energia/nucleone}$$

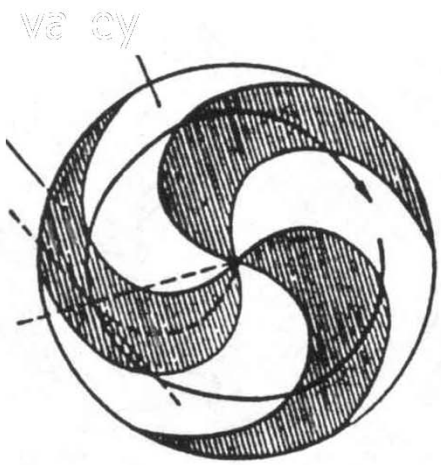
$$K_{Foc} = \frac{q \cdot R_{ext} \cdot c}{2} \cdot \sqrt{C^2(1+2\cdot\tan^2(\zeta))}$$

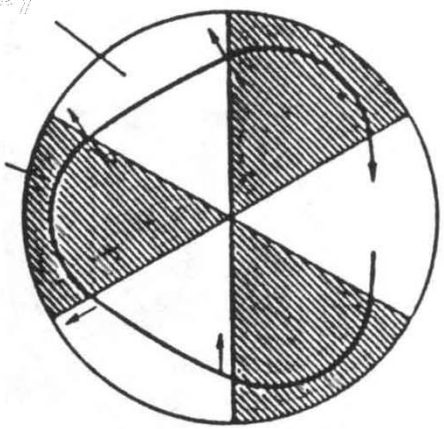
$$\frac{T_{\max}}{A} \le \left(\frac{Q}{A}\right) \cdot K_{Foc} \quad \text{limite in energia/nucleone}$$

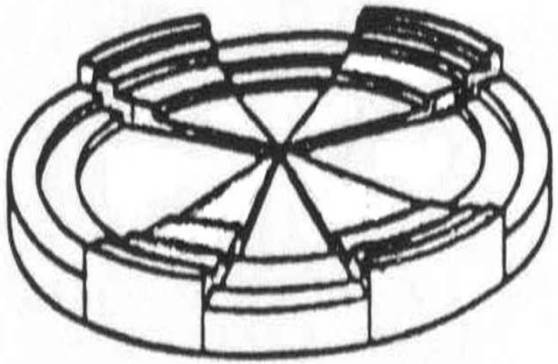
RF designer problem:

to fit the RF accelerating system inside the valley or between the hills.



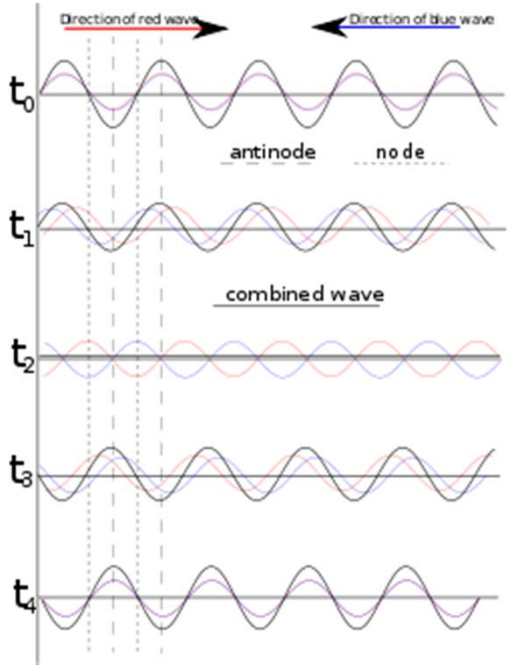




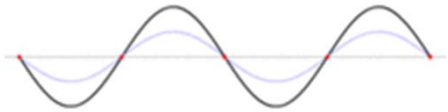


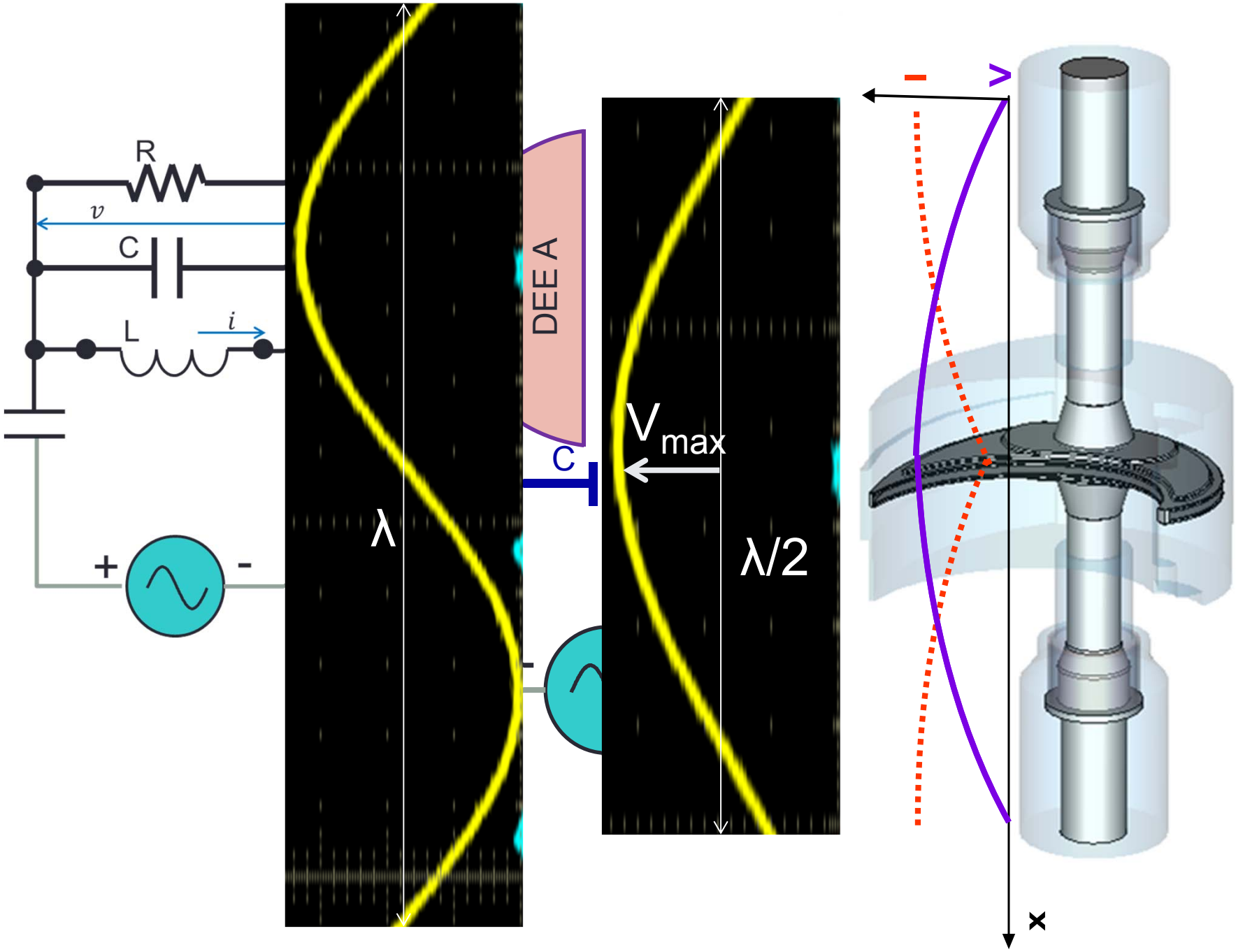
Different pole shapes (for 'flutter') for AVF isochronous cyclotrons

IN OUR CASE THE CAVITY CAN BE SEEN AS A TRANSMISSION LINE CLOSED IN A SHORT CIRCUIT, IN THIS CASE ZL=0.
IF WE USE A CLOSED GEOMETRY IN SUCH A WAY, THE EQUIVALENT DIMENSION IS PROPORTIONAL TO THE WAVELENGTH OF THE RF SIGNAL OR TO A MULTIPLE OF THE ¼ LAMBDA - A STATIONARY STANDING WAVE



In a resonator, standing waves occur during the phenomenon known as resonance




R
v
C
L
i
+
-
λ
DEE A
C
V max
λ/2
-
y
x

RF CAVITIES

In cyclotrons where the rf frequency has to be varied (e.g. to accelerate ions with different *q/A*), tuning is achieved by:

- using variable capacitors or inductors
- or by incorporating an E-M cavity tunable by
changing its dimensions mechanically
or including a ferrite tuner.

RF cavities also become essential in higher energy cyclotrons, where orbits and hardware approach rf wavelengths in size:

$f\lambda = c = 3 \times 108$ m/s = 300 MHz-m

so for $f = 23$ MHz, $\lambda = 13$ m $\rightarrow \lambda/4 = 3.25$-m cavities at TRIUMF

and for $f = 50$ MHz, $\lambda = 6$ m $\rightarrow \lambda/2 = 3$-m cavities at PSI

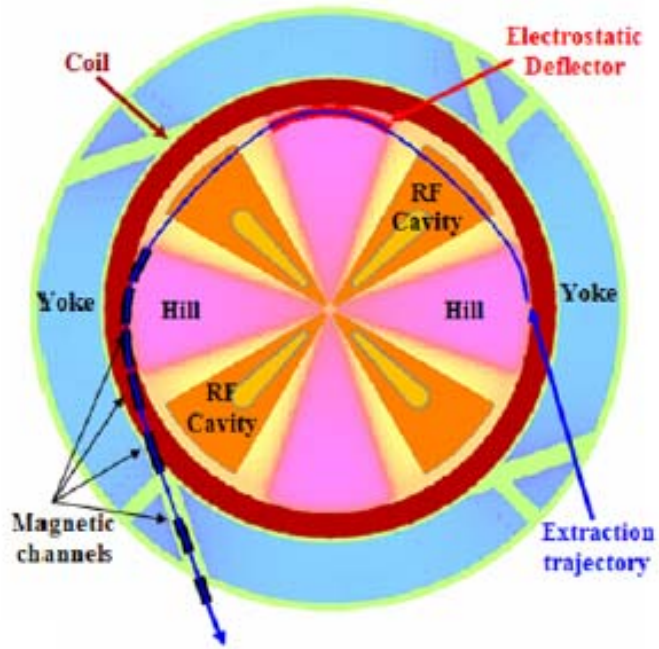
1. RLC circuits (Q ~ 100)
2. T-lines circuits/cavities (Q = several 1000)
3. Wave guide resonators (Q > 10000)

RLC circuit

- Only one resonance (ideally!)
- Small dimensions

T-Line or Waveguide cavities:

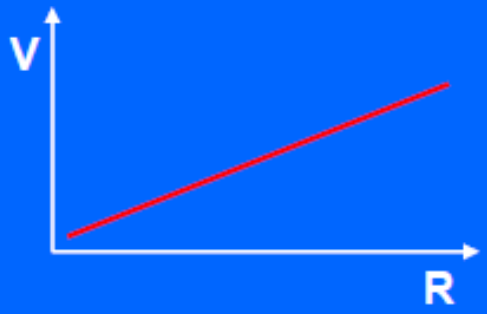
- ∞ resonant modes
- Dimensions depend on wavelength fractions (typically $\lambda/4$ and $\lambda/2$)

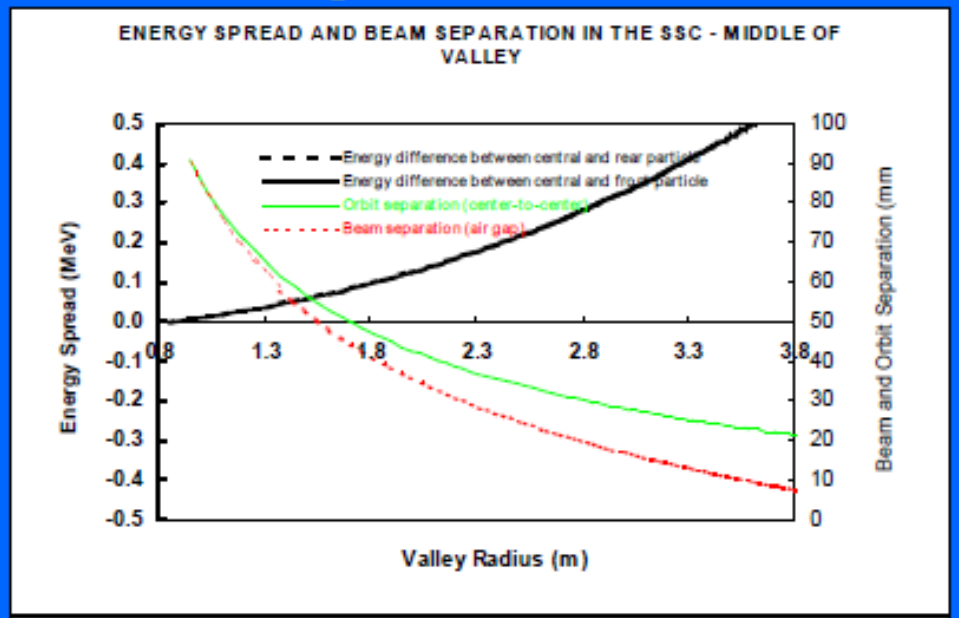


QUANTIFYING BEAM QUALITY – 2nd ORDER

WITHOUT FLAT-TOPPING

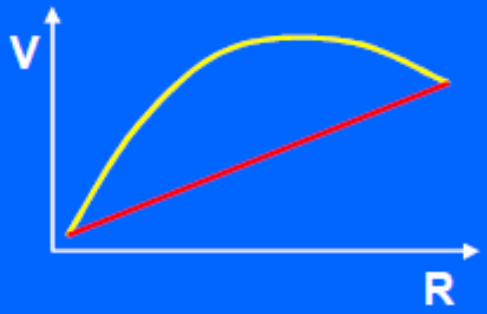
Bunch length = 15 rf-deg

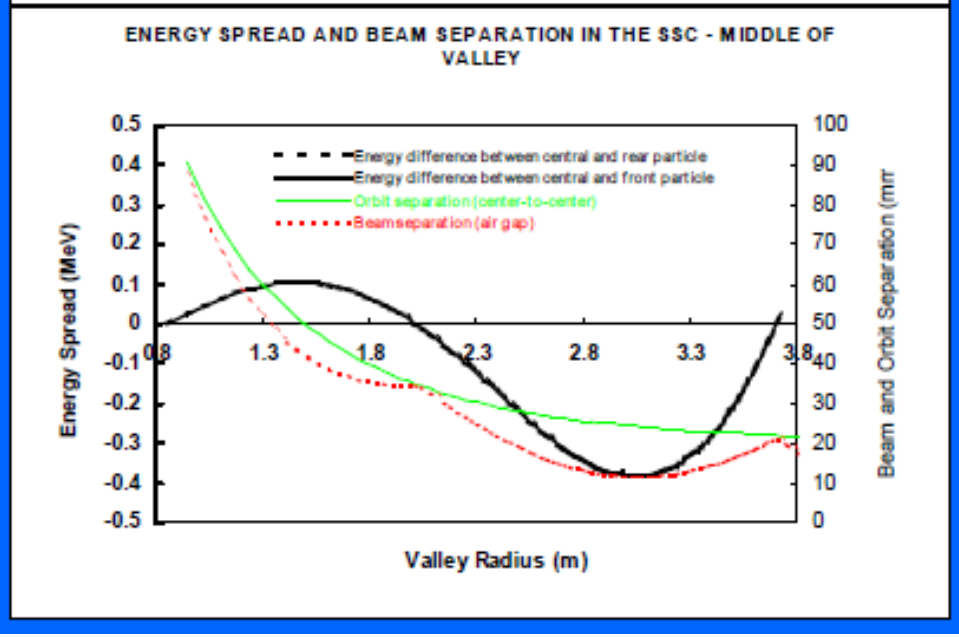


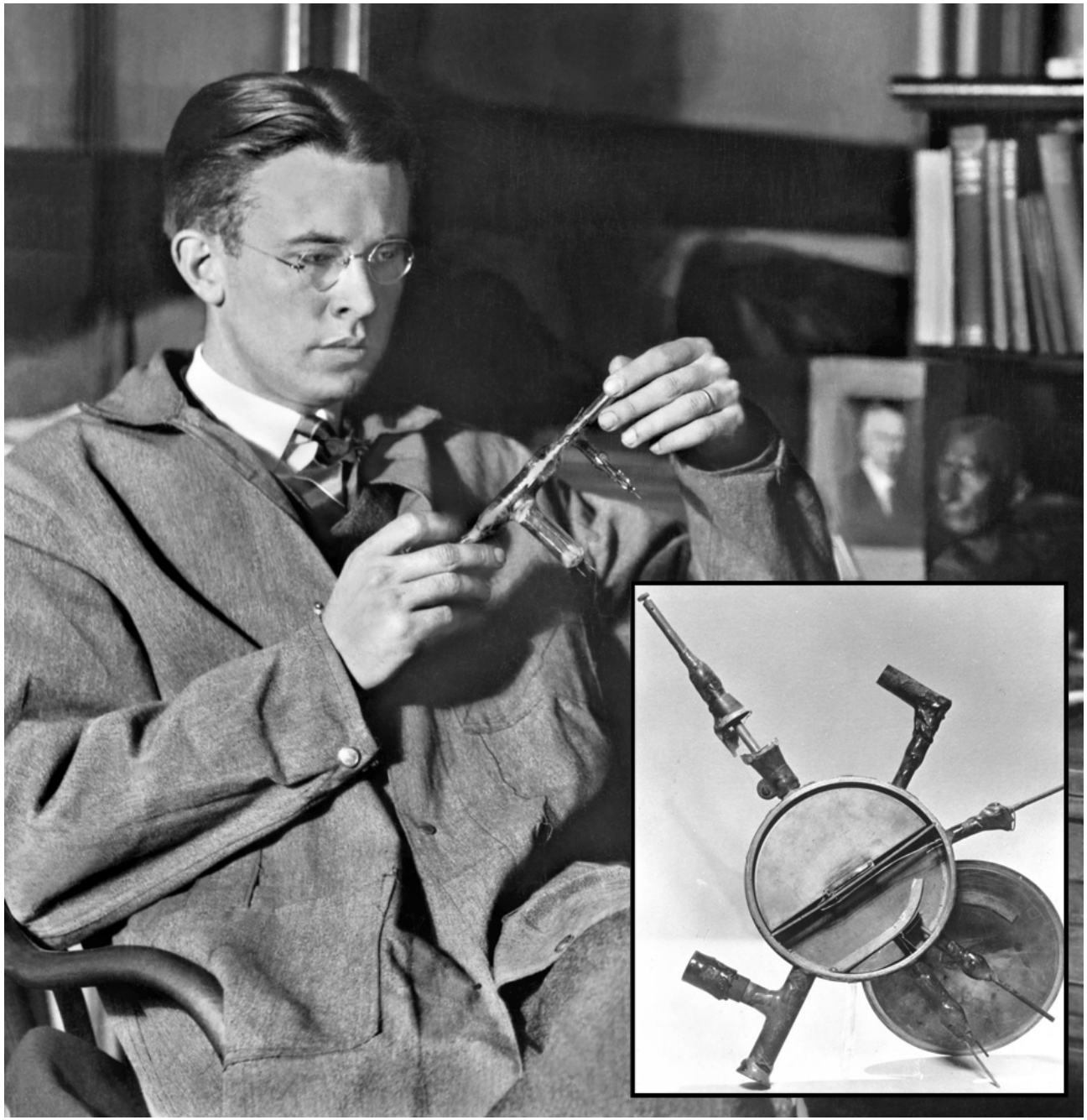


WITH FLAT-TOPPING

Bunch length = 30 rf-deg



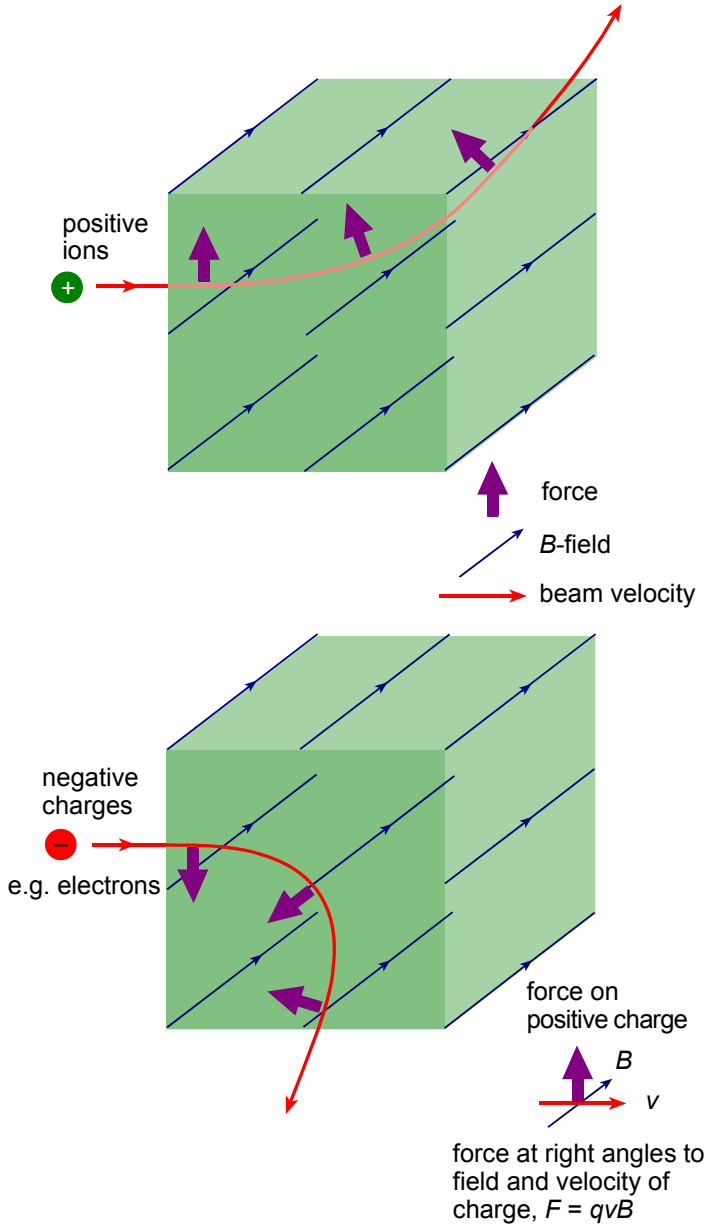


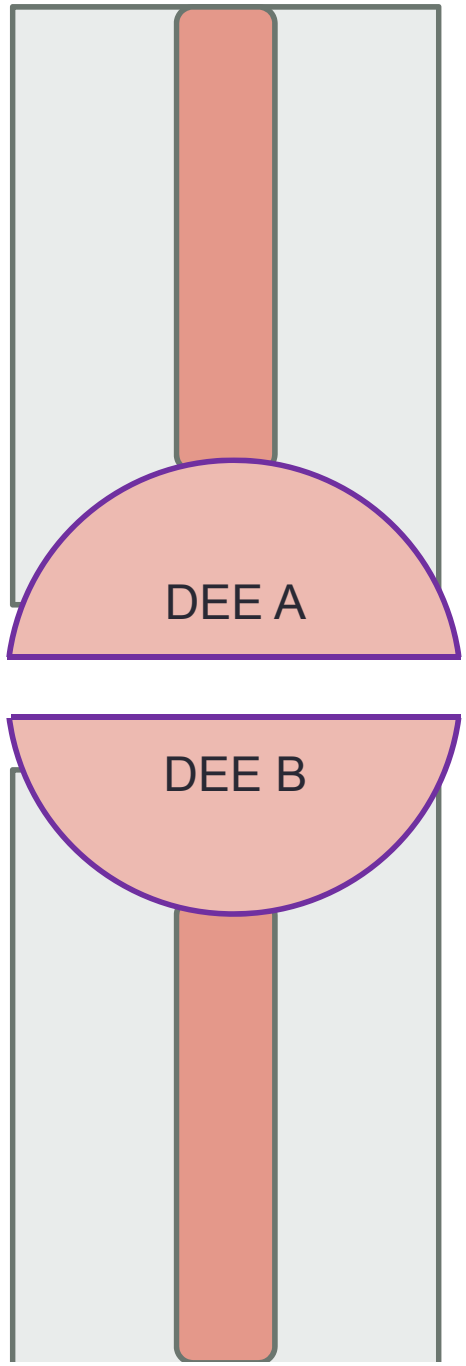


M. Stanley Livingston

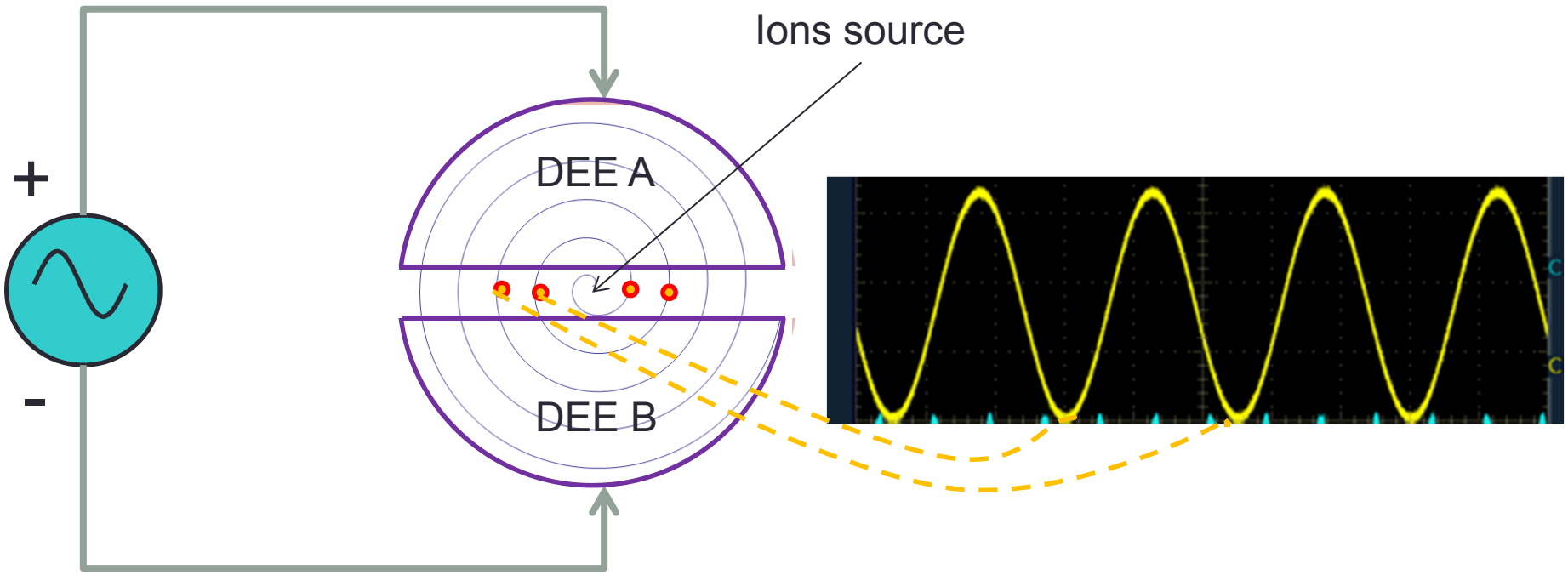
Early cyclotroneers (left to right): J. J. Livingood, F. Exner, M. S. Livingston, D. Sloan, Lawrence, M. White, W. Coates, L. J. Laslett, T. Lucci.

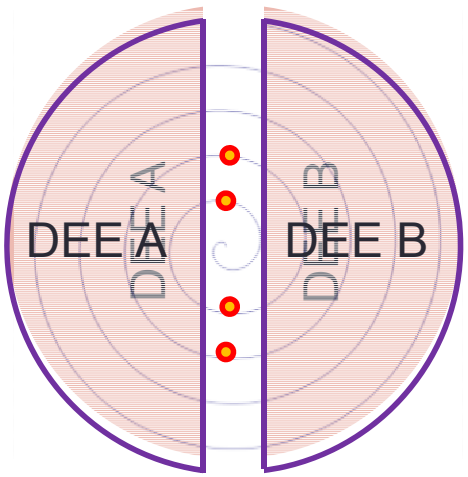
Magnetic deflection

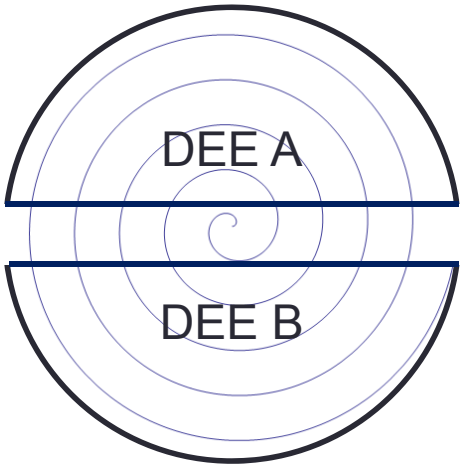


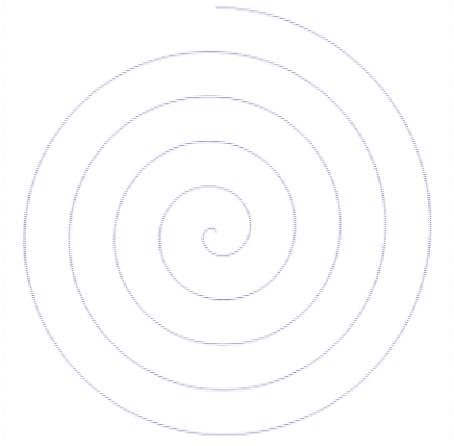


Magnetic fields deflect moving charged particles in circular paths


Ions source
+
-
DEE A
DEE B


DEE A
DEE B
DEE A
DEE B


DEE A
DEE B



Lalinea di trasmissione chiusa su corto circuito vista come un RLC alla risonanza. Tutta l'anergia passa, anche in questo caso dalla componente induttiva a quella capacitiva. Un alto Q permette di spendere la minima energia possibile per alimentare questo scambio energetico, questa risonanza. Nel nostro caso possiamo avere diversi adattamenti geometrici per questo tipo dilinea, ma come vedremo dalle caratteristiche operative che un sistema RF deve fornire, è la migliore soluzione.

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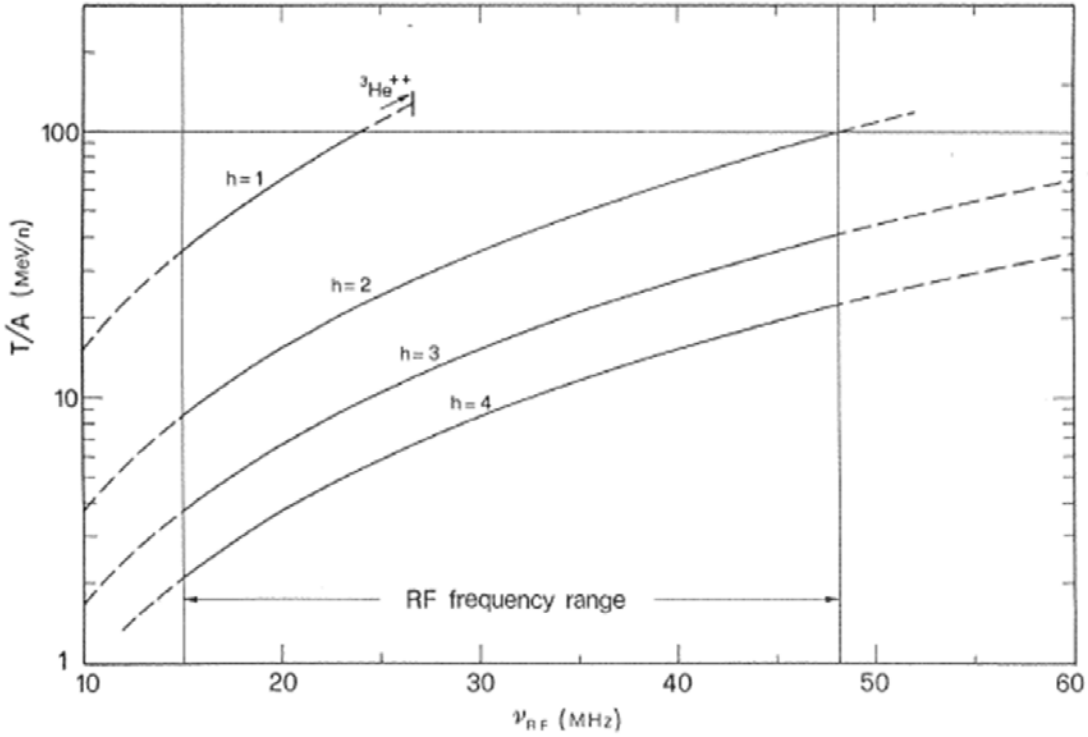
IF WE USE A CLOSED GEOMETRY TALE CHE THE EQUIVALENT DIMENSION IS PROPORTIONAL TO THE WAVELENGHT OF THE RF SIGNAL OR TO A MULTIPLE OF THE ¼ LAMBDA A STATIONARY STANDING WAVE

Cavity resonators
A *cavity resonator* is a hollow conductor blocked at both ends and along which an electromagnetic wave can be supported. It can be viewed as a waveguide short-circuited at both ends (see Microwave cavity).
The cavity has interior surfaces which reflect a wave of a specific frequency. When a wave that is resonant with the cavity enters, it bounces back and forth within the cavity, with low loss (see standing wave). As more wave energy enters the cavity, it combines with and reinforces the standing wave, increasing its intensity.



Ions energy vs. RF frequency for the different harmonic modes listed.