


# *Linear Accelerators*

Mikael Wendelsten
Norrlands University Hospital
Umeå Sweden

*Linaccar (Linjäracceleratorer)*

# *The scope of this presentation*

We will go thru a very interesting article I found for the next hour…

Proceedings of the 1966 Linear Accelerator Conference, Los Alamos, New Mexico, USA

SIMPLE MODELS FOR BEAM-BLOWUP†

William M. Visscher
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

## I. Introduction and Summary

The study of beam-blowup commenced a fairly large number of years ago, and many of the results of this paper are already contained in the considerable existing literature about it.[1] Much of the following discussion and exposition is included principally for the sake of completeness and a unified point of view.

A chain of independent cylindrical cavities is a simple model for a linac and is the one which we consider in Section III. The normal-mode fields are described in detail, as is their interaction with an off-axis beam, and the resulting equation for beam deflection is displayed. The magnitude of the coefficient in this equation has a simple physical interpretation; namely, it is the electrostatic force attracting the bunch to its image induced in the wall of the accelerating tube.

Section IV is devoted to a discussion of deflection caused by cooperative buildup of the transverse fields by the beam bunches in a more general linac model. An equivalent circuit description of a chain of cavities with linear coupling to nearest neighbors is worked out. The relations between the eigenvectors and eigenvalues of this system and the parameters of the bunched off-axis beam which are relevant to beam-blowup are discussed, as is the section-to-section variation in the normal modes which is consistent with coherent transverse-field buildup.

The next few paragraphs contain an elementary discussion of energy flow between the various degrees of freedom in a linac.

## II. Degrees of Freedom in the Linac

The purpose of a linear accelerator is to transform electrical energy into unidirectional kinetic energy of a beam of charged particles. Figure 1 is a block diagram showing how this is done. The RF source is the circle in the upper left, the box at the upper right represents the longitudinal kinetic energy in the beam. The presence of the other elements of Fig. 1, which are modes of storage, transfer, and dissipation of energy, is regrettable but unavoidable.

For instance a TM mode in the accelerator cavity serves as an intermediary between the RF power supply and the longitudinal kinetic energy of the beam. This accelerating mode interacts with the charge-current of the beam bunches. McMillan's application[2] of Earnshaw's Theorem to the linac tells us, though, that any interaction (top center circle on Fig. 1) which causes a phase-stable acceleration necessarily also causes defocussing. Hence we must add another leg (lower left) to the diagram, ending in a box containing transverse kinetic energy. The defocussing can then be neutralized by inserting strong-focussing quadrupole lenses, which can exchange energy between the transverse and longitudinal kinetic energy boxes.

This completes the block diagram for an ideal accelerator whose structure has no deflecting modes. This is, unfortunately, impossible, and the part of Fig. 1 below the diagonal, that involving the deflecting modes, must be added. Energy is fed into these modes mainly from the longitudinal kinetic energy of the off-axis beam, and from them goes into the transverse kinetic energy, the box at the lower left. Too much transverse kinetic energy can be disastrous. The aim of studying beam-blowup is to find means for keeping the amount small.

The deflecting mode amplitude in a given cavity is built up over the course of time by the coherent contributions of each passing bunch. This is the feature which puts its effect on the transverse beam motion in a different category from that of the accelerating mode, which is essentially known, constant in time and compensated for by the quads.

Energy flow around the lower right-hand corner of Fig. 1, from longitudinal to transverse kinetic energy, can be inhibited in three distinct ways. First, the structure might be so designed that it is very lossy for these modes but not for the accelerating mode. Second, the phase of the deflecting mode in some of the sections can be reversed and its magnitude increased enough so that the net deflection over many sections averages to zero. Third, the properties (frequency, eigenvectors) of the deflecting modes in the various sections can be tampered with in such a way that the contributions of successive bunches to the deflecting mode amplitude become incoherent.

In practice, it is impossible to consider calculating all of the interactions in Fig. 1 at once. Most calculations take account of only one or two of the connections, and, in fact, consider some of the energy flows to be unidirectional.

We will truncate the diagram as far as is reasonable for our purposes. We keep the two kinetic energy boxes and the deflecting mode energy box and the interactions connecting them. Furthermore, we consider the longitudinal velocities to be prescribed functions of time.

The discussions of the next two sections differ only in the models they assume for the deflecting mode.

## III. Deflecting Mode Buildup in a Chain of Independent Cylindrical Cavities.

The normal modes of the electromagnetic fields and their interaction with the beam can be described in complete detail for the cylindrical cavity with no holes or drift tubes. For numerical orientation and because it will lead to some physical insight, we do so now.

### A. Beam Current as the Source of the Field

The vector potential $\vec{A}(r,t)$ is the solution of

$$\Box^2 \vec{A} = \left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{A} = -\mu_0 \vec{j} \qquad (1)$$

(in which $\vec{j}(\vec{r},t)$ is the beam current) which satisfies metallic boundary conditions on the conducting surfaces;

$$B_\perp = E_\parallel = 0. \qquad (2)$$

$\vec{B}$ and $\vec{E}$ are the fields derivable from $\vec{A}$ by

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$\frac{\partial \vec{E}}{\partial t} = c^2 \vec{\nabla} \times \vec{B}. \qquad (3)$$

A formal solution of Eq. (1) is

$$\vec{A}(\vec{r},t) = -\mu_0 \int G(\vec{r},\vec{r}';t,t')\vec{j}(\vec{r}',t')d^3r'dt', \quad (4)$$

where the Green's function satisfies

$$\Box^2 G(\vec{r},\vec{r}';t,t') = \delta(\vec{r}-\vec{r}')\,\delta(t-t'), \qquad (5)$$

with metallic boundary conditions. A Fourier integral representation

$$G(\vec{r},\vec{r}';t,t') = \frac{1}{2\pi}\int_C \tilde{G}(\vec{r},\vec{r}';\omega)e^{i\omega(t-t')}d\omega \quad (6)$$

defines $\tilde{G}$, which satisfies

$$\left[\nabla^2 + (\omega/c)^2\right]\tilde{G}(\vec{r},\vec{r}';\omega) = \delta(\vec{r}-\vec{r}'). \qquad (7)$$

The contour C in Eq. (6) will be chosen so as to make G a causal function; i.e., it will vanish for $t < t'$.

### B. Normal Modes of the Cavity

A set of scalar functions $G_\omega(\vec{r})$ satisfying

$$\left(\nabla^2 + (\omega/c)^2\right)G_\omega(\vec{r}) = 0 \qquad (8)$$

facilitates an explicit expression for $\tilde{G}$, namely,

$$\tilde{G}(\vec{r},\vec{r}';\omega) = \sum_\omega \frac{G_\omega(\vec{r})\,G_\omega^*(\vec{r}')}{\left(\frac{\omega}{c}\right)^2 - \left(\frac{\omega'}{c}\right)^2}, \qquad (9)$$

provided that

$$\sum_\omega G_\omega(\vec{r})\,G_\omega^*(\vec{r}') = \delta(\vec{r}-\vec{r}')$$

$$\int d^3r\, G_\omega^*(\vec{r})\,G_{\omega'}(\vec{r}) = \delta_{\omega,\omega'}, \qquad (10)$$

and that G satisfies appropriate boundary conditions. The transverse components of $\vec{A}$ can be neglected for our purposes; therefore $\vec{A} = (0,0,A_z)$ and we require

$$\frac{\partial G_\omega}{\partial \varpi} = 0 \quad \text{at } r = a$$

$$\frac{\partial^2 G_\omega}{\partial r \partial z} = \frac{\partial^2 G_\omega}{\partial \varphi \partial z} = 0 \quad \text{at } z = 0, \ell, \qquad (11)$$

where r, φ, and z are cylindrical coördinates in one cavity, and a and ℓ are the radius and length of a cavity, respectively (See Fig. 2).

A set of G's which complies with these specifications is

$$G_\omega(\vec{r}) = A_{\mu k t} \cos\mu(\omega-\varphi_0)\cos\frac{\pi k z}{\ell} J_\mu\left(\frac{\pi\beta_{\mu t} r}{a}\right), \qquad (12)$$

provided that

$$\left(\frac{\omega}{c}\right)^2 = \left(\frac{\pi k}{\ell}\right)^2 + \left(\frac{\pi\beta_{\mu t}}{a}\right)^2, \qquad (13)$$

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# *The scope of this presentation*

- Short presentation of why I'm talking here / Intro ≈ 10 min
- The basics of the linear accelerator ≈ 10 min
  - Common themes for both accelator types (TW / SW)
    - Some basic RF – theory
    - Connection between frequency and size
    - Bunching of electrons
  - Travelling Wave Accelerator (TW) basics ≈ 10 min
  - Standing Wave Accelerators (SW) basics ≈ 15 min
- More advanced conceps of the Linac – the rest of the remaining time

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# *Know your audience*

- Experience in the field
  - 0-5 years
  - 6-10 years
  - 11-beyond years
- Anybody that have attended somekind of university course or similar more in depth type focused on linacs?

https://wheelofnames.com/

# *The scope of this presentation*

More advanced topics of the Linac

- Travelling Wave – how can the electric field be faster than light ?
- Travelling wave – what is the purpose of the discs?
- Travelling Wave – what is constant impedance and constant gradient?
- Standing Wave – why do we have several resonance frequencys?
- Standing Wave - How is the electric fields measuered in a Linac in the factory?
- Standing Wave - What does a ”mode” mean (π/2 mode) ?
- Standing Wave – what is the purpose of the ”nose cones” (drift tubes)?
- Standing Wave – how can we make the linac shorter?
- Standing Wave – what happens with the doserate when you do beampeaking?
- Standing Wave – why do we have the ”horns” on the LD PWR signal?

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# *The scope of this presentation*

Travelling Wave – how can the electric field be faster than light ?

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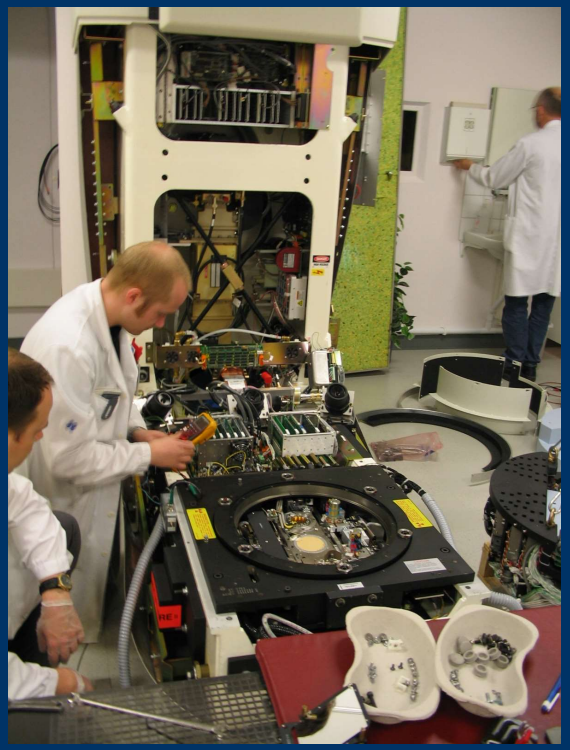
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# *Who am I talking about Linacs?*
# *Mikael Wendelsten*

- Born and live in Umeå Sweden https://maps.app.goo.gl/61NuSe6ZEfCHh8a87







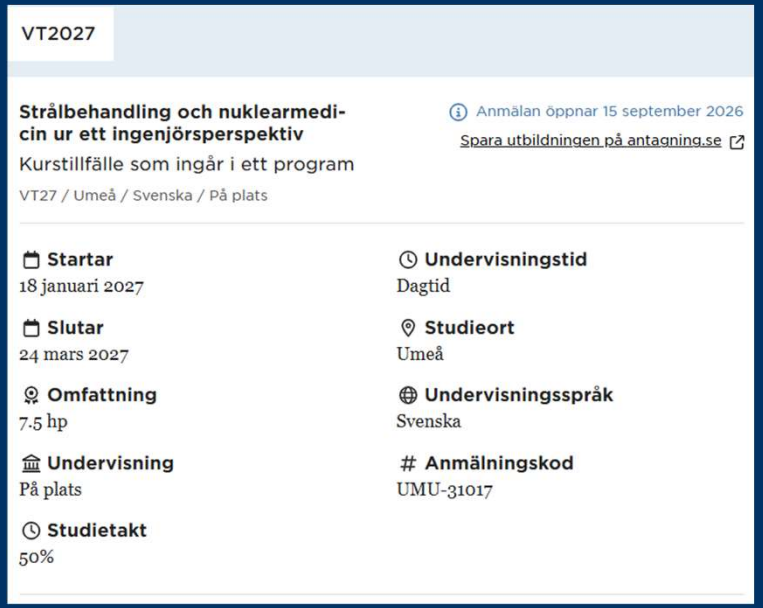






# *Radiation thearapy and Nuclear medicin from a engineering perspective Course in Umeå Sweden*



# Radiation thearapy and Nuclear medicin from a engineering perspective

## Lectures

| Topic | Duration |
|---|---|
| Introduction to Radiation Therapy, Dose Distribution, Detectors and Radiation Protection | 1 h 45 min |
| Introduction to Medical Linear Accelerators | 1 h 45 min |
| Treatment Head, Beam Steering and Dose Monitoring | 1 h 45 min |
| Linear Accelerators | 1 h 45 min |
| Electron Gun | 1 h 45 min |
| Klystrons and Magnetrons | 1 h 45 min |
| Automatic Frequency Control (AFC) | 1 h 45 min |
| Microwave Components | 1 h 45 min |
| Vacuum Technology | 1 h 45 min |
| Beam Transport | 1 h 45 min |
| Modulator and Thyratron | 1 h 45 min |
| Gamma Cameras: Conventional and CZT | 1 h 45 min |
| SPECT Image Reconstruction and Filtering | 1 h 45 min |
| Quality Control of Gamma Cameras | 1 h 45 min |
| PET and Quality Control | 1 h 45 min |
| Cyclotron Technology | 1 h 45 min |
| Radiation Protection in Nuclear Medicine | 45 min |
| Course Review and Summary | 1 h 45 min |

**Total lecture time:** ~30 hours

## Laboratory Sessions

| Laboratory | Duration |
|---|---|
| Radiation Field Measurements | 5 h |
| Weekly Quality Control | 5 h |
| Vacuum Technology | 2 h |
| Gamma Camera Imaging Parameters | 5 h |
| Preventive Maintenance | 5 h |

Covers off, show and tell, measuerments, calibration and oscillsoscope

**Total scheduled laboratory time:** ~22 hours

**10-15 hour laborations**

**20 hour theory**

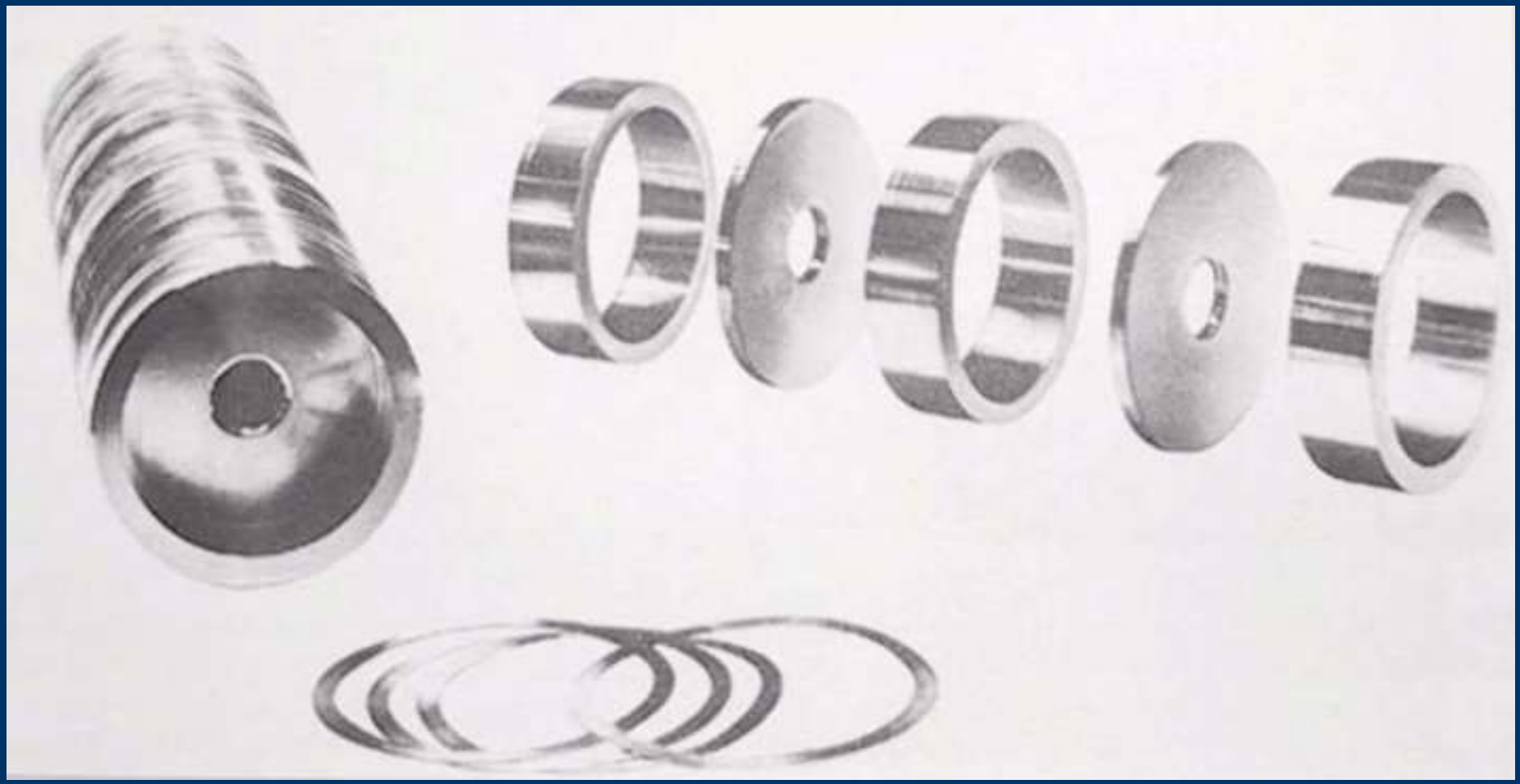
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# General common themes for a linear accelerator

- A long tube that contains ”cavities”
  - Vaccum
  - The length can vary
  - Electrons (10-20) keV are injected in the beginning
  - Magnetron or Klystron
  - Electric field accelerates electrons from keV to MeV
  - Common frequency in medical Linacs is about 3 GHz

# General Acceleratorstructure
## Cavities

*From: "A Primer on Theory and Operation of Linear Accelerators in Radiation Therapy" by C. J. Karzmark, Robert J. Morton*

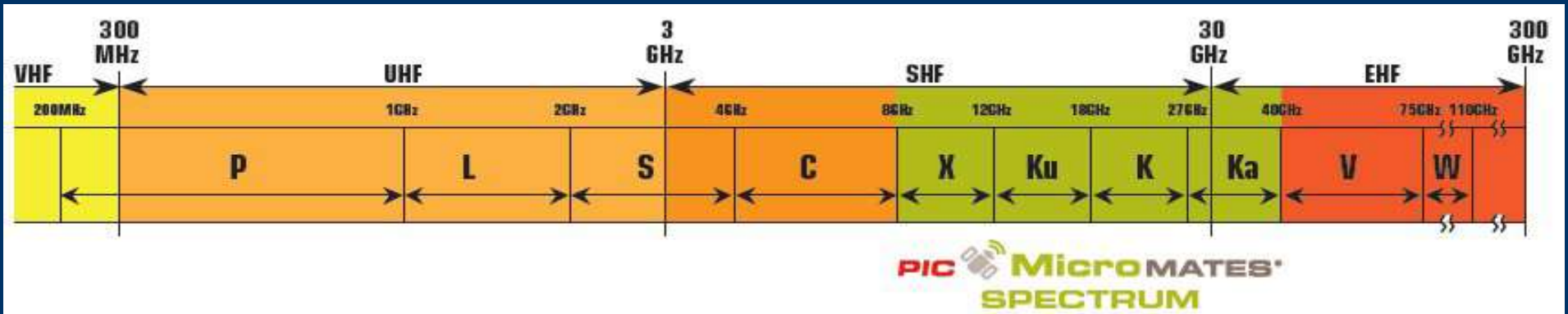


# Microwaves

## Microwave (RF)

- Microwave frequency ranges from 300 MHz to 300 GHz
- Nothing Magical with 3 GHz – WW2 Radar was the driving force (10 cm)

Elekta / Varian



# *Microwaves*

## Microwave (RF)

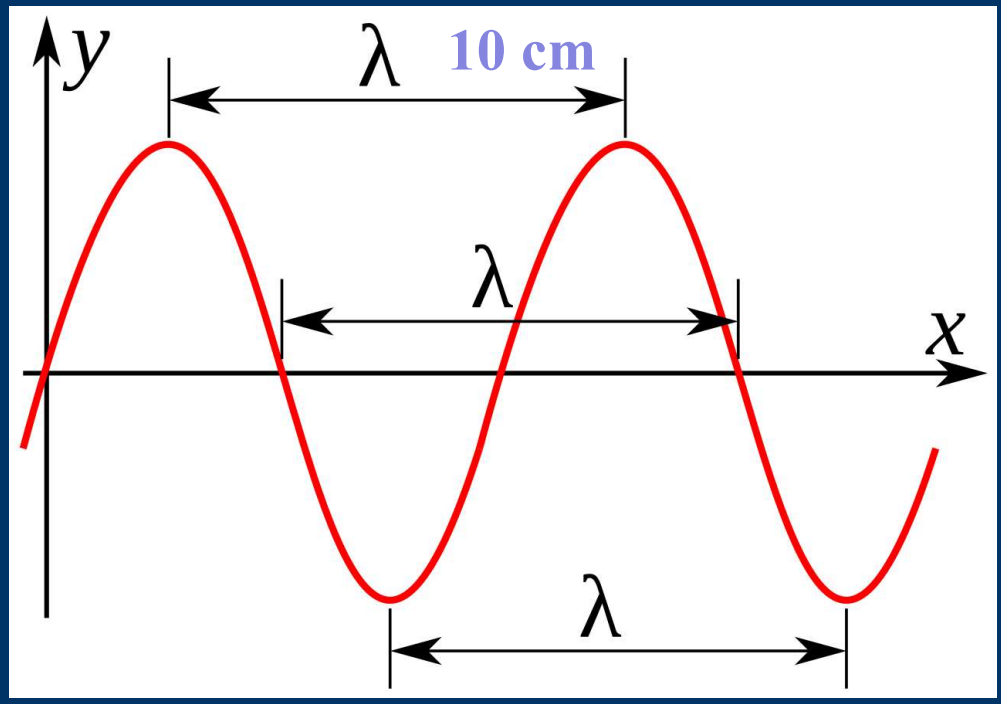
- Wavelength λ (Lambda)
  $\lambda = \frac{c}{f}$ **(100cm – 1mm)**

  Speed of light in vacuum c= 2,9979*$10^8$ m/s

- Medical accelerators (Elekta/Varian):
  2998MHZ (λ=10cm) or 2856MHz (λ=10,5cm)

# *Microwaves*

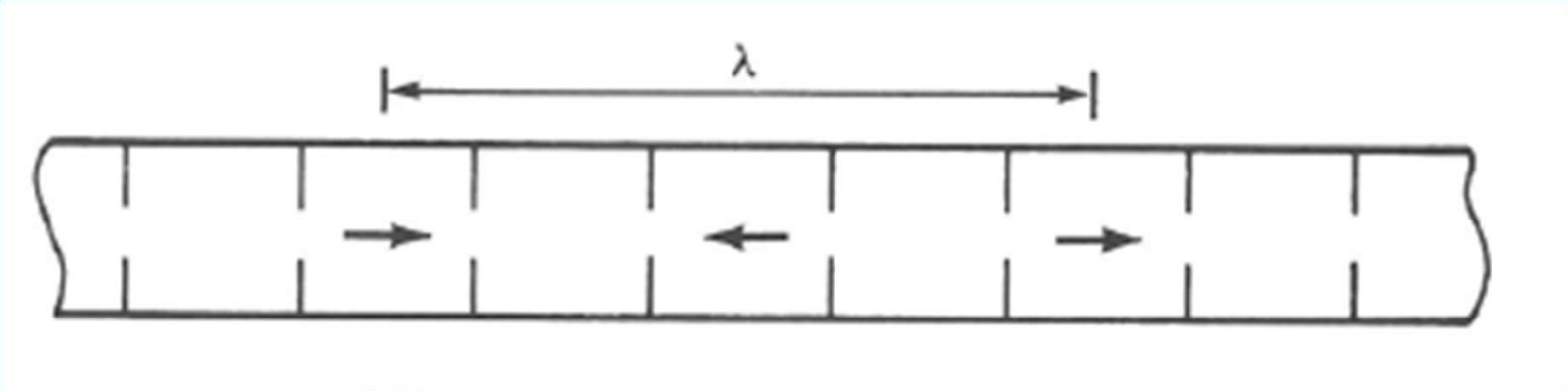
## Microwave (RF)



# *Microwaves*

## Size and frequency

- The length of the cavities is proportional to the frequency of the RF – higher frequency → smaller cavities
- The total length of an accelerator for a given energy (6 MV) is proportional to $\sqrt{frequency}$ (the length of all the cavities)
- The diameter of the cavities (accelerator tube) is proportional to the frequency



# *Microwaves*

## Wavelength vs accelerator physical size

- A 3 GHz accelerator cavitie (that have 2 cavities/wavelength) is usually 5 cm long (half the wavelength)
- A 9 Ghz accelerator wavelength is 10/3 cm = 3.3 cm
- A 9 Ghz accelerator cavitie (that have 2 cavities/wavelength) should be 1.6 cm long (half the wavelength)

# *Microwaves*

## Wavelength vs accelerator physical size

**Do we have Linacs with higher frequencys than 3 GHz?**

# *Microwaves*

## Wavelength vs accelerator physical size

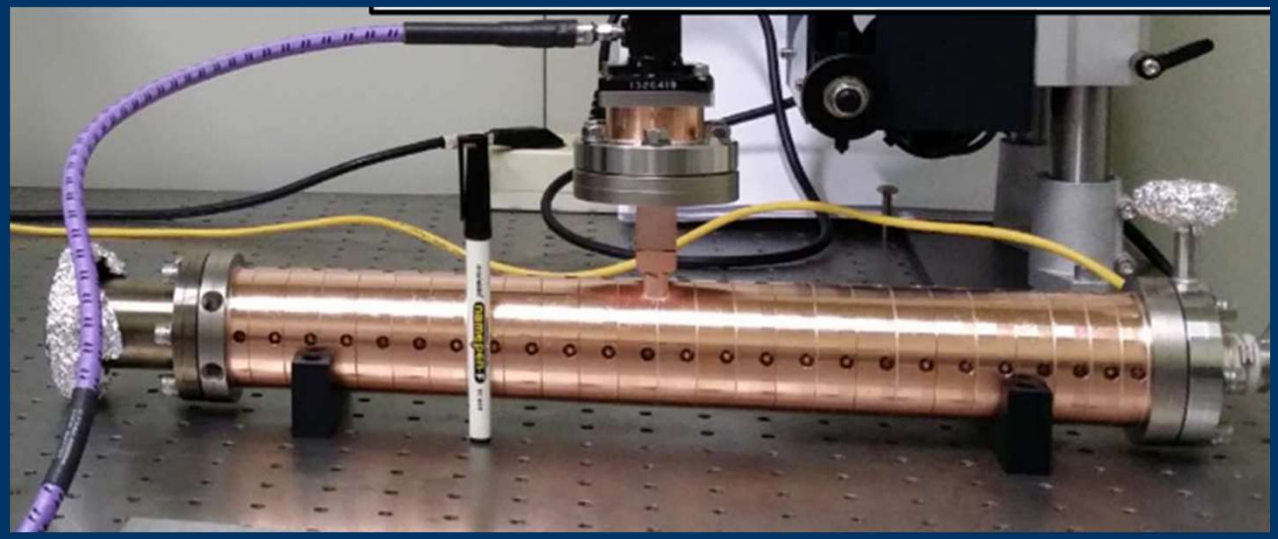
- **The Cyberknife radiation Therapy machine have a need for a lighter Linac**



# *Microwaves – trust but verify…*

**Information from an article describing the Cyberknife accelerator** ”STATUS OF KAERI 6 MeV 9.3 GHz X-BAND ELECTRON LINAC FOR CANCER TREATMENT SYSTEM”

**24.5 cells with 10 bunching cells**
**central frequency ~ 9.302 GHz**
**length ~ 0.4 m**
**unloaded $Q$ ~ 11319**
**coupling beta ~ 1.11**
**$R_{sh}$ ~ 80 MΩ/m**
**Power for 6 MeV ~ 1.5 MW**
**Cell length ~ 16.1 mm**
**Radius ~ 14.2 mm**
**Gradient ~ 17 MV/m**
**Weight ~ 8 kg**

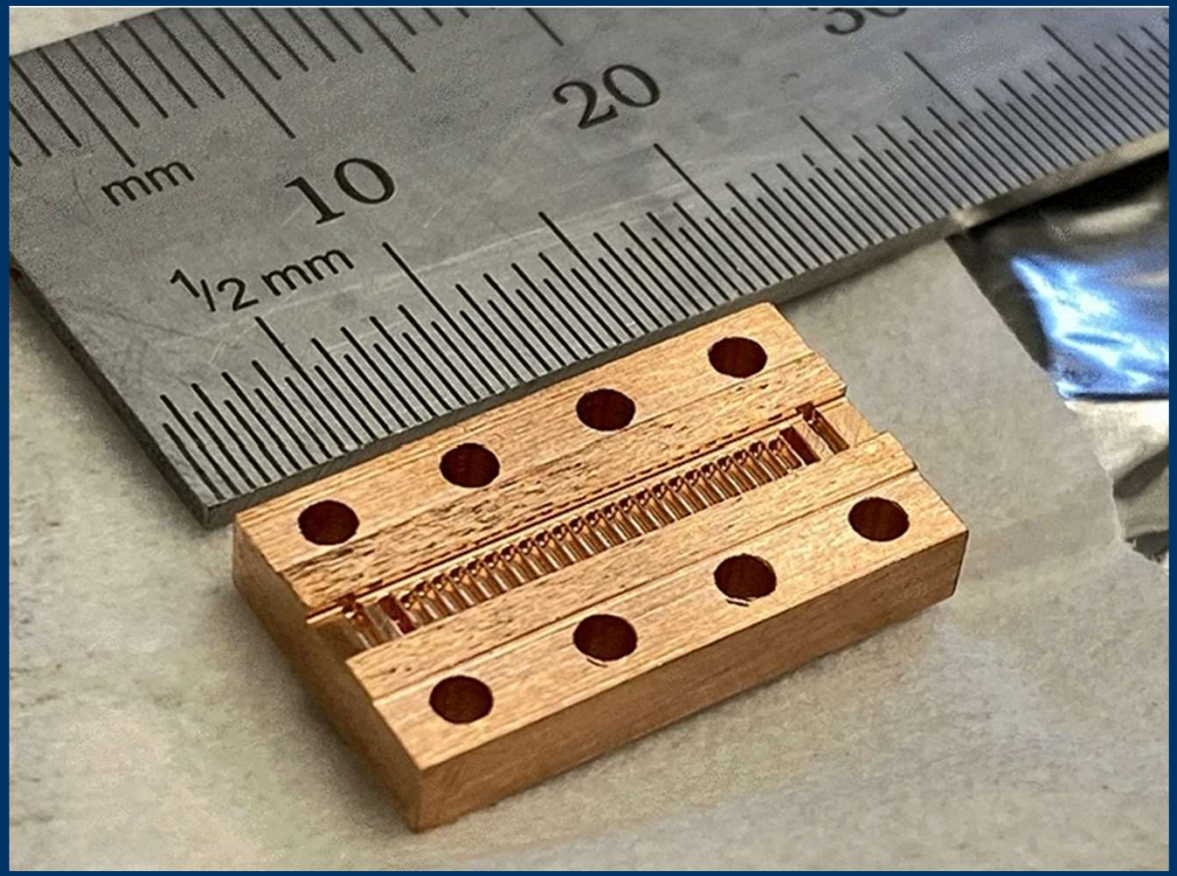




# *Microwaves*

## Wavelength vs accelerator physical size

- An image of a 182 GHz Linac



# Acceleratorlingo in Linac Articles

**FUNDAMENTALS OF ION LINACS**

*M. Weiss*
CERN, Geneva, Switzerland

**Abstract**
The operating principles of ion RF linear accelerators are described, based on the concept of 'slow waves' generated in 'loaded cavities'. Fundamental cavity parameters are presented, and equations describing the action of electromagnetic fields on the particles are given. Space charge influences are touched upon only briefly. Various types of linear accelerators are introduced according to their use at different particle energies and frequencies.

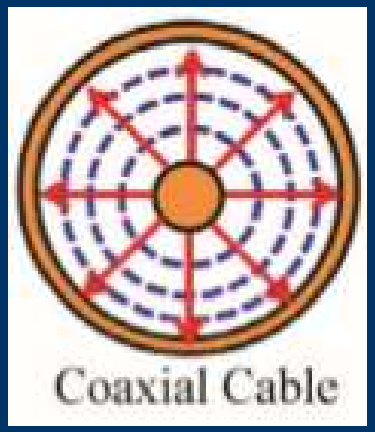
## 2. EMPTY CAVITIES: WAVE TYPES AND MODES

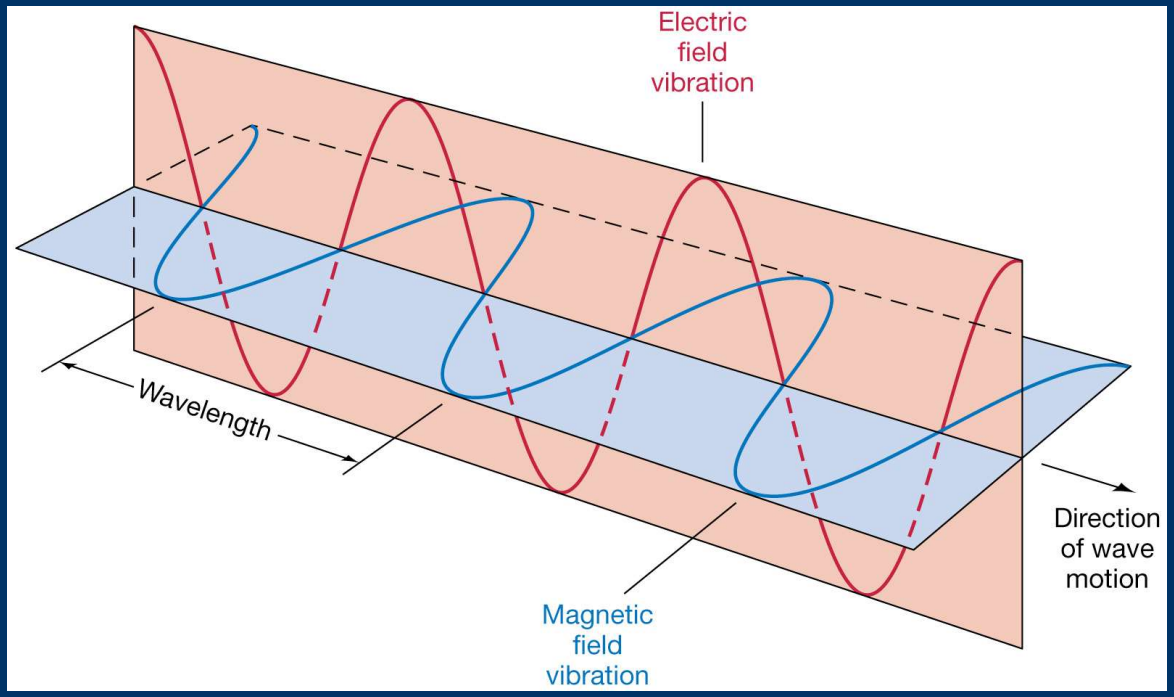
In free space, the electromagnetic wave has electric and magnetic field vectors perpendicular to the direction of propagation. Such a wave type is called the *transverse electromagnetic wave (TEM)*. In bounded media, where the boundary is a perfect conductor, such a wave type is not possible because the boundary conditions cannot be satisfied. On the boundary, the tangential component of the electric field $E_t$, as well as the normal component of the magnetic field $B_n$, have to be zero. These conditions are satisfied if the wave has one of the field components in the direction of propagation (the longitudinal or $z$-axis of the coordinate system). If it is the electric field component $E_z$, the wave type is called *transverse magnetic (TM)*; if it is the magnetic field component $B_z$ the wave type is called *transverse electric (TE)*, [1].

In linacs one distinguishes between two wave velocities: the *phase velocity* $v_{ph}$ and the *group velocity* $v_g$. The former is the velocity of the *wave phenomenon*, like that of rapid wave propagation along the shore, resulting from an obliquely incident sea wave. Electromagnetic waves, moving with the velocity $c$ and falling obliquely on the side walls of a cavity, would result in a longitudinal (along the cavity) wave phenomenon moving with a phase velocity bigger than the velocity of light $c$. Of course, the wave energy does not move in the

# *Microwaves (RF)*

- RF have a electric and a magnetic field that can be in 3 diffrent ”modes” (TEM, TM and TE)
- In Coaxial cables and free air we have TEM mode (E och M field is transverse to direction of motion)



# *Microwaves (RF)*

## TM and TE mode in waveguides

**In a rectangular waveguide we can have both Transverse Electric mode or Transverse Magnetic mode.**

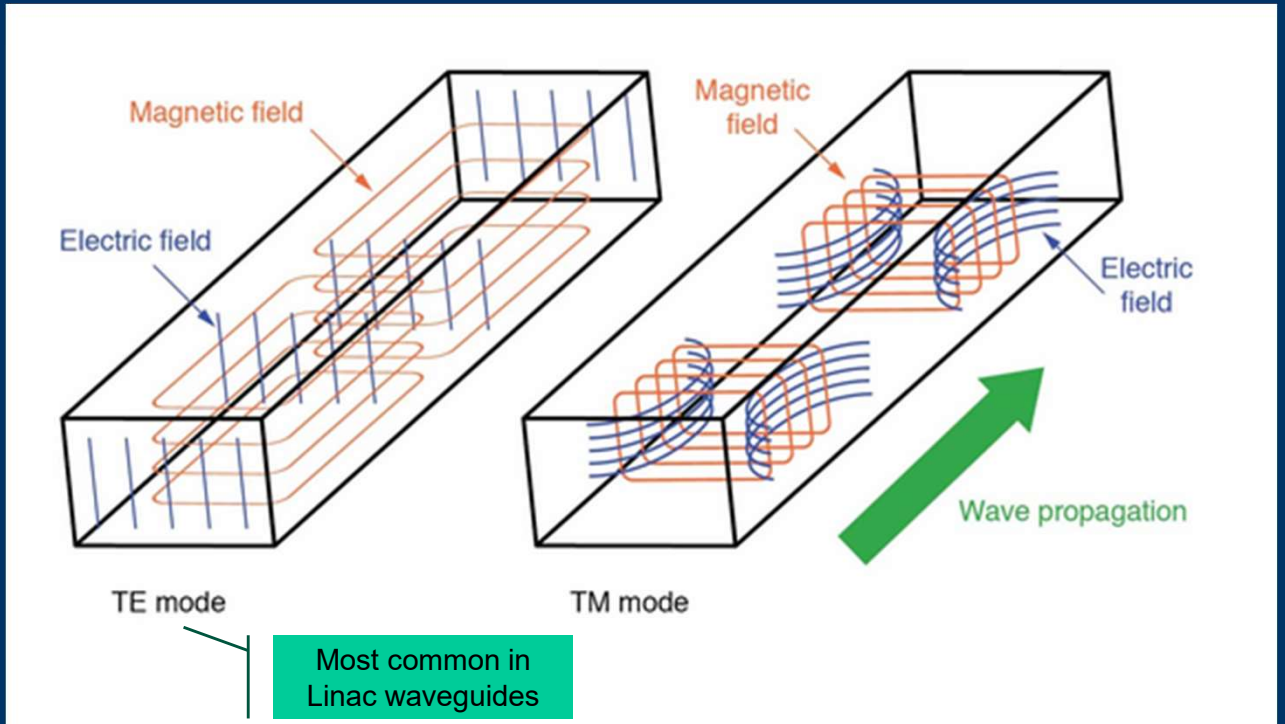



Figure 3: Understanding Transmission Lines and Waveguides

# *Microwaves (RF)*

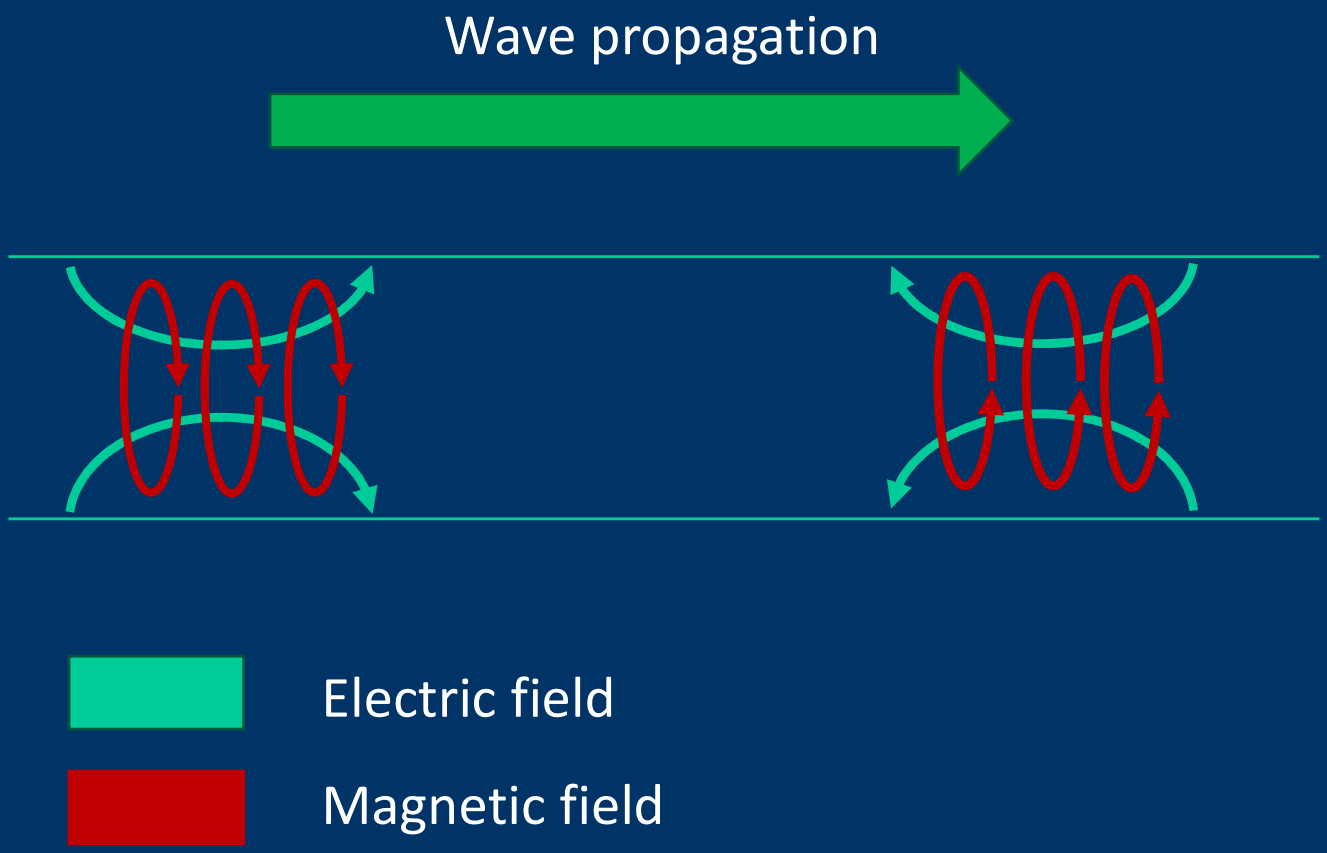
**What mode do we need in a Linac**

**TEM, TE or TM?**

# *Microwaves (RF)*

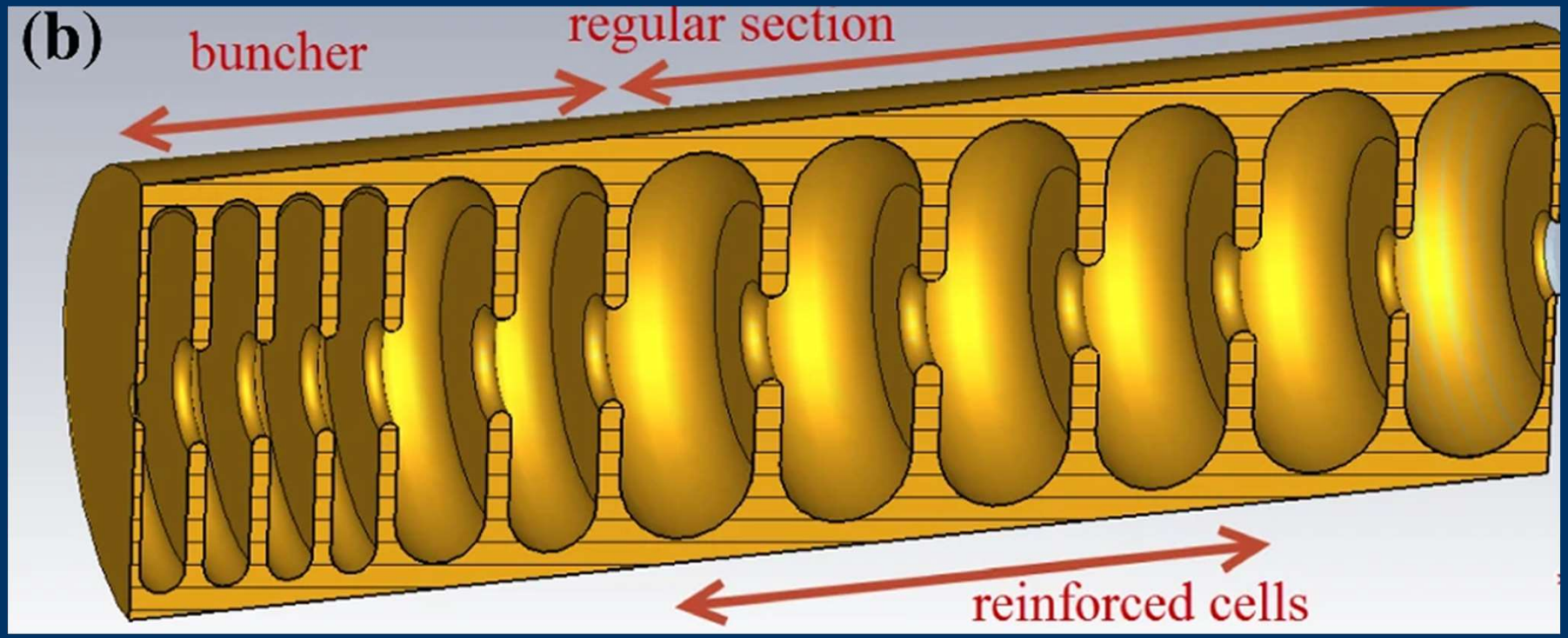
## TM mode (Transverse Magnetic)

**In an accelerator guide we need to have TM-mode (so the electric field is in the direction of the waveguide)**



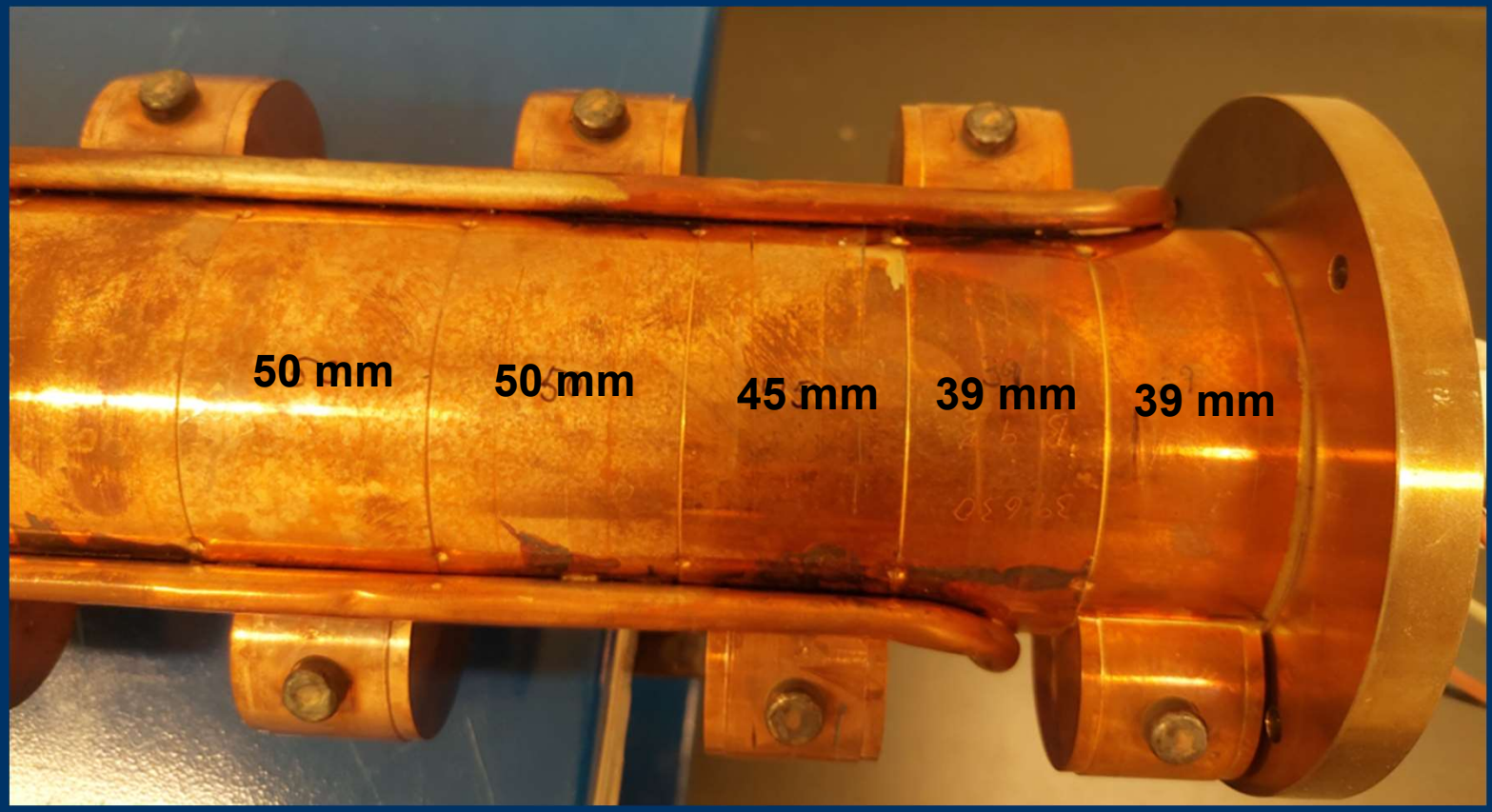
# *Buncher sections in Linacs*

What do we mean with a buncher section in a Linac?



# *Buncher sections in Linacs*

Image of the first section of a Siemens Standing Wave Accelerator



# *Buncher sections in Linacs*

Image of a Travelling wave accelerator

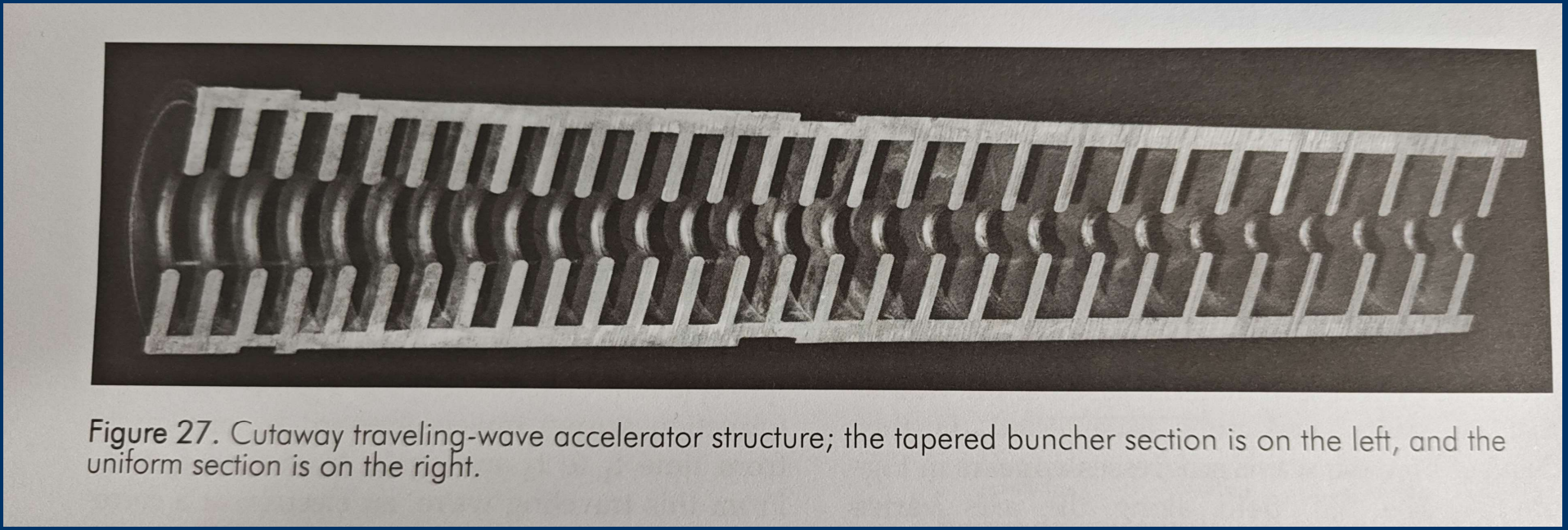


Figure 27. Cutaway traveling-wave accelerator structure; the tapered buncher section is on the left, and the uniform section is on the right.

# Buncher sections in Linacs

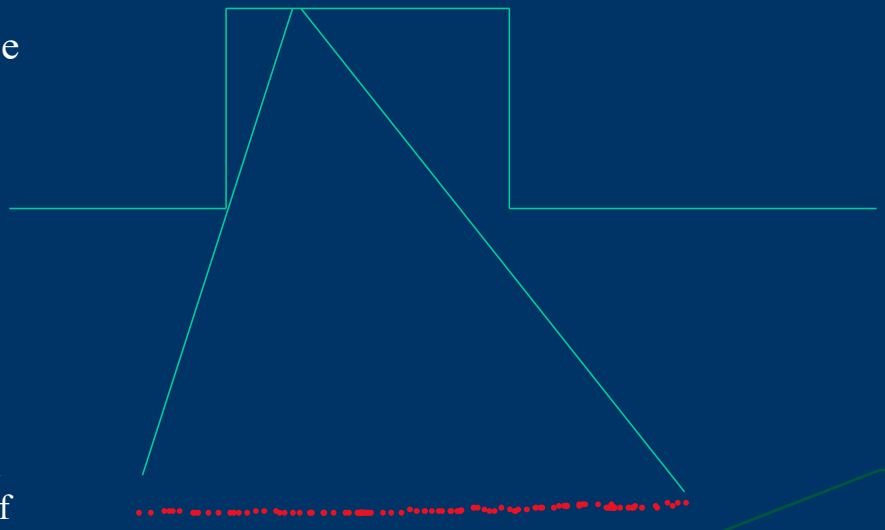
| | Energy | Relative Velocity |
|---|---|---|
| Buncher Section | 10keV | 0.197 |
| | 15keV | 0.242 |
| | 1MeV | 0.942 |
| | 2MeV | 0.979 |
| Main Section | 3MeV | 0.989 |
| | 4MeV | 0.993 $m = 9 \times m_0$ |
| | 5MeV | 0.995 |
| | 6MeV | 0.9969 |
| | 10MeV | 0.998 |
| | 15MeV | 0.99945 $m = 30 \times m_0$ |
| | 18MeV | 0.9996 |
| | 20MeV | 0.99968 |
| | 21MeV | 0.99971 |
| | 25MeV | 0.99979 $m = 50 \times m_0$ |
| Info only | 100MeV | 0.99998 |
| | 1000MeV | 0.9999998 |

# *Buncher sections in Linacs*

- Both TW and SW accelerators need some sort of buncher section (but the reason why is different between these two)
- The simple explanation is that electrons are slow (relative c) in the beginning compared to the microwave field which is compensated in the design in the buncher section.
- A shorter distance between the cavity walls in a TW accelerator slows electric field so that it matches the electrons speed (like speed bumps for the microwave energy)
- A shorter distance in a SW accelerator is needed so the electrons can make the distance to the next cavity in time when the electric field have shifted polarity (3 GHz changes polarity each 0,16 ns)

# Electron bunches in a Linac

GUN Pulse
5 us

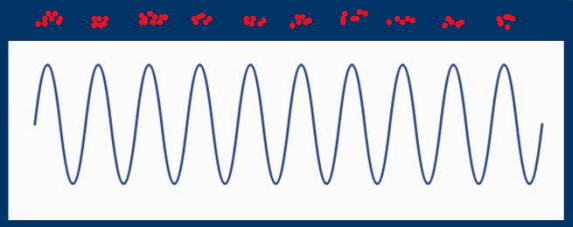


Electrons in beginning of Linac



10 cm

Electrons in the end of Linac

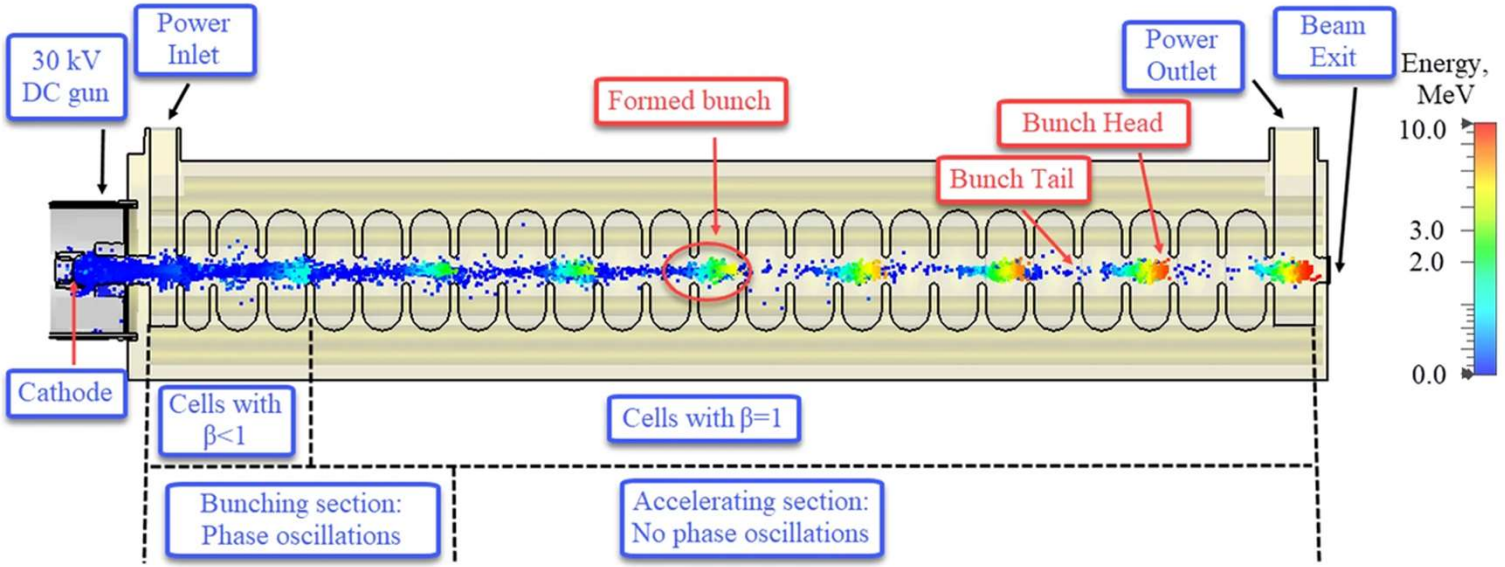


0,33 ns

# Electron bunches in a Linac

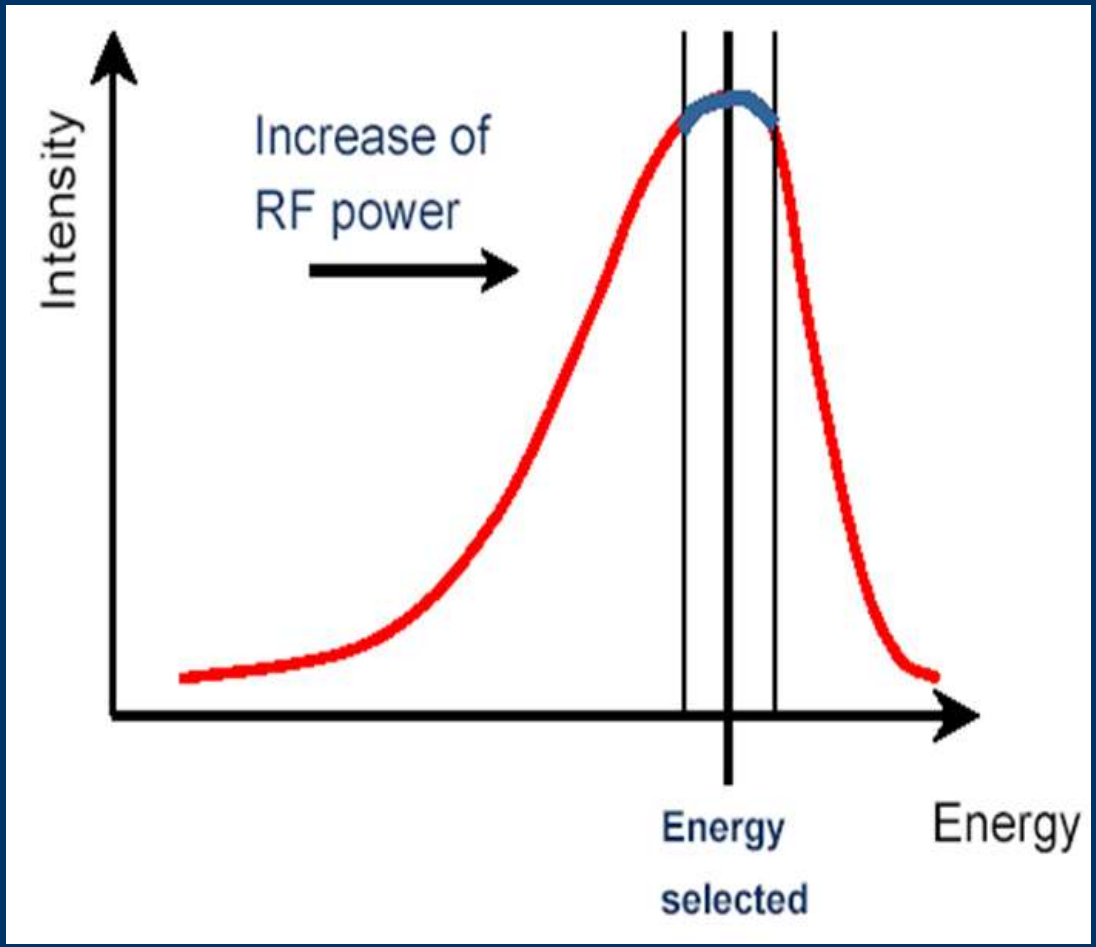
- There is a stream of electrons in the beginning and after a few cavities there is bunches statring to form
- At the end there is mostly bunches where the electrons have a spectrum of energies

**From: Electron bunchers for industrial RF linear accelerators: theory and design guide**




Acceleration of particles in a DLS-based TW electron linac, as simulated in CST Particle Studio [13]. From left to right: the electrons are emitted from the cathode, pre-accelerated in the gun, bunched in a three-cell waveguide buncher, and accelerated in the $\beta = 0.999$ constant impedance section

# *Electron bunches in a Linac*

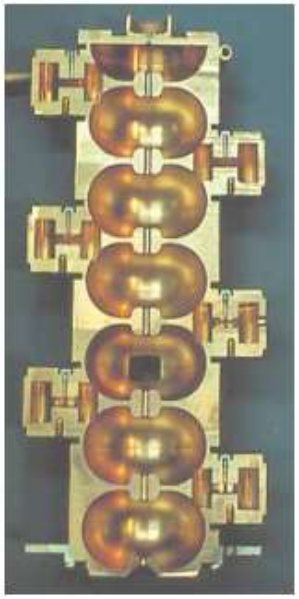


# Two different types of accelerator designs

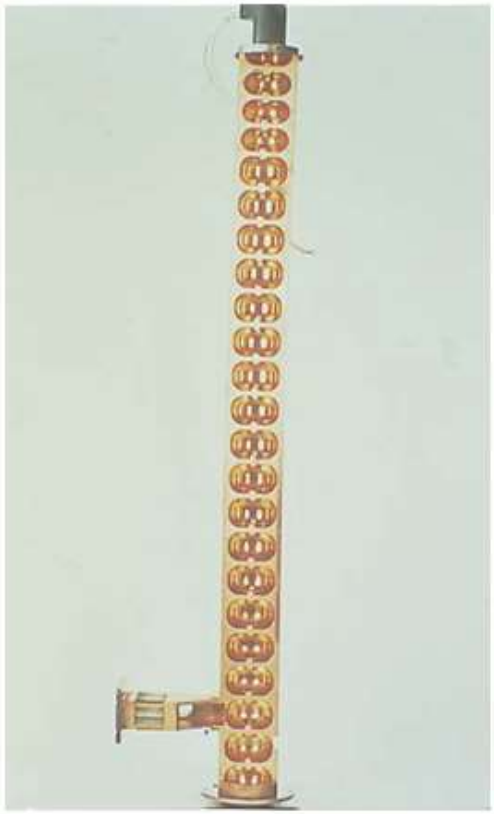
- TW (Travelling Wave) Elekta
- SW (Standing Wave) Varian



Short section - TW accelerator



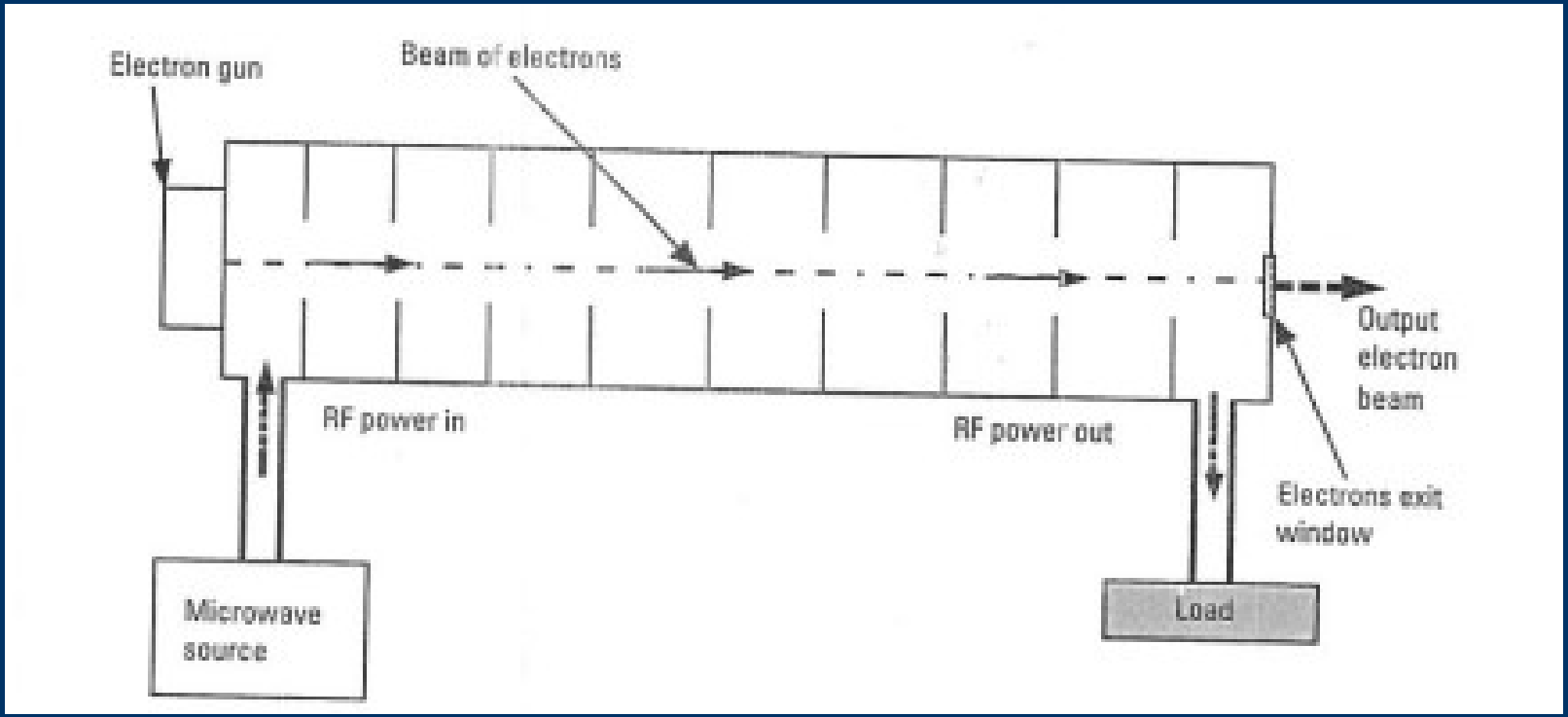
Short section
SW accelerator



Long section - SW accelerator

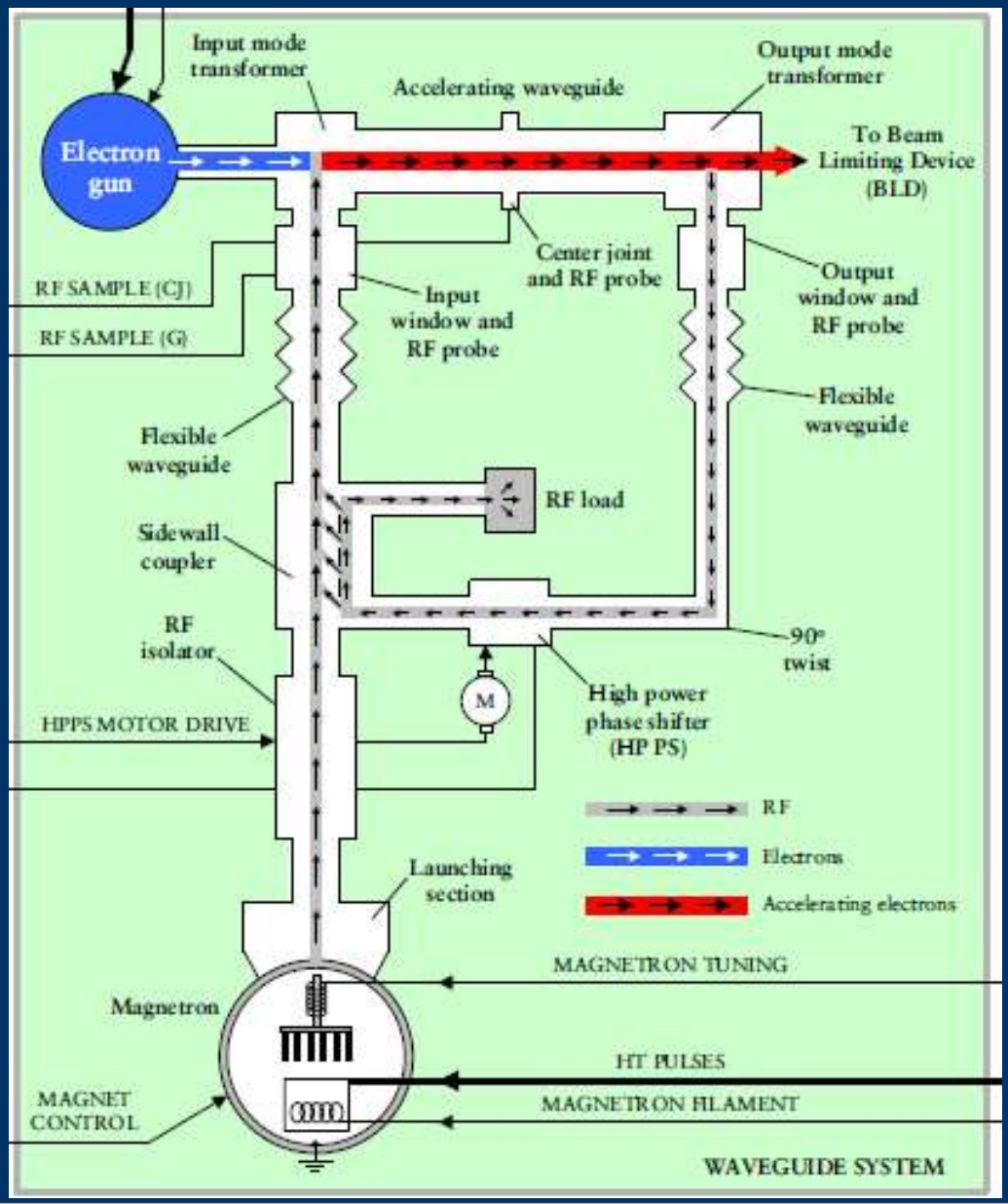
# *Travelling Wave (TW)*

- Microwave comes in in the beginning and exits at the end



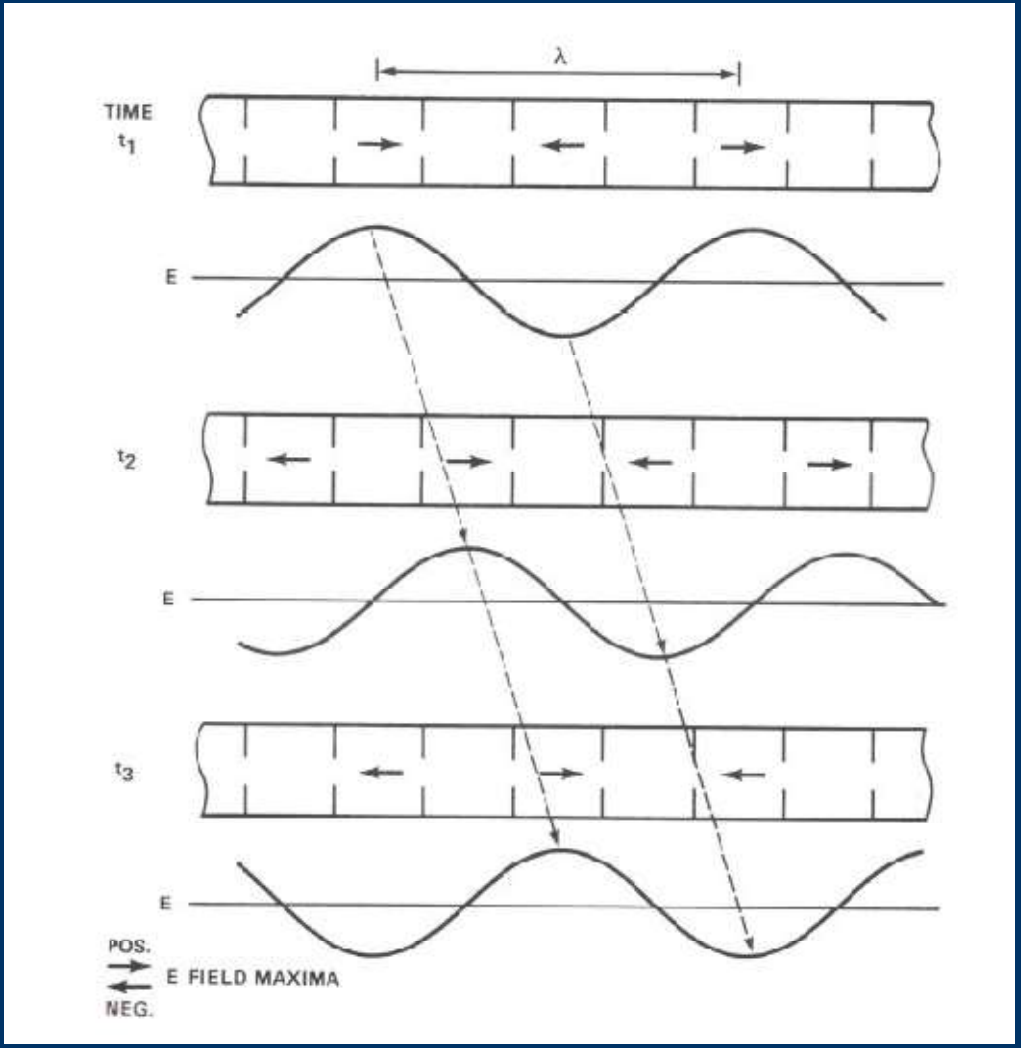
# *Travelling Wave (TW)*

- On a Elekta TW is some of the microwave energy recycled



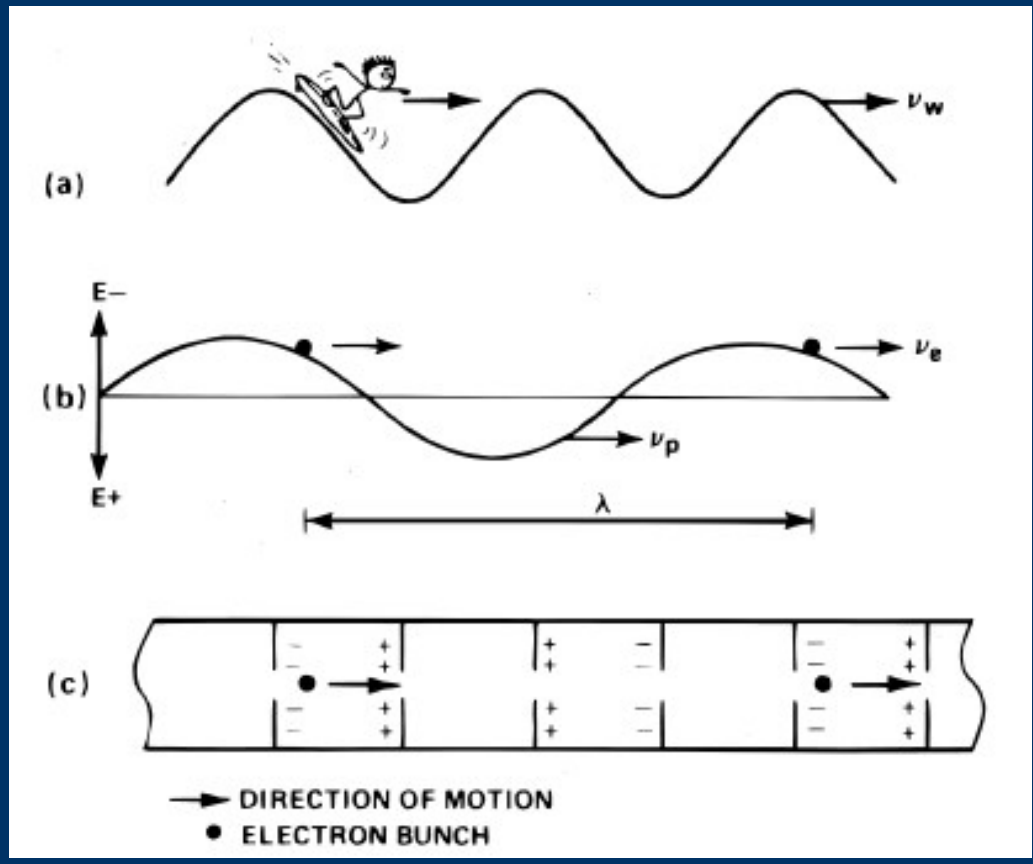
# *Travelling Wave (TW)*

- A TW-tube have ”discs” to slow the RF-energy to match the electron speed
- In this example we have 4 disc-cavities per wavelength (2.5 cm)
- The electric field moves from left to right (like a wave on the ocean)



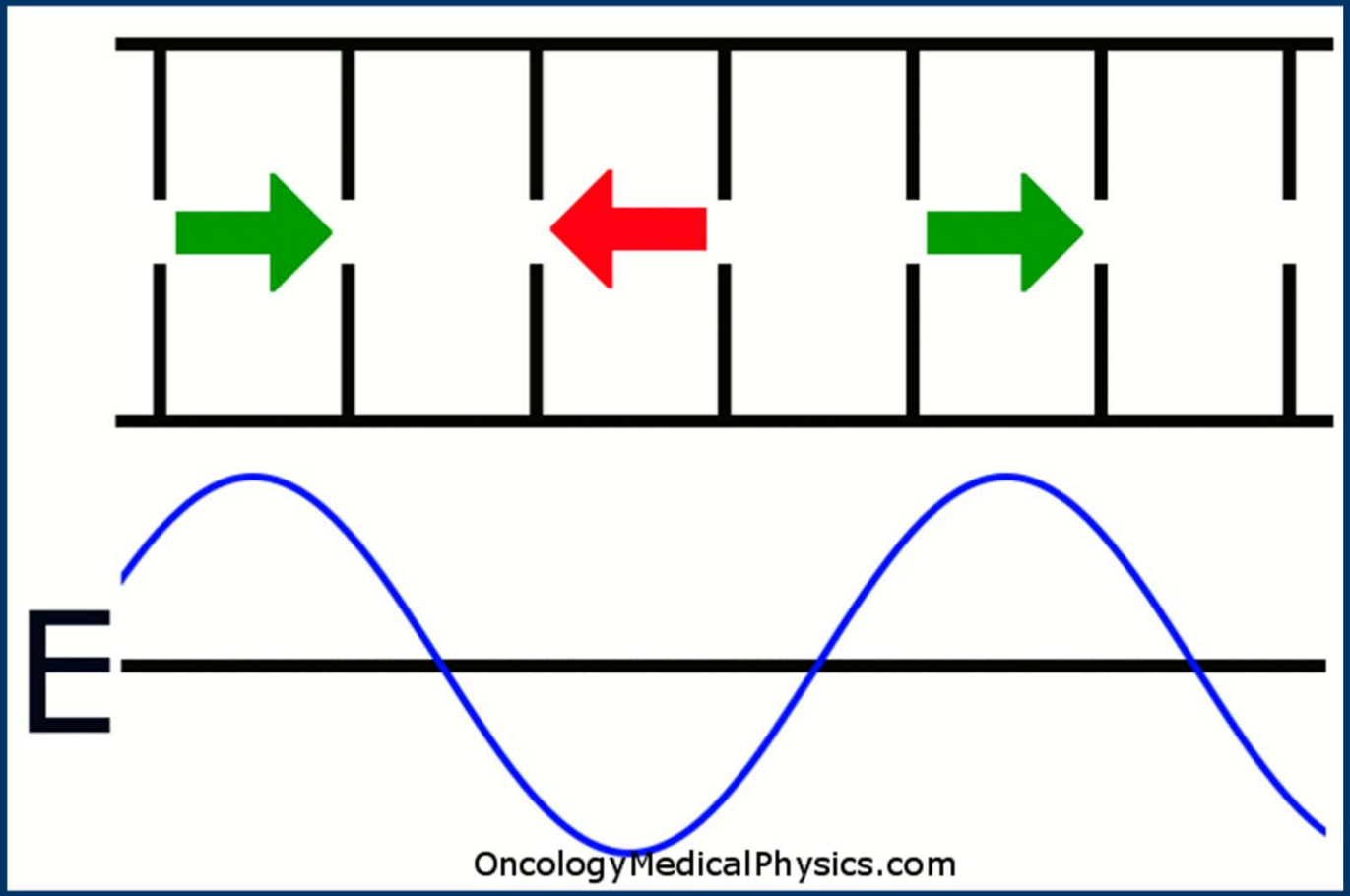
# *Traveling Wave (TW)*

- A common analogy is a surfer that is surfing on a wave
- The surfer (electrons) follows the same wave and takes energy from it
- We only have electron bunches in every fourth cavity



# Travelling Wave (TW)

TW_linac_animation.html



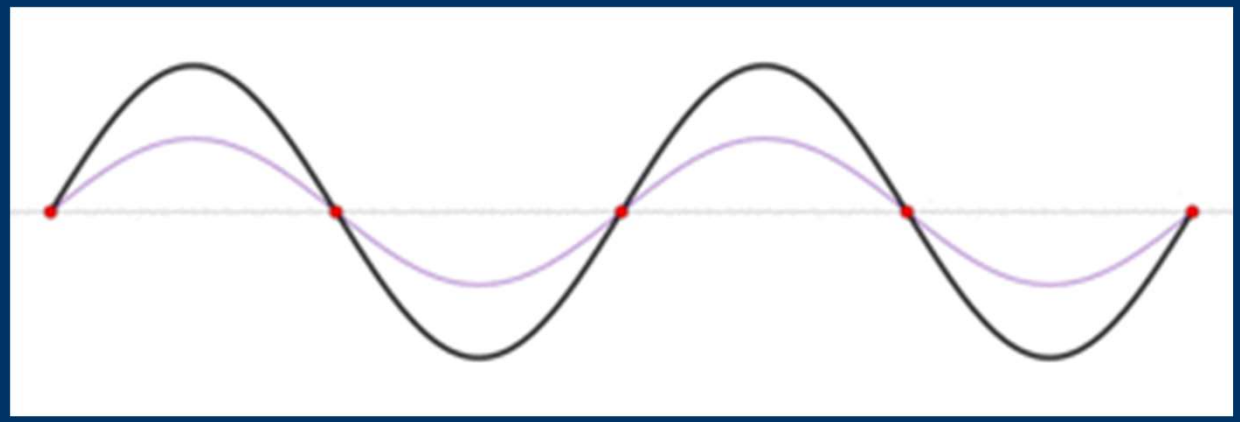
# *Standing wave (SW)*

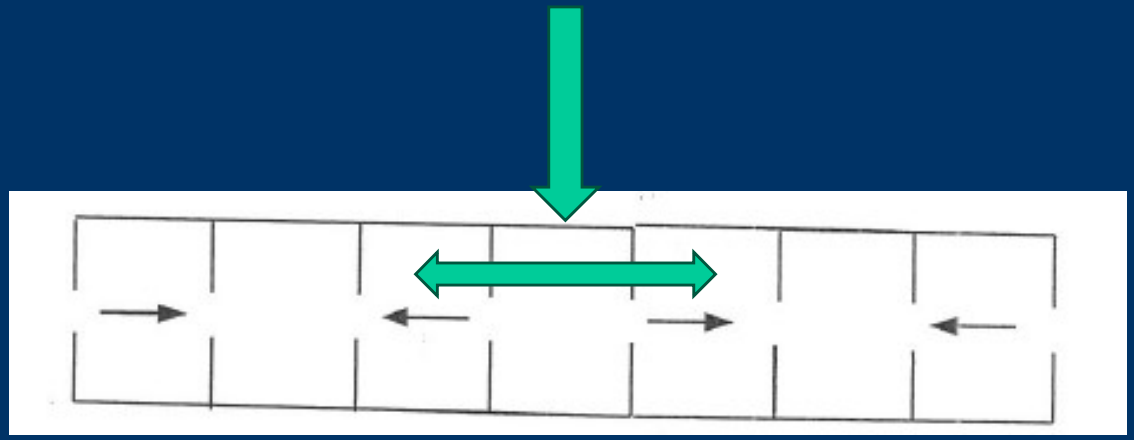
There are som similarities with a TW linac but
there is some important differences

- The linac is electrically shorted in both ends to make the microwave energy to be reflected.
- The microwaves are fed in the linac in the middle (give or take…)
- Standing waves are generated (the sum of forward and backward electric fields)
- The cavities are resonant and have one or more resonant frequencys (Think of a RLC circuit)

# *Standing wave (SW)*

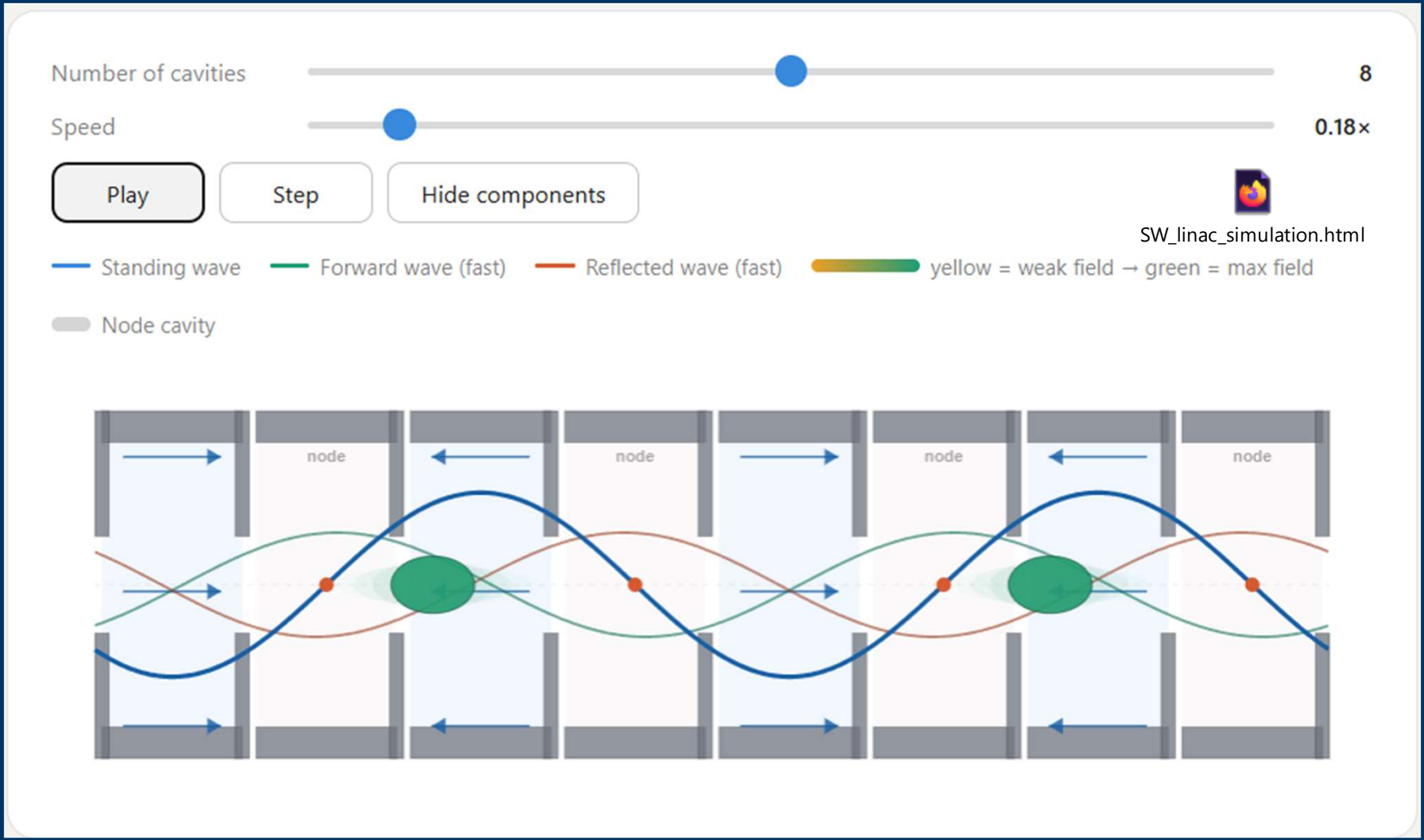
The standing wave linac uses reflection by electrically shortcut the linac in both ends.





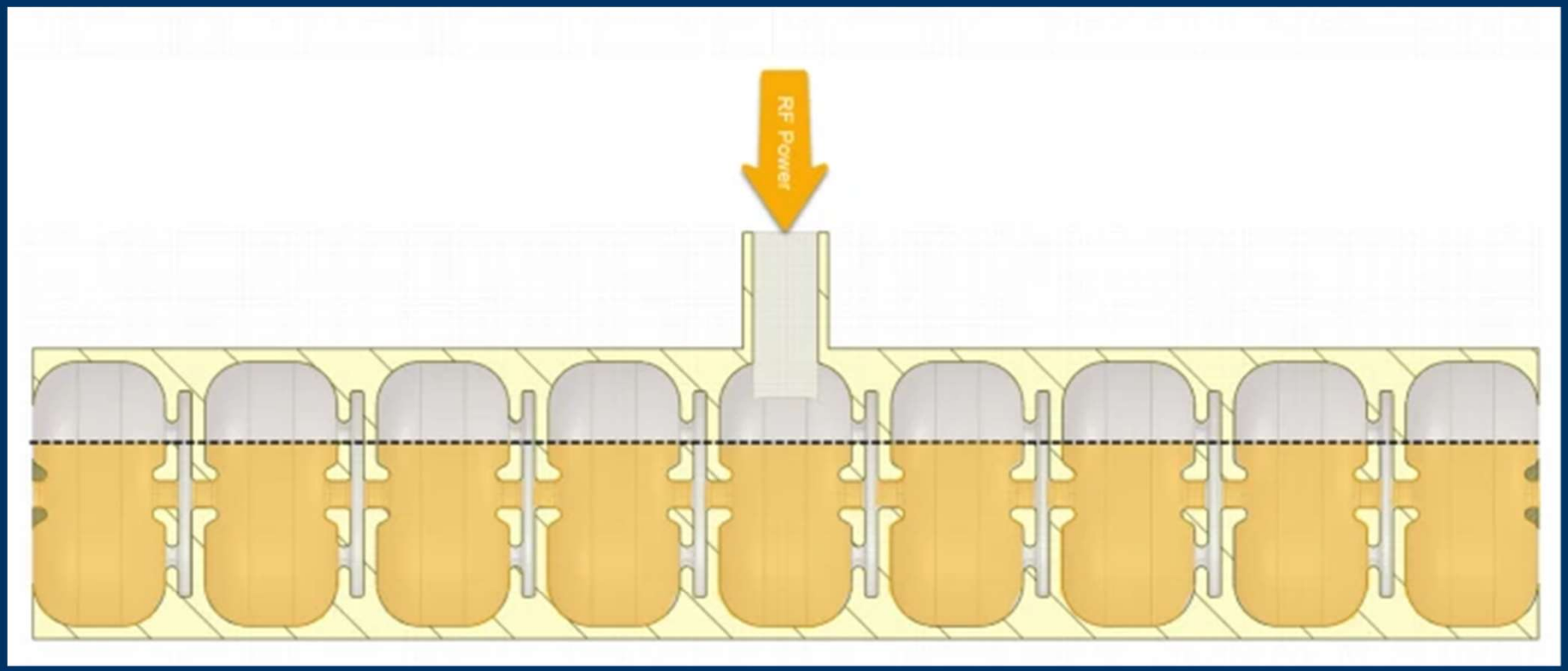
- The electric field strength for the standing wave is higher than the individual electric fields
- Normally the SW-linac can be shorter than the TW-linac

# Standing wave (SW)



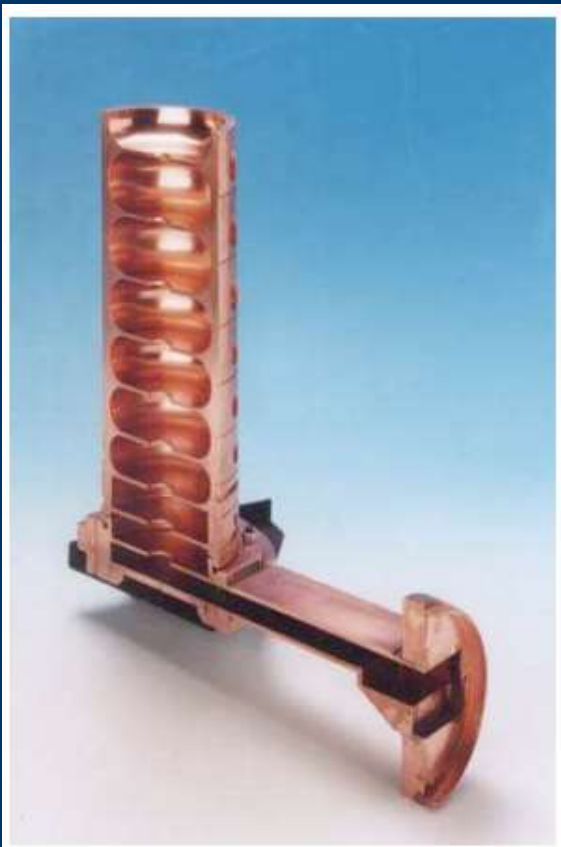
# *Standing wave (SW)*

- The electric field strenght is constant throuout the SW-linac so there is a linear energy transfer

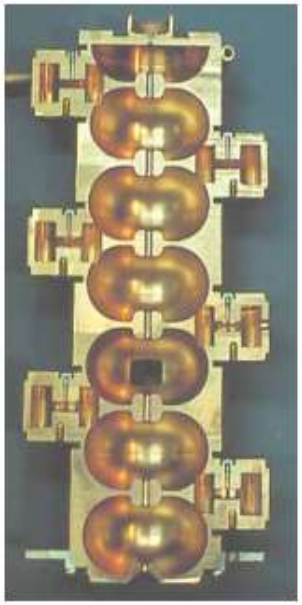


# *Standing wave (SW)*

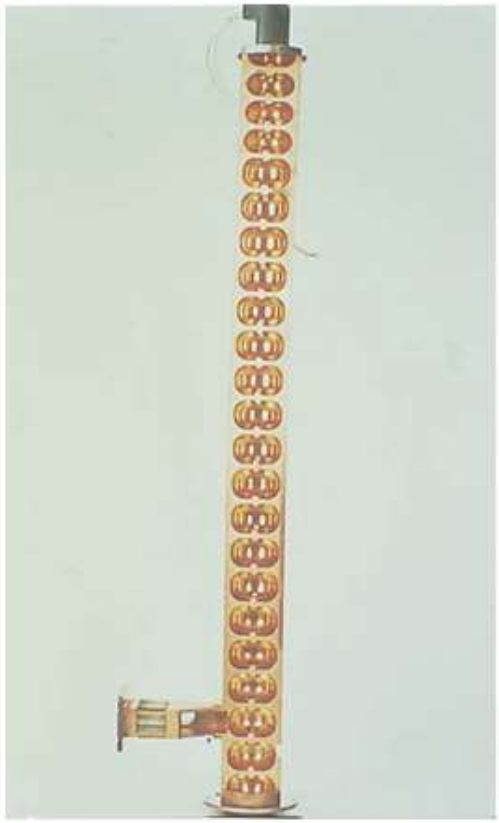
Different variants of TW och SW Linacs



Short section - TW accelerator



Short section
SW accelerator



Long section - SW accelerator

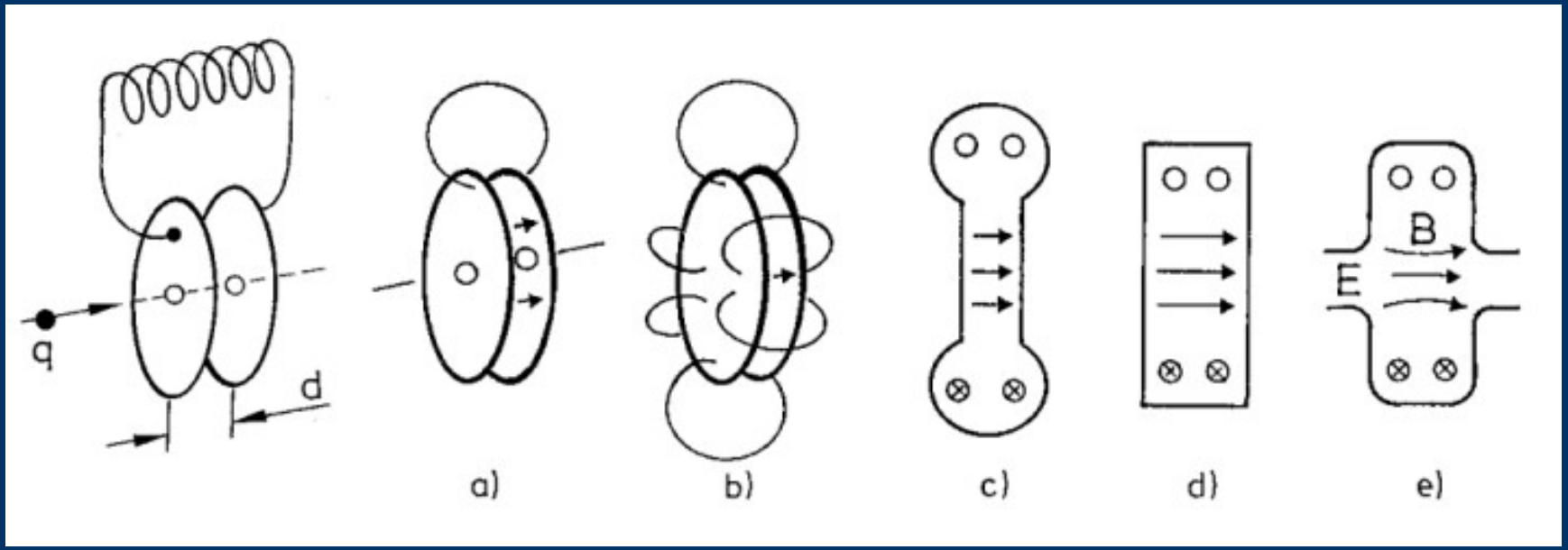
# *Standing wave (SW)*

What electric circuit is a cavity eqvivalent to



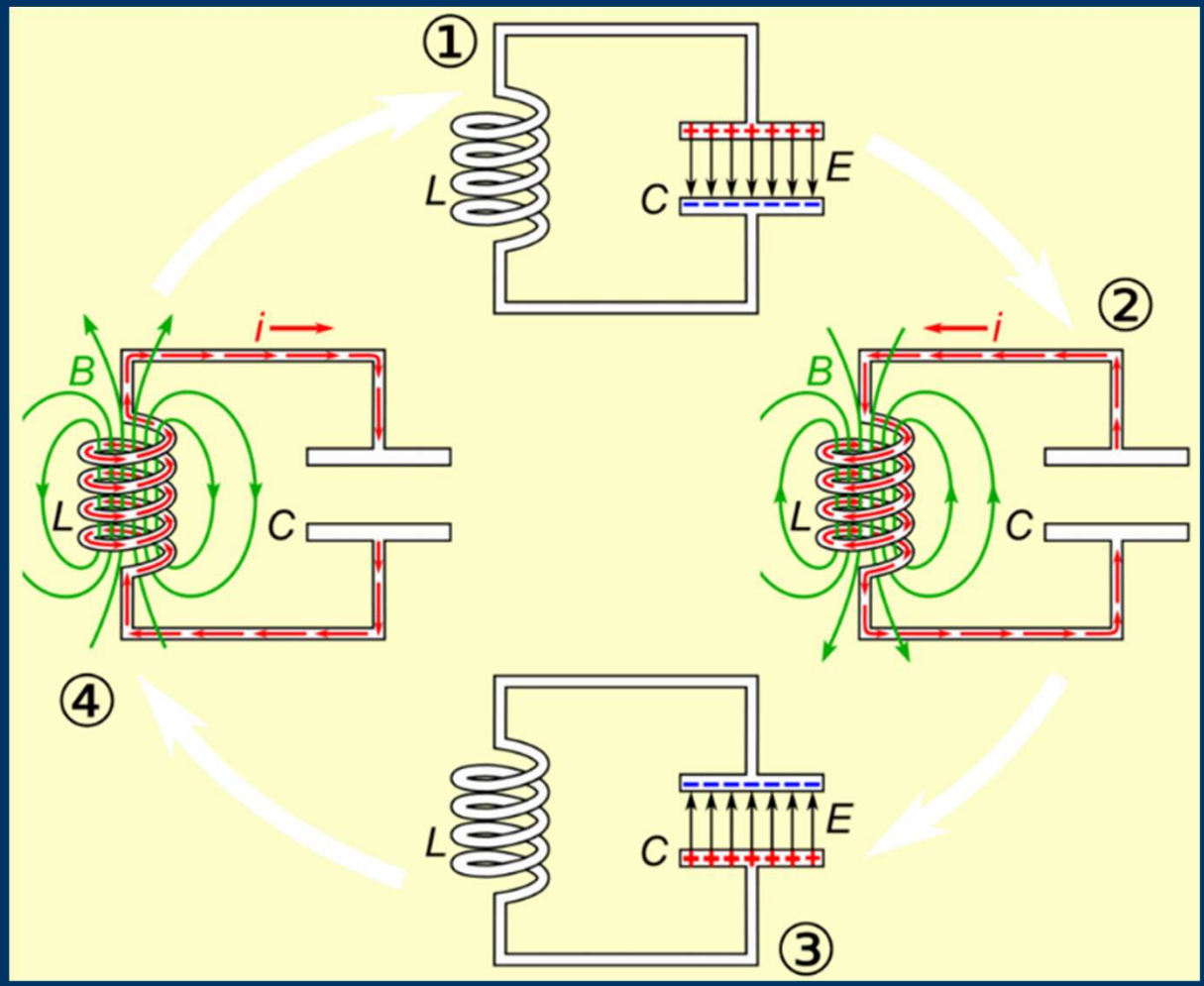
# *Standing wave (SW) – Cavities as a RLC circuit*

- The cavities in a SW-linac have RLC properties which means they have a resonance frequency



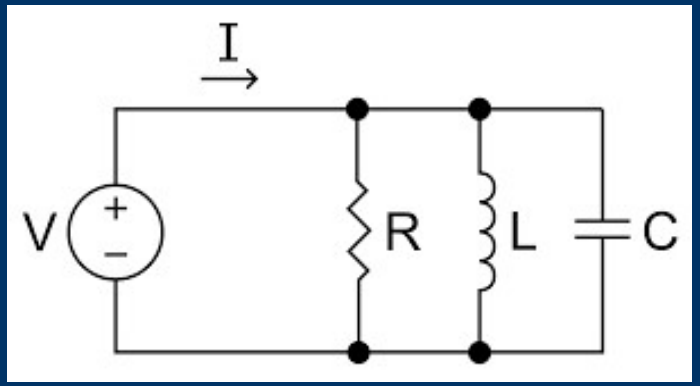
# *Standing wave (SW) – Cavities as a RLC circuit*

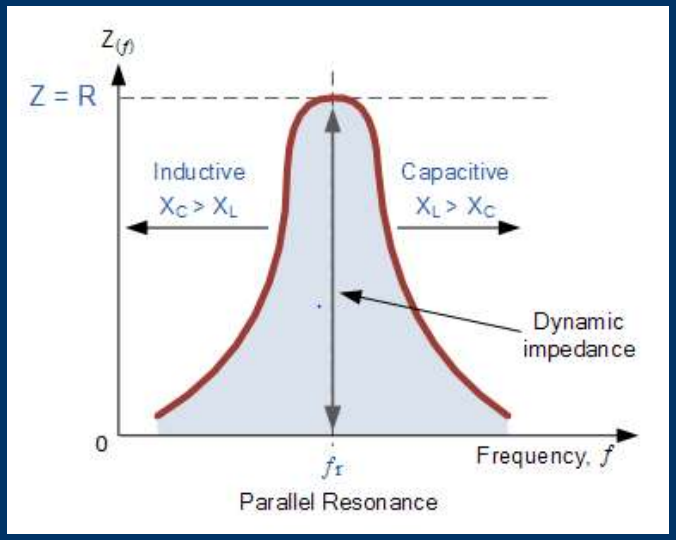
- The energy in a cavity is going between the two different energy states (electric and magnetic)
- Some energy is lost due to the skin effect and the resistivity in the copper walls
- Depending of the L and C properties there will be a specific resonance frequency



# *Standing wave (SW) – Cavities as a RLC circuit*

- A parallell RLC circuit have a resonant frequency $f_0$ when the impedance over the RLC circuit is the greatest (least energy loss and best acceleration of electrons)

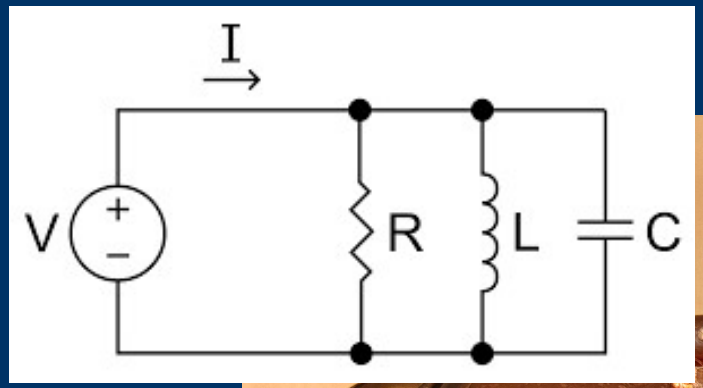


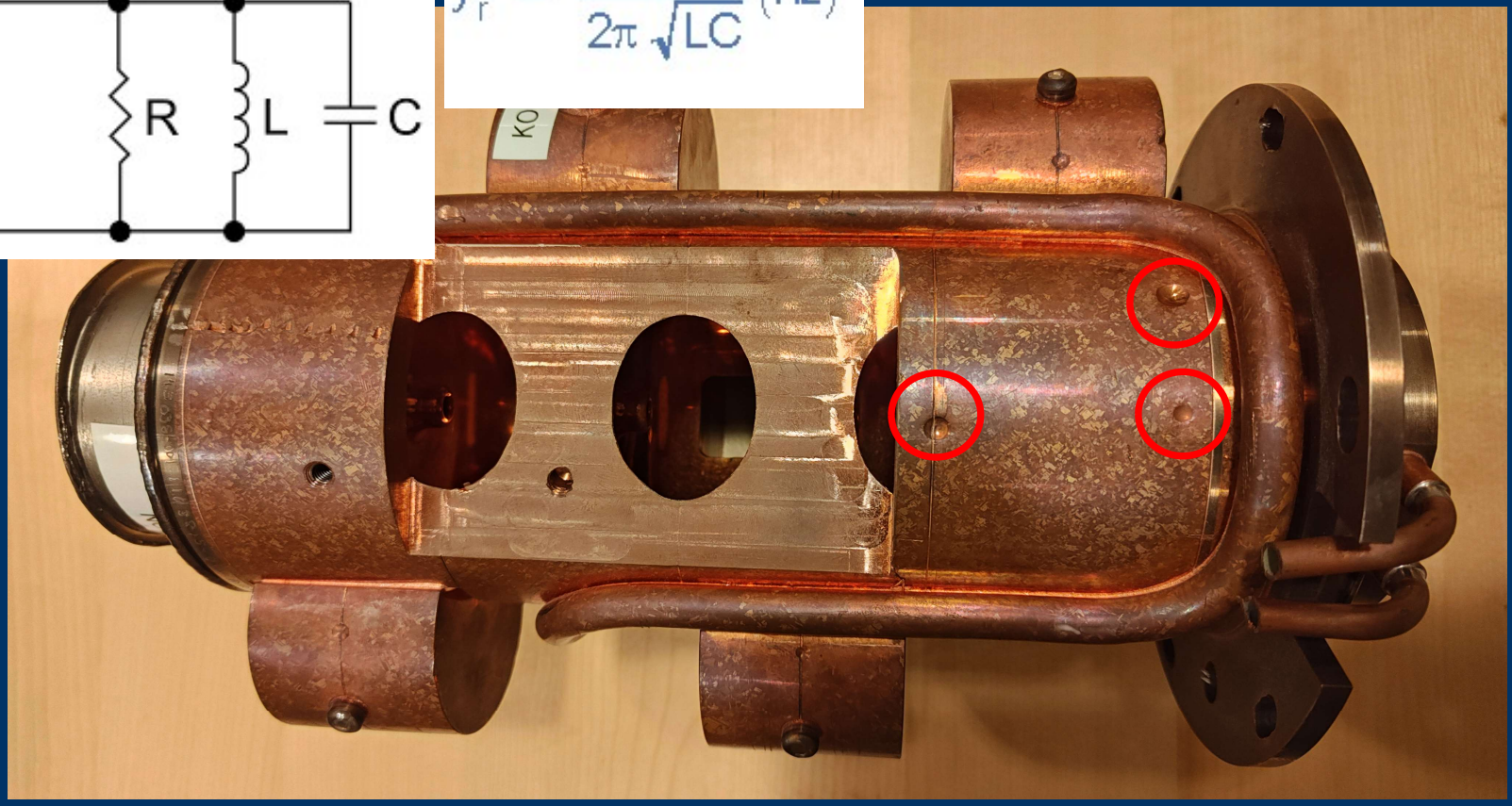

$$f_r = \frac{1}{2\pi\sqrt{LC}} \text{ (Hz)}$$

# *Standing Wave (SW) – Cavities as a RLC circuit*

What are the dents in a SW-Linac?




$$f_r = \frac{1}{2\pi\sqrt{LC}}\,(\mathrm{Hz})$$



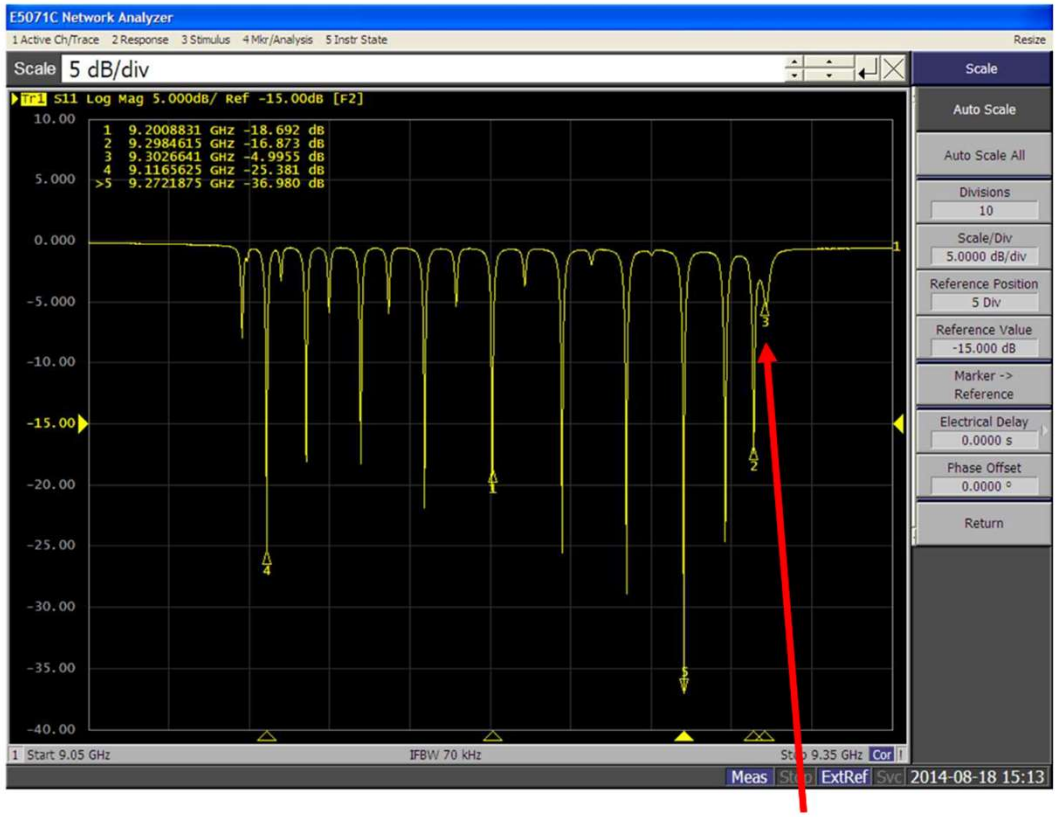
# *Standing Wave (SW) – Cavities as a RLC circuit*

Reflected microwaves before tuning the linac (9.3 GHz KAERI)

## X-band Linac - Fabricated Linac

KAERI

**S11**




**KAERI did Great Design & Fabrication!**

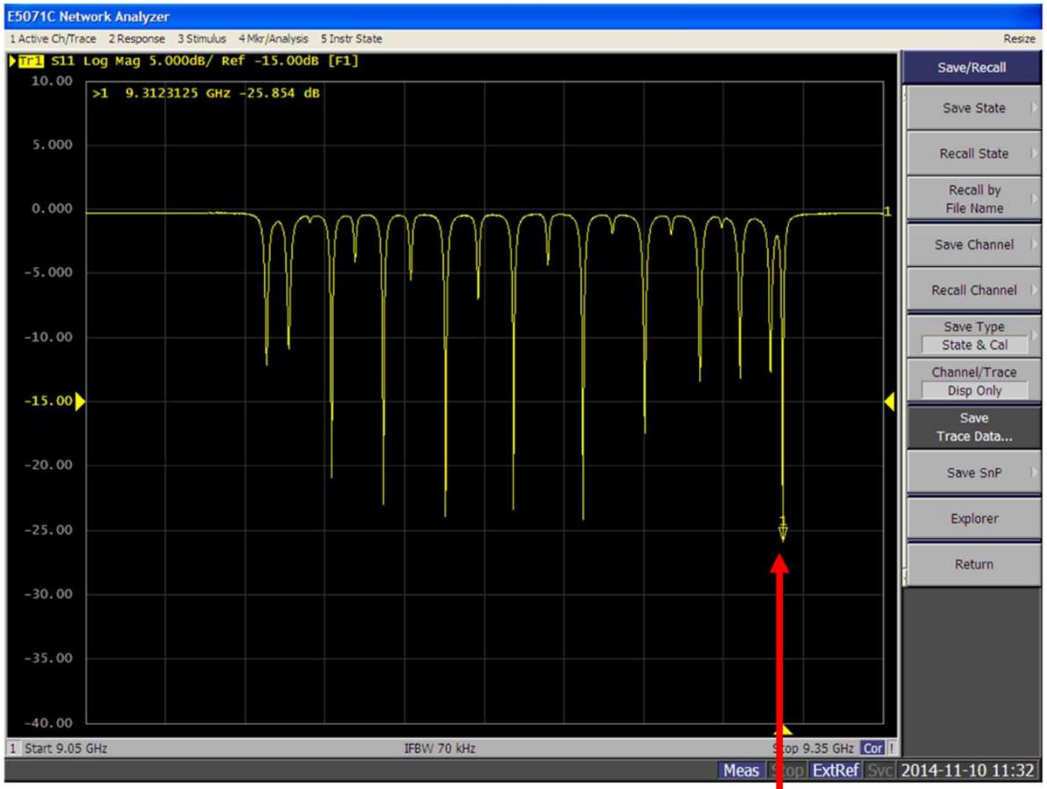
**Right After Fabrication**

**π mode ~ 9.302 GHz with -5.0 dB**

# Standing Wave (SW) – Cavities as a RLC circuit

Reflected microwaves after tuning the linac (9.3 GHz KAERI)

## X-band Linac - Fabricated Linac




**After Final Tuning @ Tempearture = 30 degree**

**π mode ~ 9312.31 MHz with -27 dB**

**(0.2% reflection)**

**KAERI did Great Tuning!**

*Linaccar (Linjäracceleratorer)*

# *Q-value (Quality value)*

- In resonant circuits there is a value called the Q-value
- This value indicates how wide the bandwith are (a higher value means a narrower bandwith)

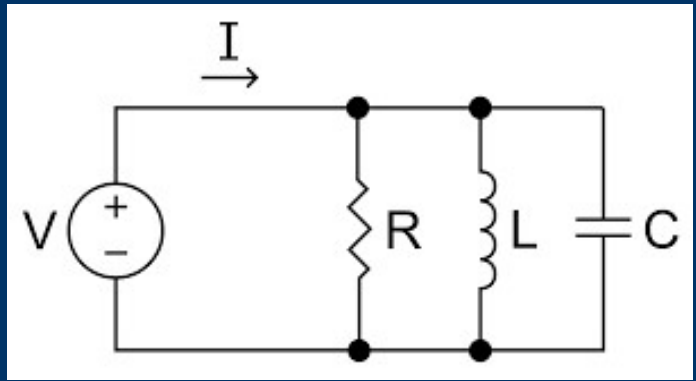
$$Q = {f_0}/{BW}$$

- Q-value also tells how good resonator the circuit is and how big the losses are

$$Q = 2\pi \times \frac{Stored\ energy}{lost\ energy\ per\ cycle}$$




| | |
|---|---|
| Structure | Side Coupled Standing Wave |
| Material | OFHC |
| Length | 40cm |
| Frequency | 2856±0.1MHz |
| Qo | 14,500 |
| Shunt impedance | 130MΩ/m |
| Beam Energy | 6MeV@2.5MW |
| Beam Current | 100mA |



*Linaccar (Linjäracceleratorer)*

# *Q-value (Quality value)*

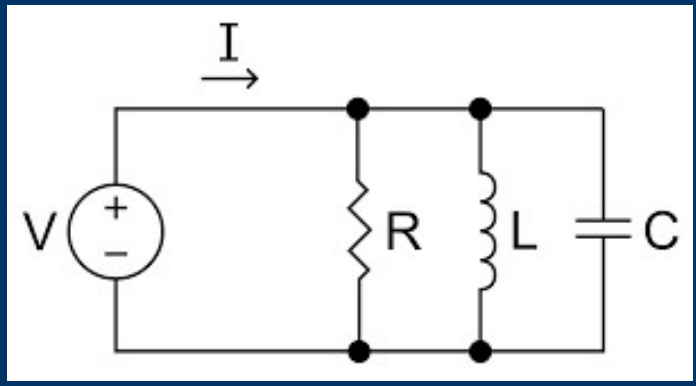
- A high Q-value is desired because you have lower losses in the walls
- Q-value can be increased using quality materials
- A typical Q-value is around 10 000 (around 3000 oscillations before the energy is dissipated to 1/3)
- A typical playground swing have a Q-value of 30 and a tuning fork around 1000

**6MeV S-Band Linear Accelerator**

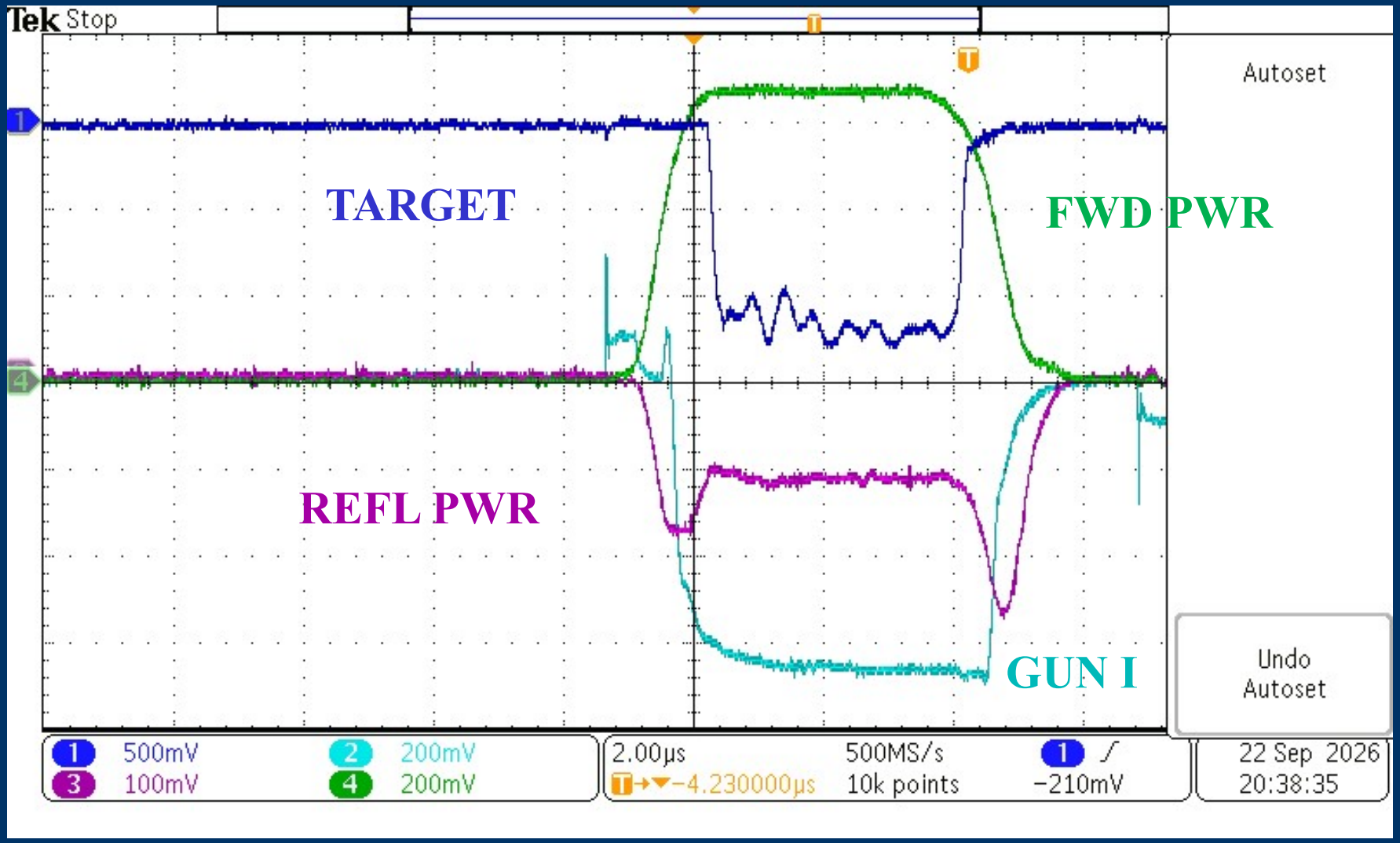
www.aetjapan.com



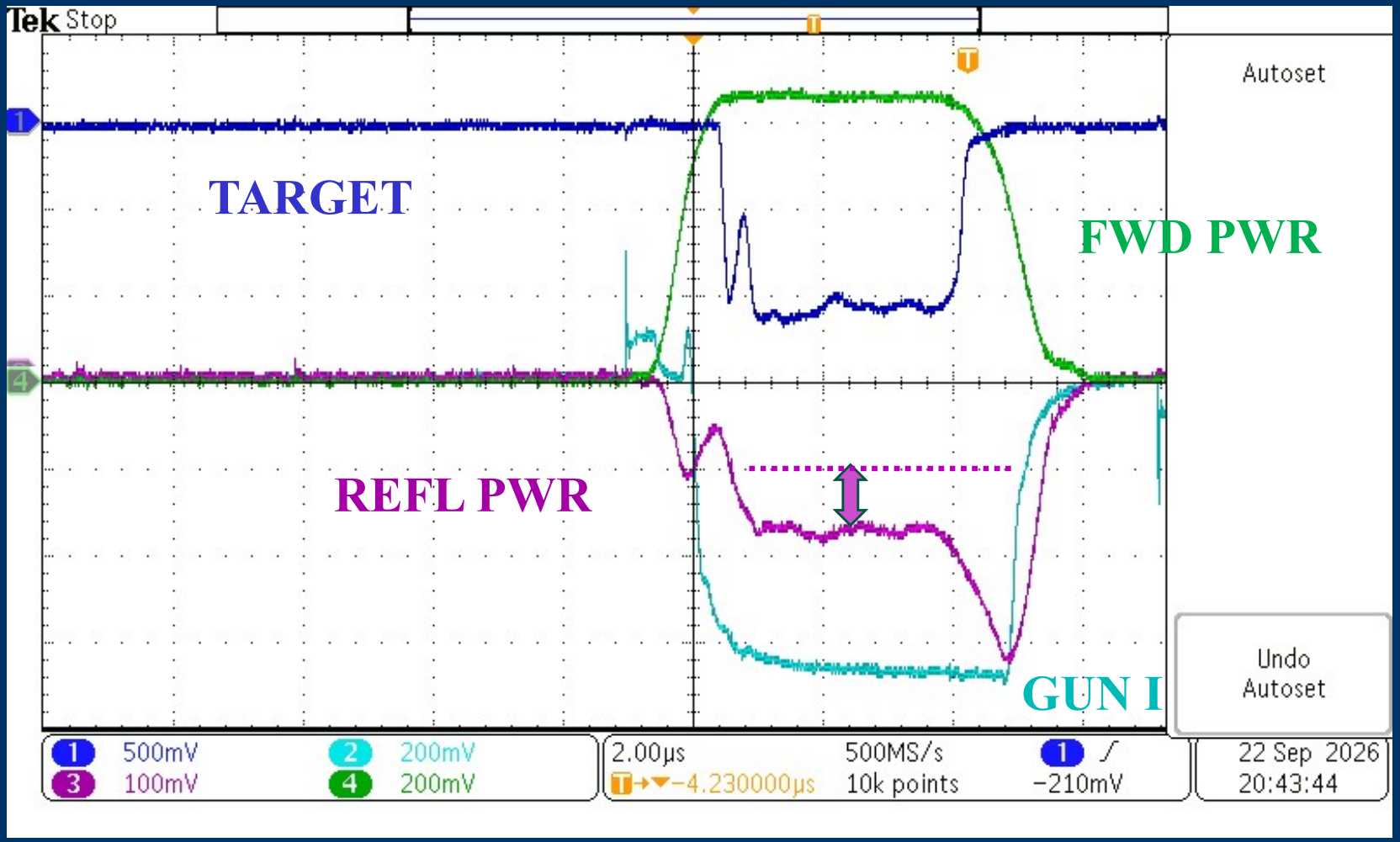
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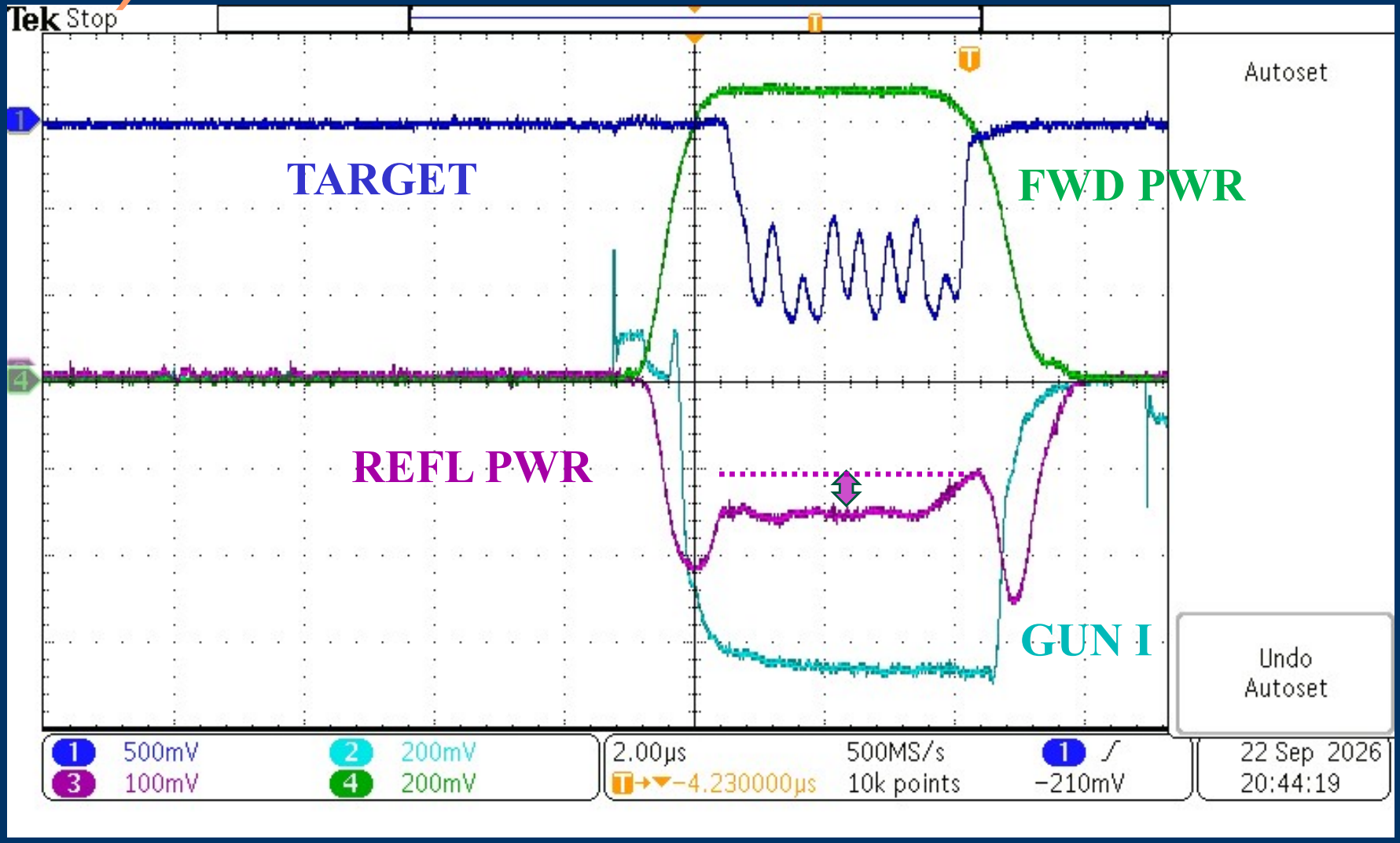
# *Standing wave (SW) – oscilloscope 6 MeV normal*



# *Standing wave (SW) – oscilloscope 6 MeV Frequency too low (400 Hz lower than optimal)*



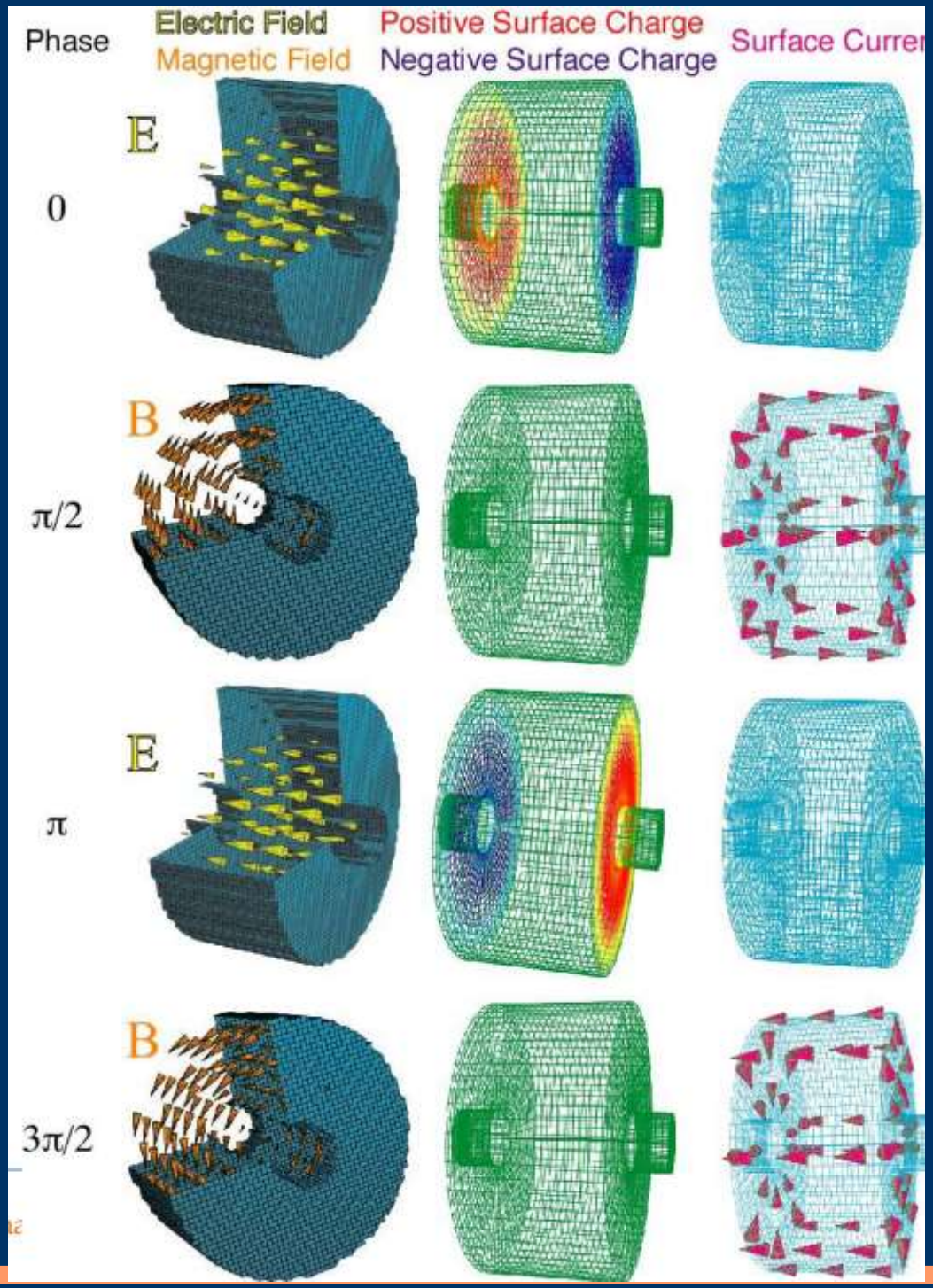
# *Standing wave (SW) – oscilloscope 6 MeV Frequency too low (200 Hz higher than optimal)*



# *Standing wave (SW) – One cycle*

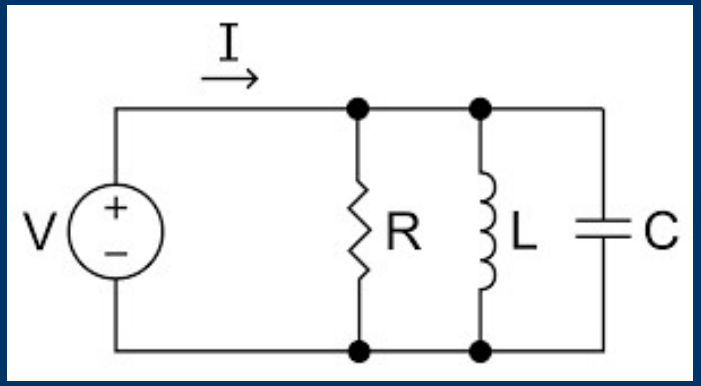
Maximum electric field – no magnetic field

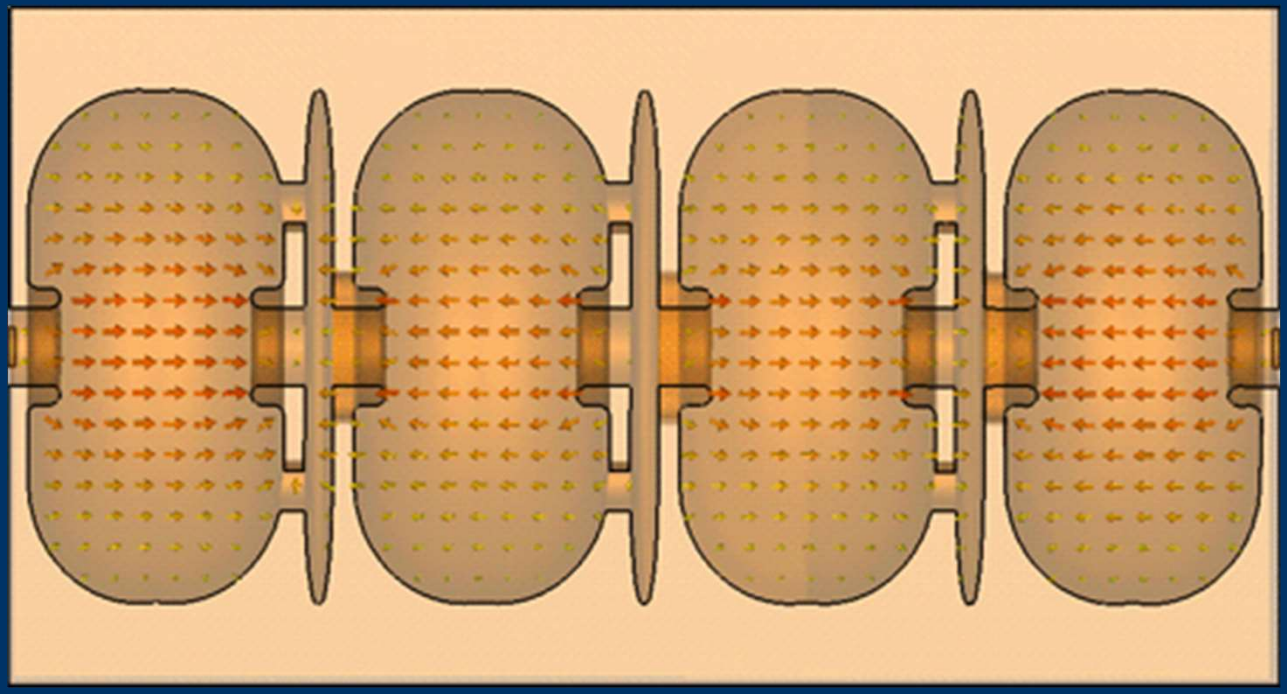
Maximum magnetic field – no electric field



# *Standing wave (SW) – Cavities as a RLC circuit*

- **For the electrons it is the electric field that matters**



# *Recap of the role the frequency have in a Linac*

- In the design/manufacturings state it have a influence on the size of the cavitys and the total weight.
- TW-accelerator: The frequency alters the phase velocity of the electric field, if wrong frequency the electric field will move to fast or to slow relative the electrons→ bad accelerating efficiency

- SW-accelerator: The frequency must match the linacs resonance frequency or else → more reflected energy → lower electric field -- > bad acceleration efficiency

# Source material

- Karzmark book "A primer on…"
- Samy Hannas book "RF Linear Accelerators"
- Varian Accelerator System Basics from Clinac Course
- The almighty Internet… Articles, other peoples presentations
- https://ionactive.co.uk/resource-hub/guidance/the-linac-accelerator-linac-medical-other-applications-video

