RF Applications

CERN Accelerator School

Mechanical & Materials Engineering for Particle Accelerators and Detectors

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Sint-Michielsgestel, 13 June 2024

Overview

- Foreword
- Introduction to RF
- General Applications
- RF Cavities
- RF Transmission
- Thermal Analysis
- Ultrahigh Precision Machining
- Closing Remarks

Foreword

In This Talk

We will concentrate on classical normal conducting RF systems. We will not cover the particular engineering aspects of Superconducting RF systems.

We will illustrate via few examples, *most related to applications and developments at PSI*, the mechanical engineering aspects relevant for the desing and production of RF accelerating structures and RF components.

Beside some key formula, basic concepts and key parameters we will try to minimize the mathematics and concentrate on the interface between RF requirements and mechanical engineering/production.

I would like to begin with an acknowledgement of Dr. Marco Pedrozzi who wrote the original slides that this talk was based on.

Constraints of RF Systems

RF systems are always (**very**) expensive

⇒ It is not uncommon if representing a large fraction of the total accelerator/project budget.

RF handles high power & voltages

⇒ Complex system with high potential of failures (can strongly influence the accelerator reliability).

⇒ Requires careful design and engineering .

⇒ Engineers must always consider maintainability during the design phase.

Some other constraints

⇒ Choice of the RF frequency is **often restricted to already existing (commercial) RF sources & components**. Developments may be unavoidable but deviations from standards imply substantial additional costs and time.

⇒ Space in the existing or planned (costs) facilities.

⇒ Significant development and procurement time.

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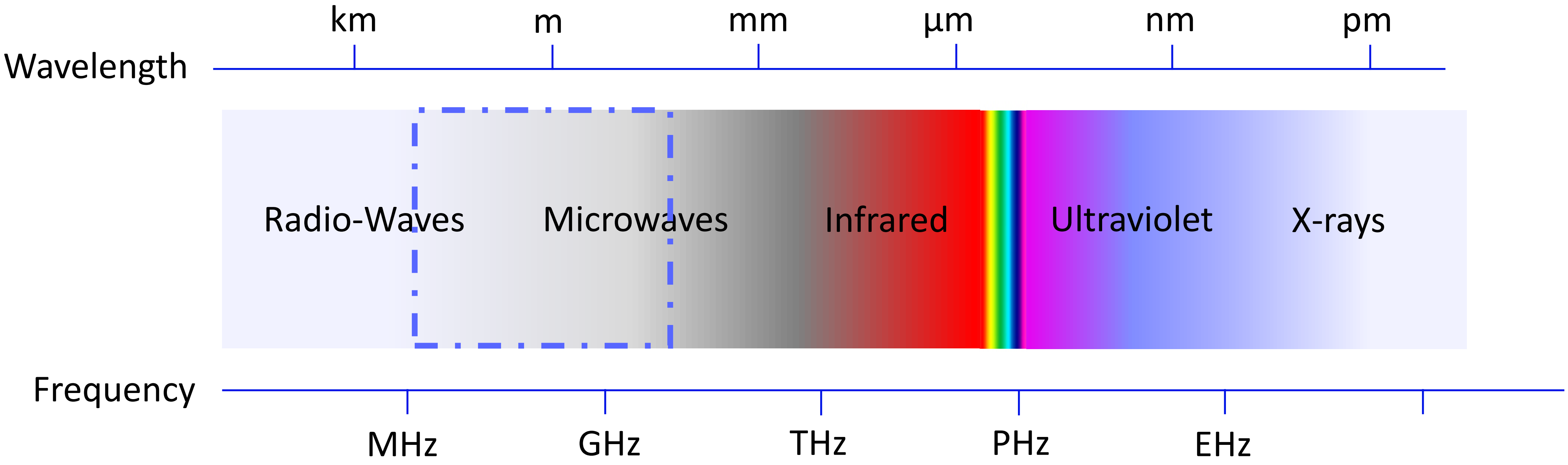
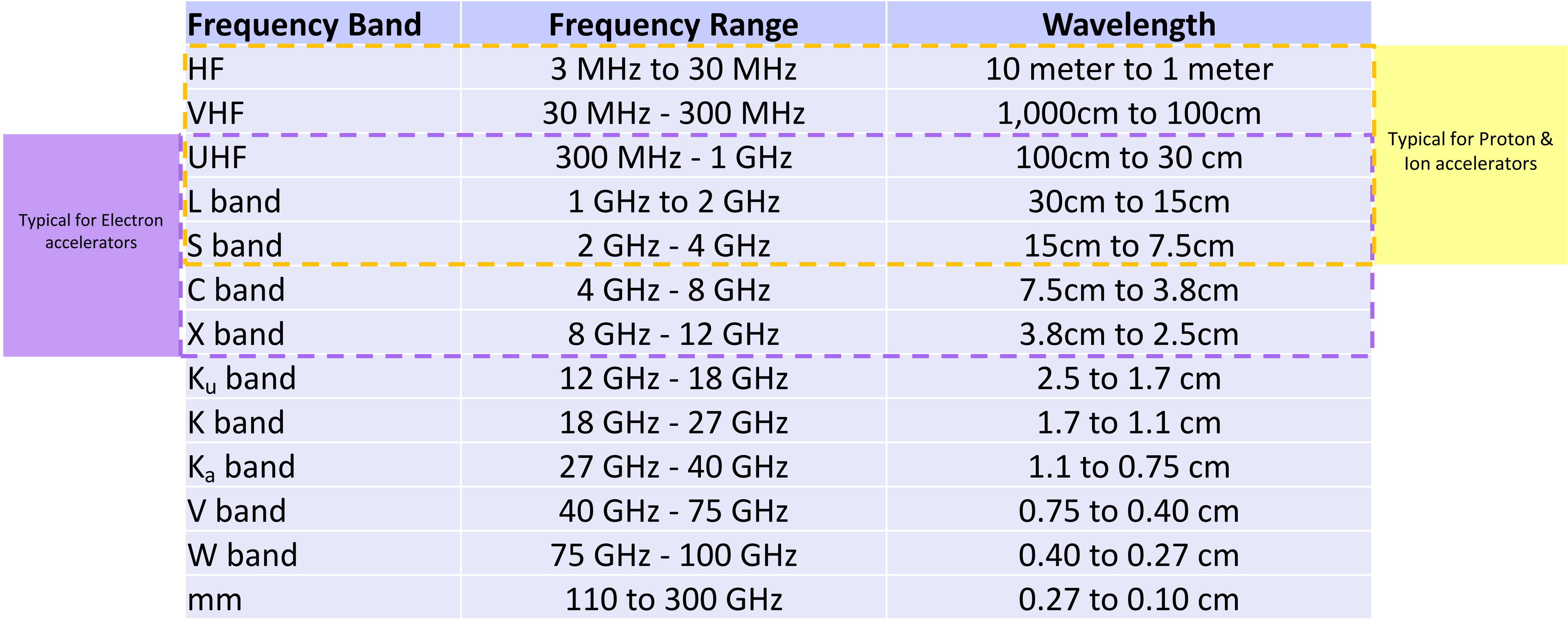
Introduction to RF and some common nomenclature

Definition of Radio-Frequency (in accelerators)



Nomenclature Frequency bands



Frequency Band	Frequency Range	Wavelength
HF	3 MHz to 30 MHz	10 meter to 1 meter
VHF	30 MHz - 300 MHz	1,000cm to 100cm
UHF	300 MHz - 1 GHz	100cm to 30 cm
L band	1 GHz to 2 GHz	30cm to 15cm
S band	2 GHz - 4 GHz	15cm to 7.5cm
C band	4 GHz - 8 GHz	7.5cm to 3.8cm
X band	8 GHz - 12 GHz	3.8cm to 2.5cm
K_u band	12 GHz - 18 GHz	2.5 to 1.7 cm
K band	18 GHz - 27 GHz	1.7 to 1.1 cm
K_a band	27 GHz - 40 GHz	1.1 to 0.75 cm
V band	40 GHz - 75 GHz	0.75 to 0.40 cm
W band	75 GHz - 100 GHz	0.40 to 0.27 cm
mm	110 to 300 GHz	0.27 to 0.10 cm

Typical for Electron accelerators

Typical for Proton & Ion accelerators

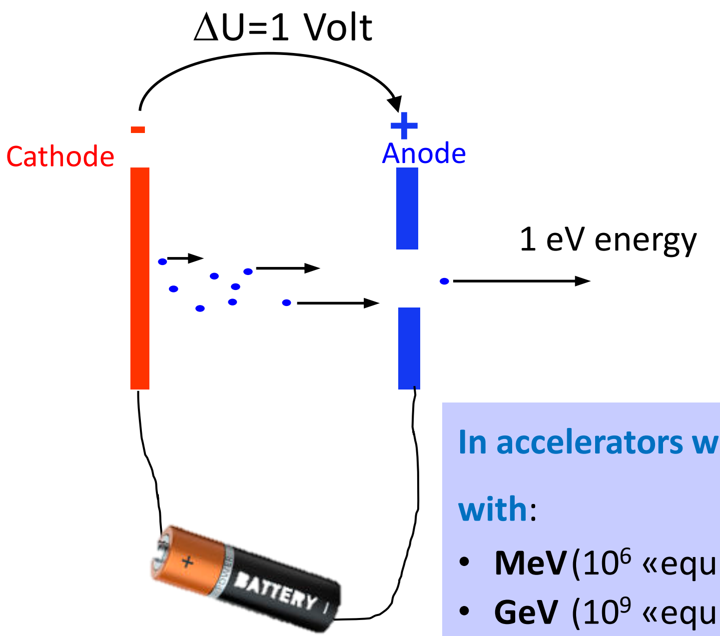
Example S-Band in Linacs: US frequency **2.856 GHz** - European frequency **2.998 GHz** (different standards)

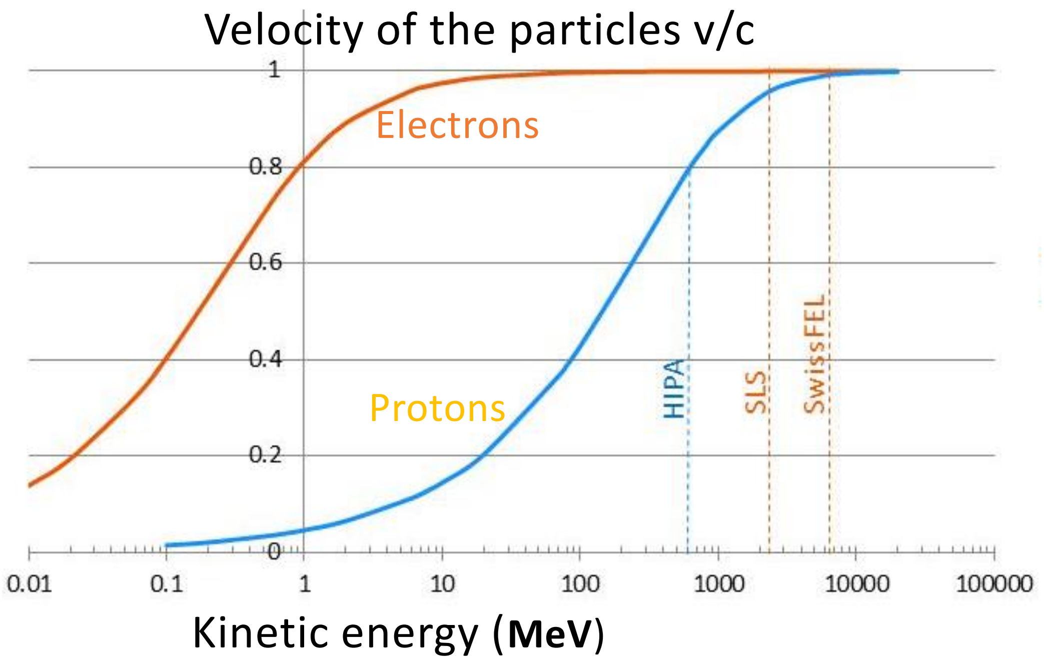
Small Parenthesis: Definition of eV

A practical unit for particle energy is the electron-Volt

1 **eV** = 1.602×10^{-19} J

This is the amount of energy that one electron gains in one volt of potential.





In accelerators we are typically dealing with:

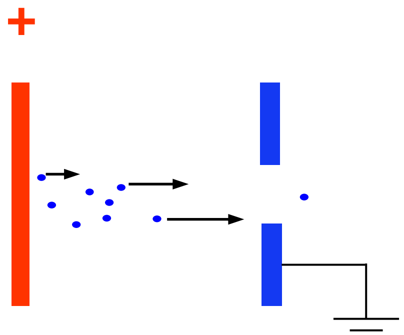
- **MeV** (10^6 «equivalent volts»)
- **GeV** (10^9 «equivalent volts»)
- **TeV** (10^{12} «equivalent volts»)

$$E_k = E - E_0 = (\gamma - 1)m_0c^2 \;\rightarrow\; \frac{v}{c} = \sqrt{1 - \frac{1}{\gamma^2}} = \sqrt{1 - \left(\frac{1}{1 + \frac{E_{cin}}{m_0c^2}}\right)^2}$$

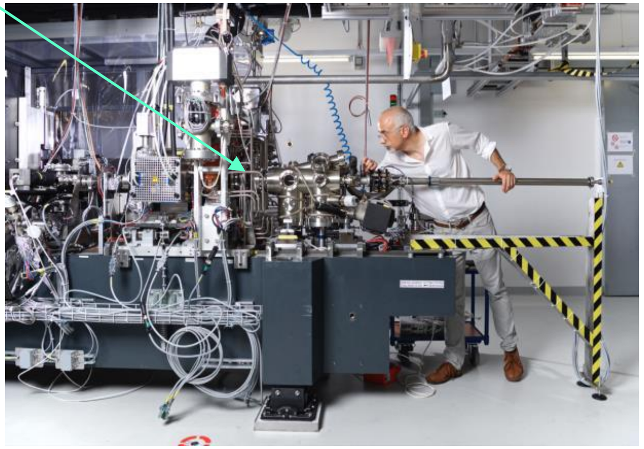
RF vs DC acceleration

1 MV Cockcroft-Walton: the first stage in the High Intensity Proton Accelerator (HIPA) facility

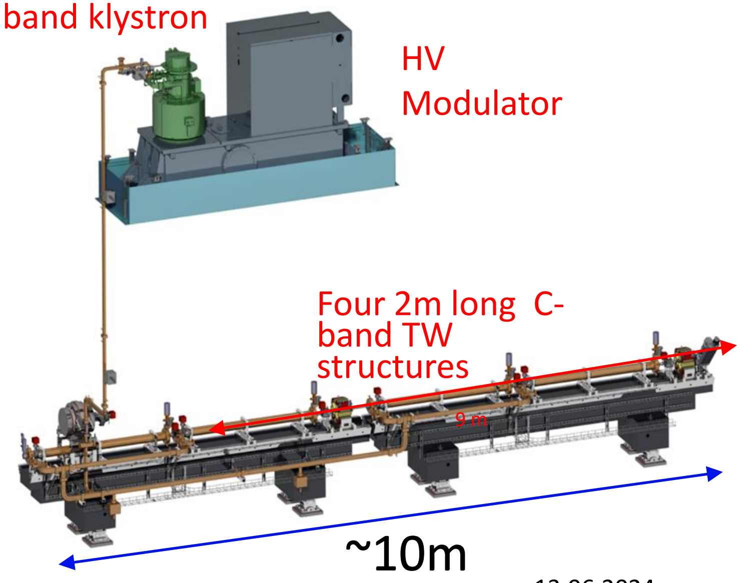
HV Housing of the ~1 MeV Proton source



7.1 MeV SwissFEL RF-Gun Peak gradient 100 MV/m



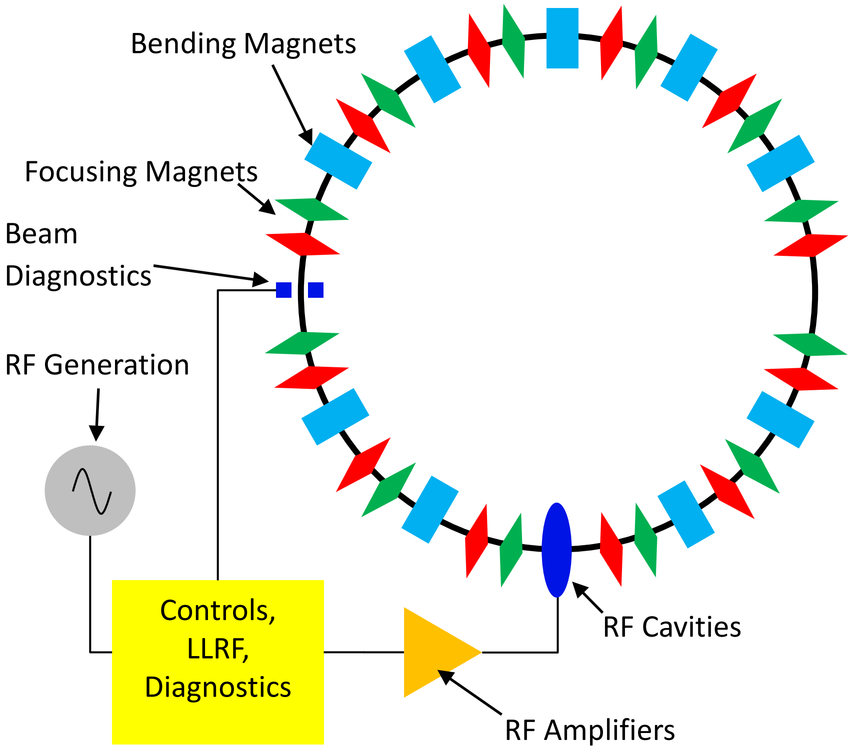
240 MeV energy gain SwissFEL C-Band RF-Module Gradient ~30 MV/m (the cavities would allow >56 MV/m if enough RF power)



RF in Particle Accelerators

Typical Accelerator Topology

The Circular Accelerator



Bending Magnets

Focusing Magnets

Beam
Diagnostics

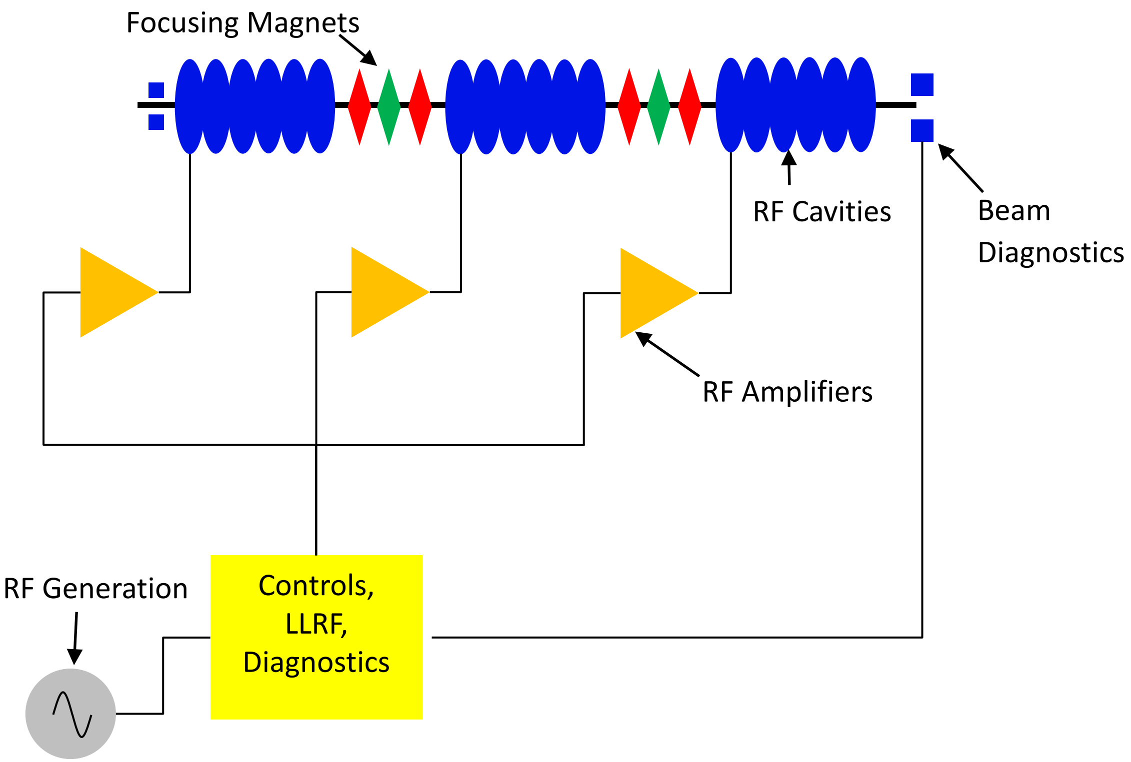
RF Generation

Controls,
LLRF,
Diagnostics

RF Cavities

RF Amplifiers

The Linear Accelerator



Focusing Magnets

RF Cavities

Beam
Diagnostics

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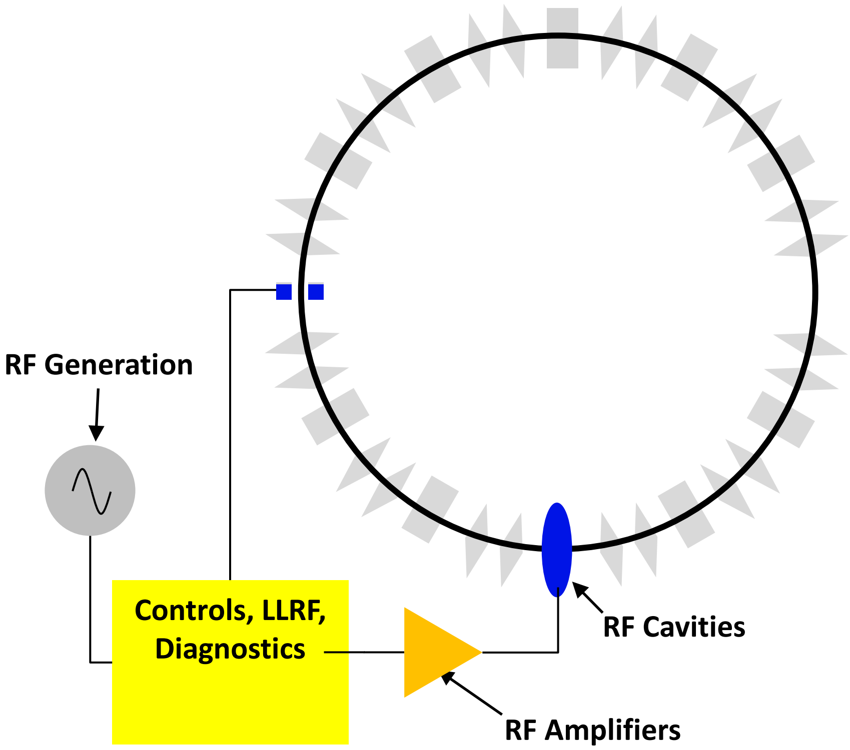
RF Generation

Controls,
LLRF,
Diagnostics

RF Systems in Accelerators

The Circular Accelerator



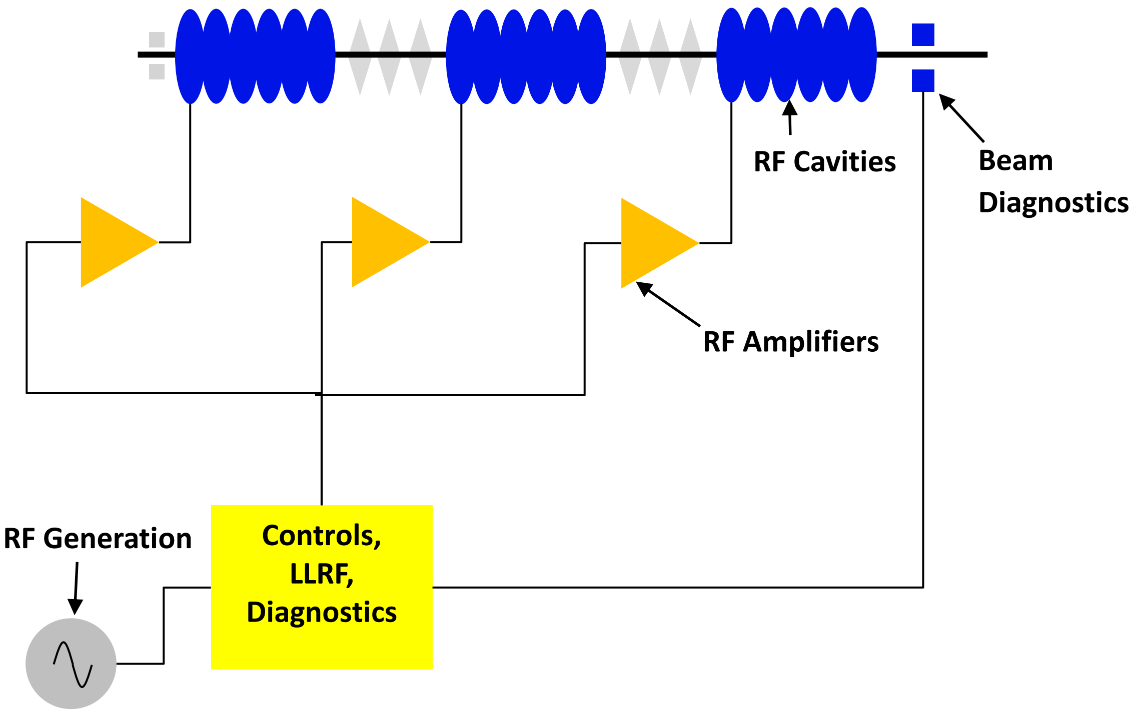
RF Generation

Controls, LLRF, Diagnostics

RF Cavities

RF Amplifiers

The Linear Accelerator



RF Cavities

Beam Diagnostics

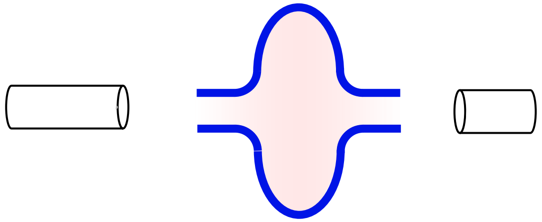
RF Amplifiers

RF Generation

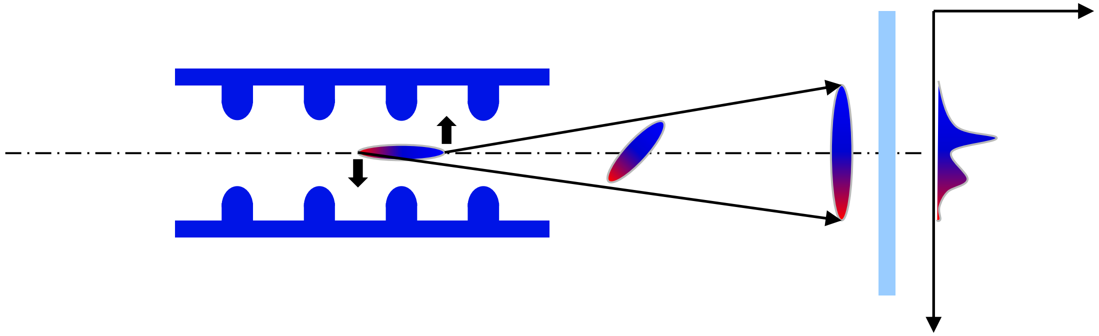
Controls, LLRF, Diagnostics

Applications of RF (1/3)

Particle Acceleration (mentioned in previous slides)
The most direct and obvious use of RF in a particle accelerator is the acceleration of particles. The RF system is what generates the high energies.

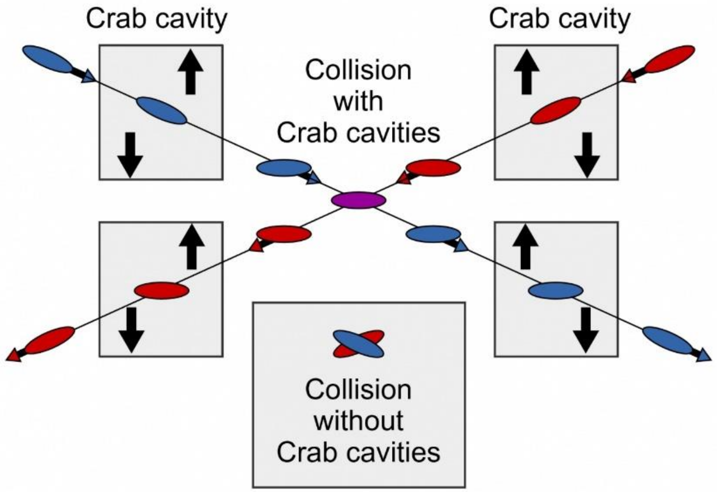


Particle Deflection for diagnostics
One can also accelerate the beam sideways. Depending on where you are on the RF you can kick the beam transversely or rotate the beam such that the head and tail are distributed transversely.

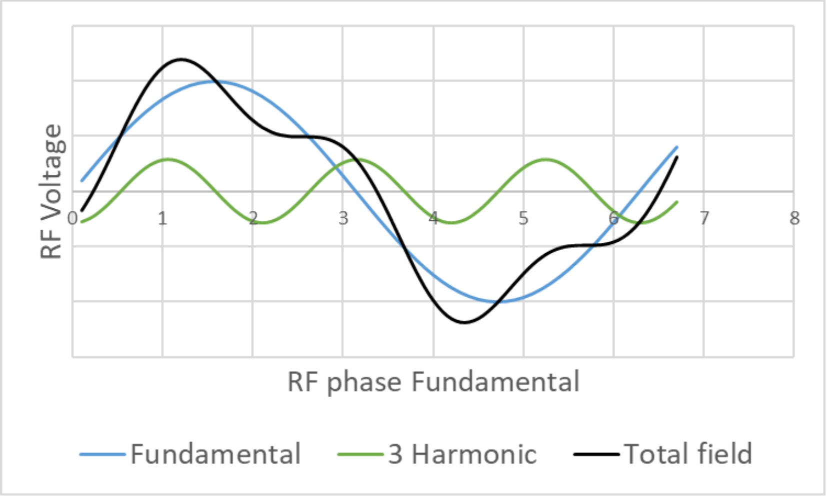


Applications of RF (2/3)

Particle Deflection for collision
Rotating the beam can also be used for colliders where the deflections allows better overlap between the two colliding bunches.

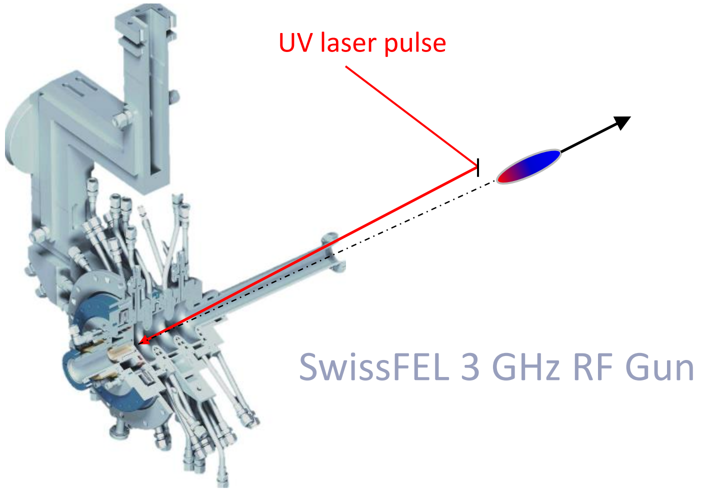


Particle Gymnastics
Manipulating the bunch shape (compression, expansion, linearisation, etc.) is possible through the use of RF. Some beam gymnastics requires a different frequency from the used for acceleration.



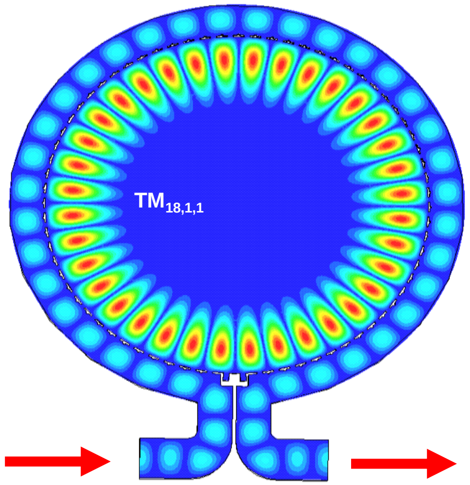
Applications of RF (3/3)

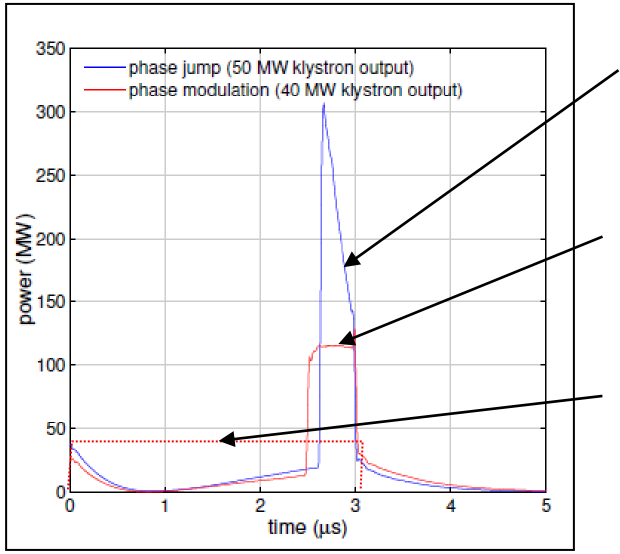
Particle Acceleration after Generation
RF can be used to accelerate the bunch after its generation. If you apply enough electric field you can even generate particles from a surface using the RF!



SwissFEL 3 GHz RF Gun

RF compression
RF components known as a pulse compressor can be used to exchange pulse length for pulse high.





Compressed RF pulse

Compressed RF pulse with phase manipulation

Klystron pulse ~40 MW

RF Cavities

Let’s look more closely at the first application: Acceleration!

Electromagnetic Modes

- Electromagnetic modes can exist in a cavity analogous to harmonics on a guitar string.
- Boundary conditions determine the frequency that can resonate.
- Transverse Magnetic (TM) and Transverse Electric (TE) modes can exist in cylindrical cavities.

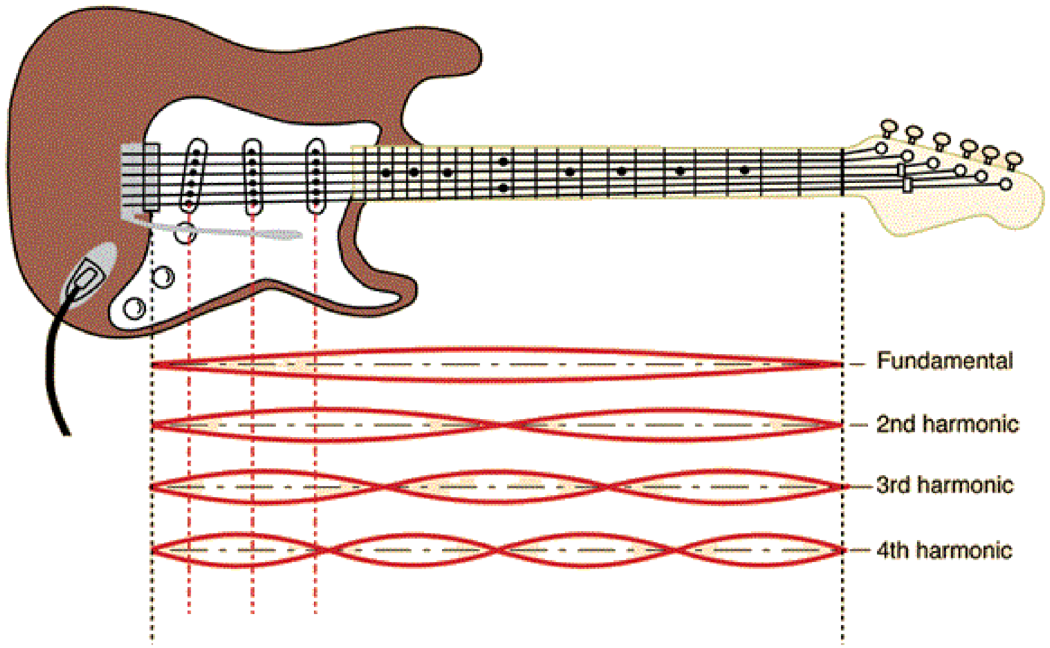
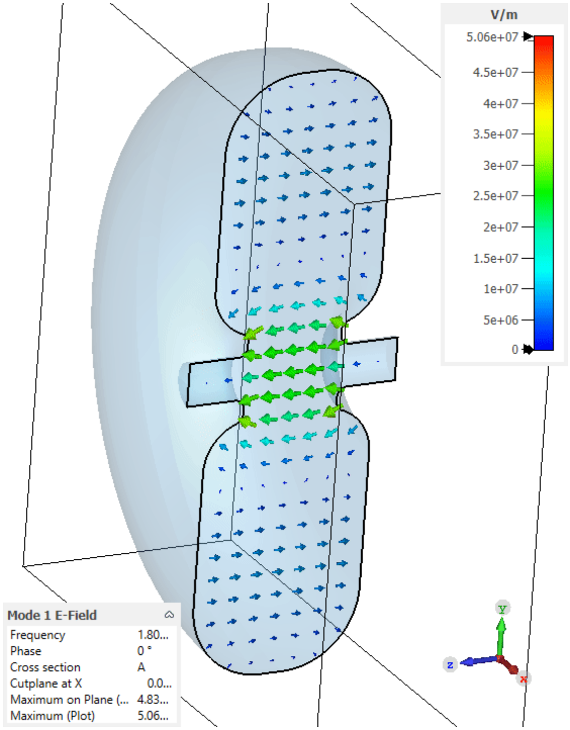
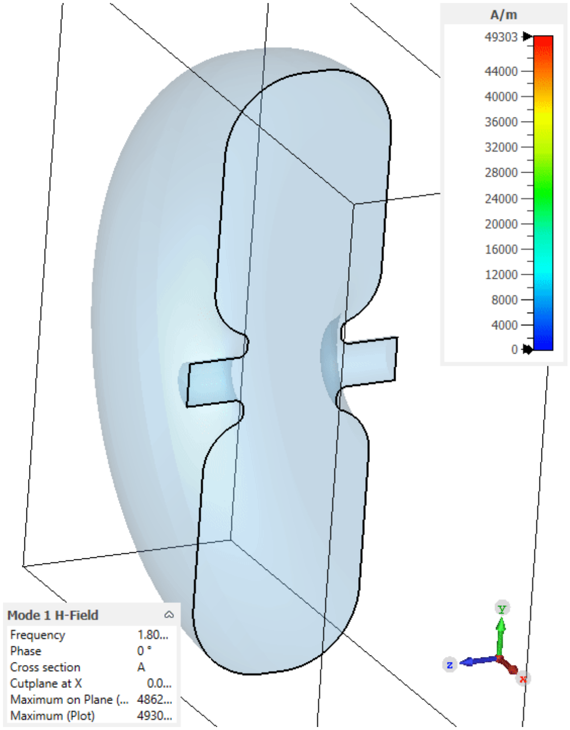


Image from: https://www.fuelrocks.com/how-to-make-your-guitar-string-vibrate-at-its-fundamental-frequency-mode/



Mode 1 E-Field	
Frequency	1.80...
Phase	0 °
Cross section	A
Cutplane at X	0.0...
Maximum on Plane (...	4.83...
Maximum (Plot)	5.06...

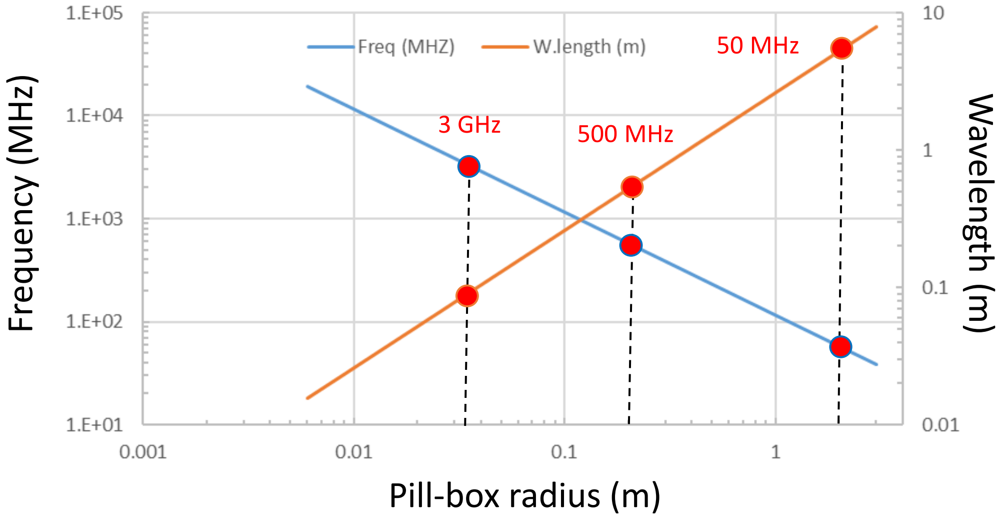


Mode 1 H-Field	
Frequency	1.80...
Phase	0 °
Cross section	A
Cutplane at X	0.0...
Maximum on Plane (...	4862...
Maximum (Plot)	4930...

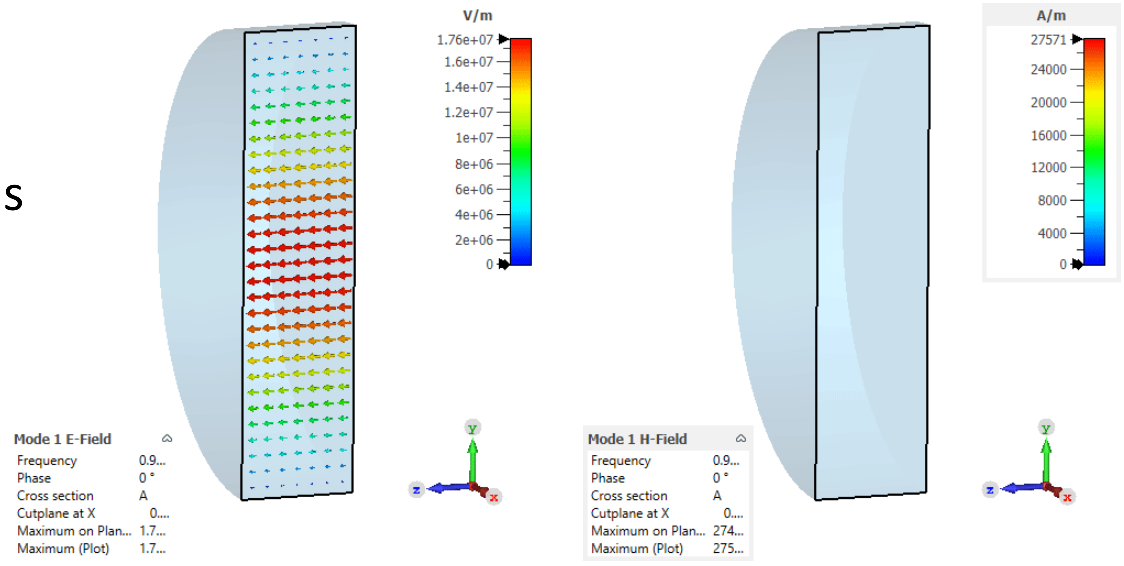
Basic RF Accelerating Structures: The Pill Box Cavity

- In a cylindrical WG TE and TM modes can be sustained.
- Fundamental mode for accelerating structures is the TM_{010}.
- This mode is wonderful for acceleration (see right). This mode's frequency is given as:

$$f_o = \frac{2.40483\, c}{2\pi a}$$



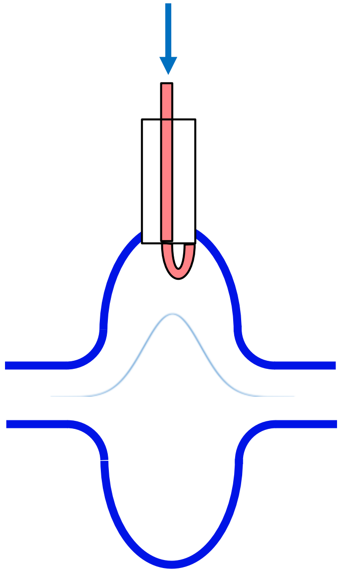
The Pill Box Cavity



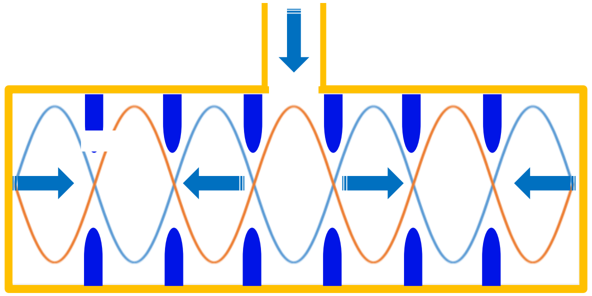
The higher the frequency, the tighter are the mechanical tolerances

More Realistic Types of Accelerating Structures

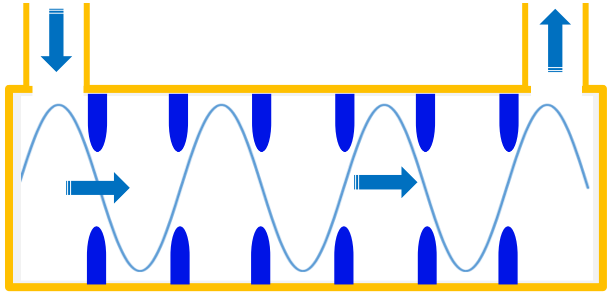
We need apertures for the beam and to power the structure



Standing wave
Elliptical shape



Standing wave
Multi Cells

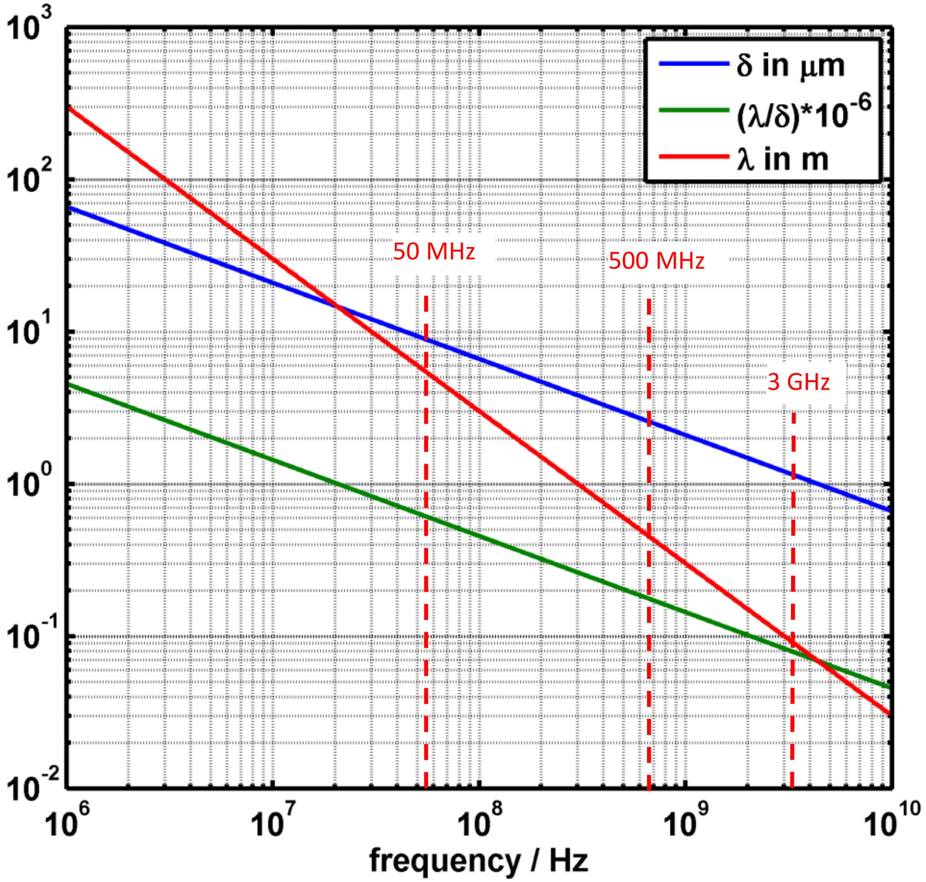


Traveling wave
Multi Cells

Constraints: The longitudinal size of the cells and spacing musts be adjusted to the transit time of the particle bunches to keep the synchronism with the RF

Typical Power Related Parameters of RF cavities

The magnetic field H tangential to the surfaces induce a current $\vec{J}_A = \vec{n} \times \vec{H}$ in the skin depth δ



$$\delta = \sqrt{\frac{\rho}{\pi f \mu_r \mu_0}}$$

ρ_{copper} = 0.017 Ω.mm²/mm resistivity
$\mu_0 = 4\pi \cdot 10^{-7}$ A/N² permeability constant
μ_r = 1 (in Vacuum) relative permeability

$R_s = \frac{\rho}{\delta} \propto \sqrt{\rho}$ is the surface resistance (1 mΩ at 1 GHz)

$P_{loss} = \iint_{wall} R_s \, |H_t|^2 \, dA$ is the total power loss on the cavity wall

$Q_0 = \frac{\omega_0 W}{P_{loss}} = \frac{f_0 2\pi W}{P_{loss}}$ defines the (unloaded) Quality factor of the cavity typically between 15000-50000 for copper cavities.

Remind $\omega = 2\pi f$ is called angular frequency.

Where $W = \iiint \frac{\varepsilon}{2}|\vec{E}|^2 + \frac{\mu}{2}|\vec{B}|^2 dV$ is the energy stored in the cavity

Reprint: Meinke, H. and Gundlach, F. W.,*Taschenbuch der Hochfrequenztechnik*, Dritte Auflage, Springer-Verlag, Berlin (1968)

Some basic parameters you may face discussing with the RF designer

Coupling factor from an external power source $\beta = \frac{P_{ext}}{P_{loss}}$

β=1 matched to the wall losses (no Beam) $\Rightarrow$ ext. source just compensating the losses

$Q_{ext} = \frac{\omega_0 W}{P_{ext}} = \frac{Q_0}{\beta}$ (P_{ext} can be alternatively interpreted as the losses from the coupler when the RF source is turned off)

With external source the total quality factor becomes $Q_L = \frac{Q_0}{1+\beta}$

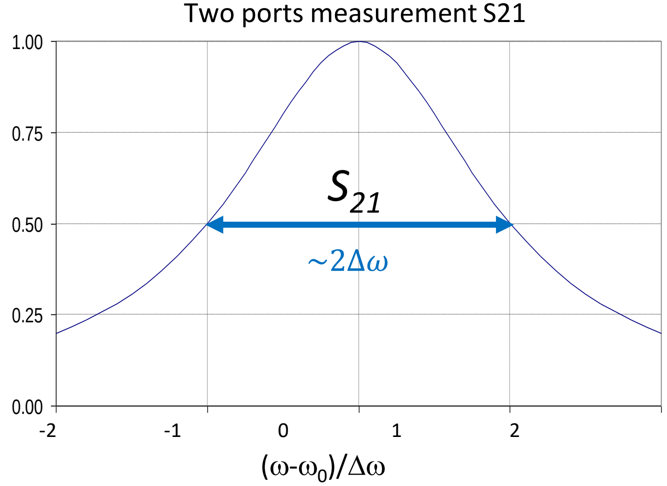
Shunt impedance: $R = \frac{|V_{acc}|^2}{2P_{loss}}$ $\Rightarrow$ Optimized by the RF designer to minimize the power requirements

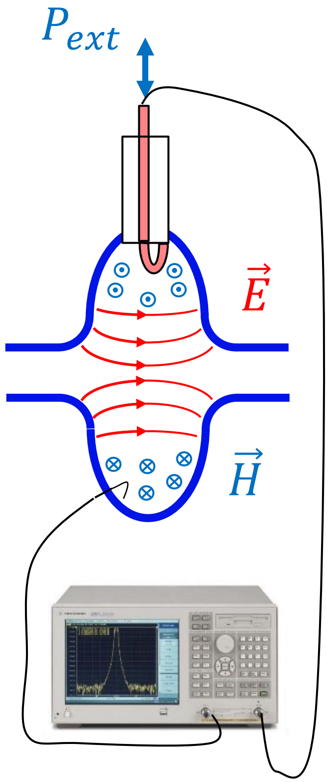
R «upon» Q: $\frac{R}{Q} = \frac{|V_{acc}|^2}{2\omega W_0}$

Figure of merit of the cavity shape (material independent) as high as possible

Cavity Bandwidth: $\Delta\omega = \frac{\omega_0}{2Q_L}$

Cavity filling time: $\tau_L = \frac{1}{\Delta\omega}$


Two ports measurement S21



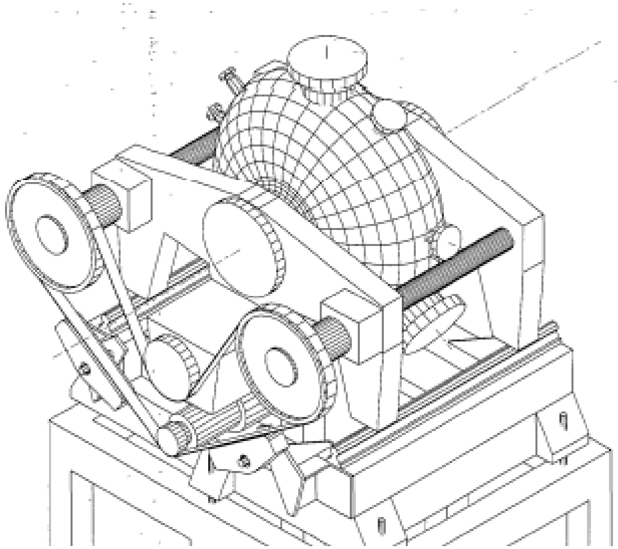
How to adjust the Resonant frequency

Permanent adjustment

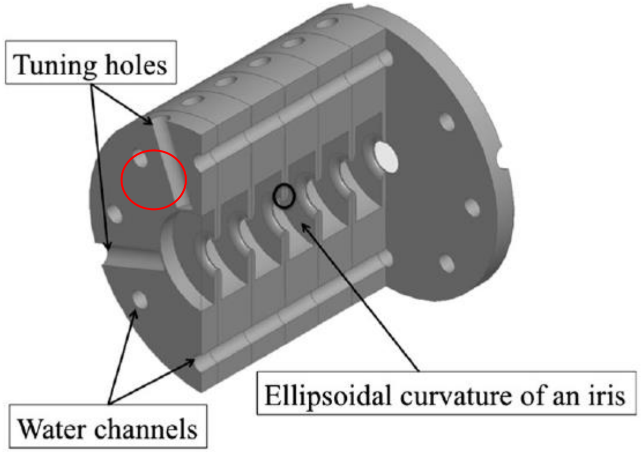
- Inelastic deformation of the cavity wall after manufacture
- Or, very precise manufacturing

Dynamic adjustment:

- deformation of the cavity wall in elastic regime (fast)
- Motorized plunger (fast)
- Temperature variation (slow)



Example motorized tuning SLS 500 MHz cavity



Example dimple tuning opening in a C-Band TW structure

Radius (m)	Res. Freq. (MHZ)	Δf with + 1°C (kHz)
0.0382	3000	-51
0.23	500	-8.52
2.2	52.2	-0.89

Example Pillbox resonant frequency variation for + 1 °C

Tendencies for frequency tune methods

High Freq. :	fix tune & temperature
Low freq. :	elastic deformation & plungers

Oxygen Free High Conductivity (OFHC) Copper material of choice for RF structures

PSI Specifications for SwissFEL:

The impurities shall be in accordance with ISO 431 except:

Element	% in Cu-OFE
Copper	99.99
Cadmium max.	0.0001
Phosphorus max.	0.0003
Sulphur max.	0.0018
Zinc max.	0.0001
Mercury max.	0.0001
Lead max.	0.001
Selenium max.	0.001
Tellurium max.	0.001
Bismuth max.	0.001
Arsenic Antimony Bismuth Selenium Tellurium Tin Manganese	Total of these seven elements not to exceed 40 ppm

Reasons

- Relatively easy to machine & with roughness at nm level
- Low Secondary Emission coefficient to reduce multipacting & breakdown risks

Suitable for high RF accelerating gradients

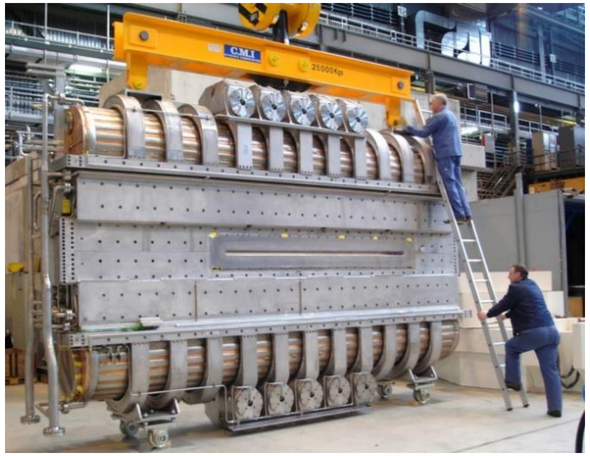
- Excellent electrical (and thermal) conductivity ⇒ minimize power dissipation
- Easy to braze/weld
- Good availability and reasonable cost

Copper must be 3D forged

- To increase mechanical uniformity, hardness and strength of the material
- Minimize number and size of defects, cracks and empty inclusions that could lead to craters or virtual leaks in vacuum after machining.

The Spectrum of RF (Cavities)

50 MHz ⟷ **12 GHz**


50 MHz Ring Cyclotron

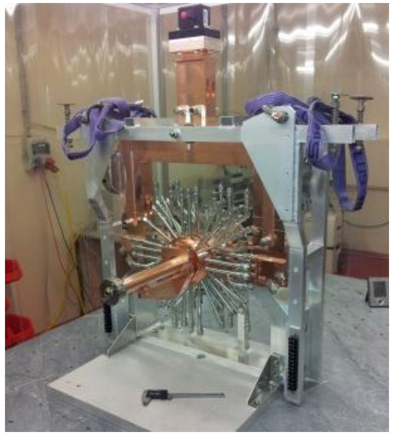

50 MHz Inj. II


150 MHz buncher

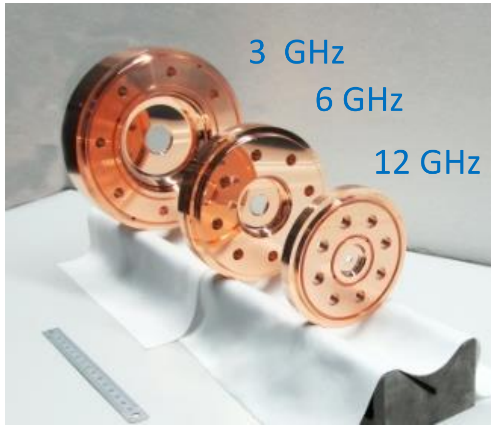

500 MHz Super-buncher


1.5 GHz 2 cell LEG

3 GHz RF-Gun
SwissFEL

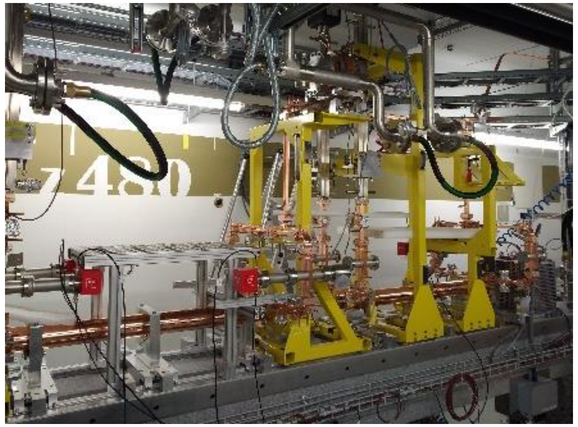


Disks for TW-struct.

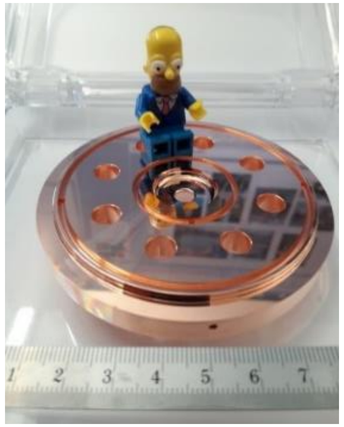


6 GHz TW-SwissFEL
After brazing at PSI

12 GHz Deflector
Assembly In SwissFEL



12 GHz Disc



Resonant cavities: few important information to be kept

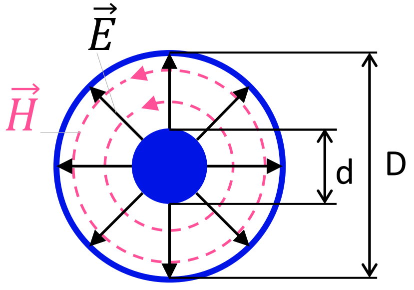
- The resonant frequency depends on the dimensions of the cavity. Active deformations are used to tune the frequency but unwanted mechanical deformations (effect of vacuum, thermal excursions, stress) have the same effect
- The highest the frequency the most sensitive is the RF structure to manufacturing tolerances or deformations $\Rightarrow$ to match the design resonant frequency within the allowed tuning range
- The power losses can be minimized with a “smart” RF design. Materials are of course important (OFHC copper). Thermal analysis starting from the simulated RF losses helps optimizing the design
- The highest the unloaded quality factors Q_0 the lower are the wall losses, and narrow the bandwidths of the structure. The final quality factor Q_L depends on the coupling factor to the source.
- The near collaboration between RF and mechanical engineer in an iterative process is essential to rapidly converge to a feasible and (reasonably) optimized design. Compromises between RF performances and mechanical feasibility can’t be avoided.

RF Transmission and (a couple of words on coupling).

Transmission line: Coaxial

Very common transmission line for low power signals

$$Z \approx \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{D}{d}\right) \quad [\Omega]$$

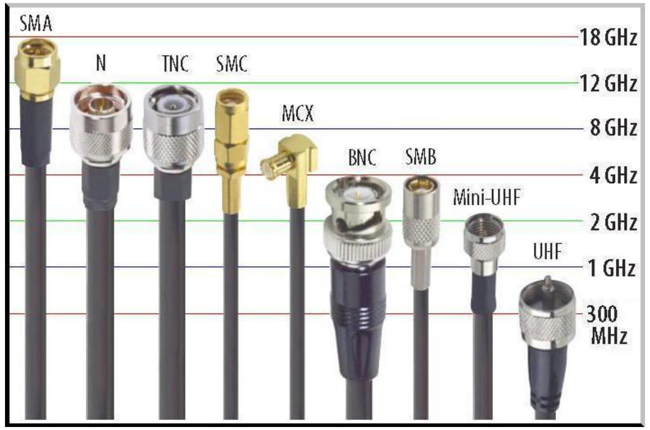


TEM

Impedance of the line

Z = 50 Ω ⇔ *D/d=2.302*

Z = 75 Ω ⇔ *D/d=3.493*



See for example:
https://www.zseries.in/electronics%20lab/cables/coaxial/#.YGrbtu2xVjE

No cutoff frequency for TEM mode, but for high frequencies and large dimensions other modes (with cut off are present) => limitation for high power @ high frequency

For high power **rigid** coaxial lines ⇒ difficulty: cooling of central conductor

Commercial rigid coax. from Spinner
https://www.spinner-group.com

Some Rigid coaxial standards (50 Ω)

Standard designation Size in inch	D (mm)	d (mm)
1-5/8"	38.79	16.87
3-1/8"	76.89	33.40
4-1/16"	99.95	43.46
6-1/8"	151.92	66.04
9-3/16"	228.60	99.31

More on coax. See for example: https://cds.cern.ch/record/865921/files/p210.pdf

Transmission line: Waveguides

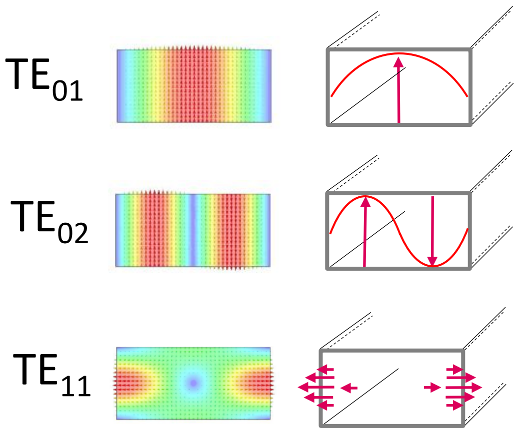
Rectangular WG basics

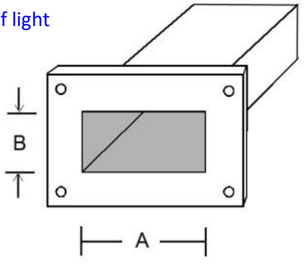
For High Power, high frequency and narrow-band applications rectangular Waveguide are commonly used to transport the RF power from the source to the RF structure.

- A WG allow the propagation of different modes with different cutoff frequencies (f_c).
- The size is selected depending on the chosen RF frequency to keep one single mode propagating (TE_{01})

$$f_c(TE_{01}) = \frac{c}{2A}$$

With c being the speed of light



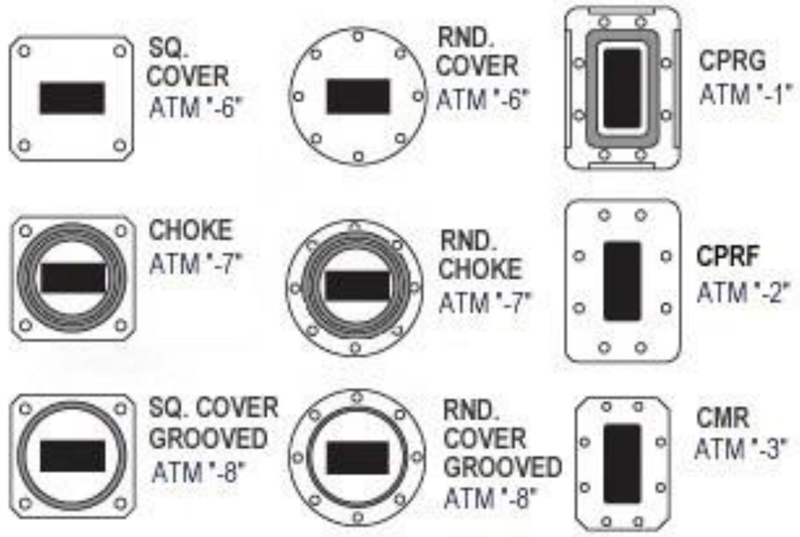


WR Designation	Standard Freq Range (GHz)	Inside dimension		Cutoff TE10 (GHz)	Cutoff Next mode (GHZ)	
		A (mm)	**B (mm)**			
WR340	2.20 - 3.30	86.360	43.180	1.74	3.47	
WR284	2.60 - 3.95	72.136	34.036	2.08	4.16	S-Band
WR229	3.30 - 4.90	58.166	29.210	2.58	5.15	
WR187	3.95 - 5.85	47.549	22.149	3.15	6.30	C-Band
WR159	4.90 - 7.05	40.386	20.193	3.71	7.42	
WR137	5.85 - 8.20	34.849	15.799	4.30	8.60	
WR112	7.05 - 10.00	28.499	12.624	5.26	10.52	
WR90	8.2 - 12.4	22.860	10.160	6.56	13.11	X-Band
WR75	10.0 - 15.0	19.050	9.525	7.87	15.74	
WR62	12.4 - 18.0	15.799	7.899	9.49	18.98	

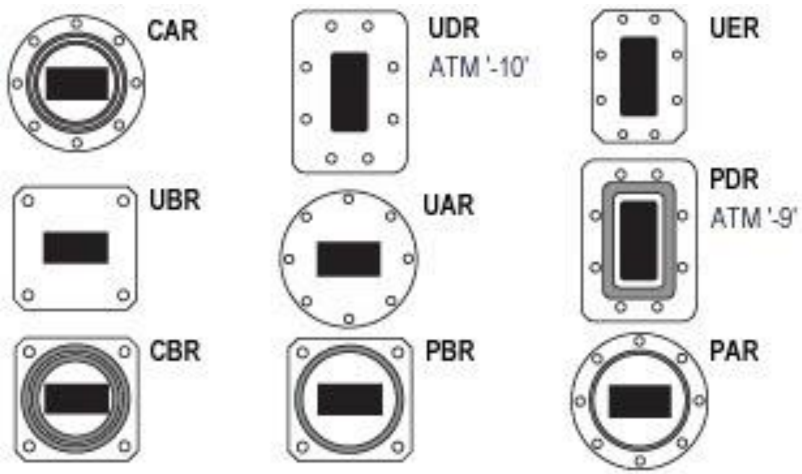
Standard WG (Industrial references are easily available on the Internet)

Transmission line: Waveguides

WG Flanges



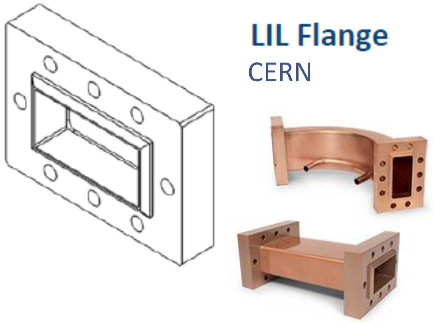
North American EIA Standard Flanges



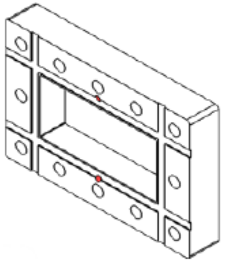
European IEC Standard Flanges

Examples of WR284 Flanges developed by acc. institutes

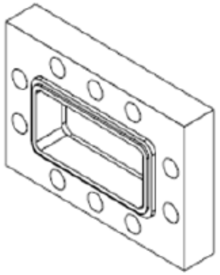
- **High power**
- **Vacuum compatible**
- **Excellent electrical contacts**



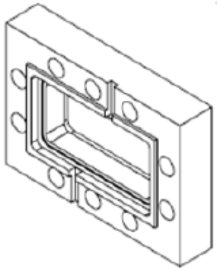
LIL Flange
CERN



DESY Flange



Male SLAC



Female SLAC

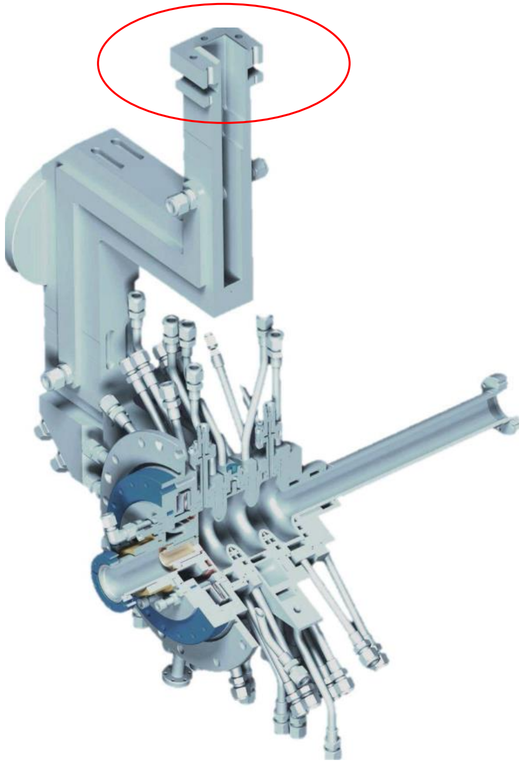
Reprint standard flanges from: https://www.microwave-link.com/microwave/microwave-waveguide-flange/

Transmission line: Waveguides and Coaxial Lines

Important Takeaways

- Waveguides and Coaxials are the main ways to transport RF between Systems.
- Coaxial is used generally at low power and nearly always for low frequency as waveguides become too large.
- Waveguides are used for mid to high power, high frequency applications.
- Rigid coax lines are necessary to handle high power. For RF frequencies higher than ~500 MHz rigid coax are not suited for high power (>100 kW)
- Waveguide are standardized industrial products, the operating frequency determines the WG dimensions
- The RF and mechanical design of the interface with the RF structure must be matched to the required WG standard
- Waveguide can be operated in Vacuum, on air or with insulating gases as Sulfur hexafluoride (SF6) => Flange quality is essential
- No Cutoff frequency for the TEM Mode (Coaxial). Signals can propagate from DC to high frequencies. Waveguide have a finite bandwidth.
- High power operation in vacuum requires very clean surfaces. An advantage if compatible with 120-150 °C bake-out
- The best waveguide flanges were designed by acc. Institutes and commercialized => good electrical contact and vacuum compatibility

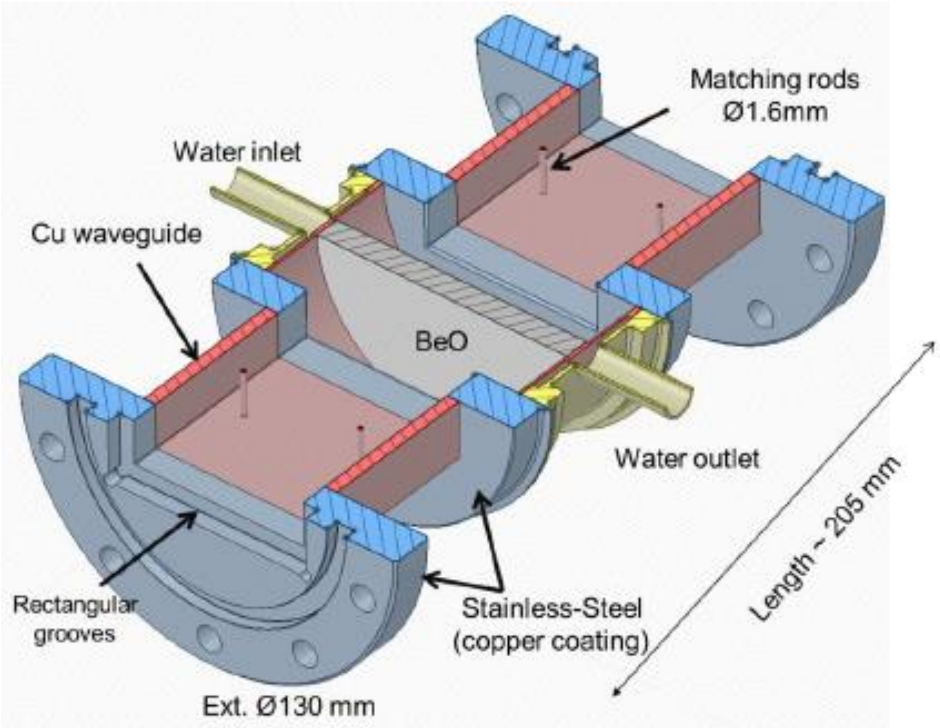
Interface to WR284 with LIL flange



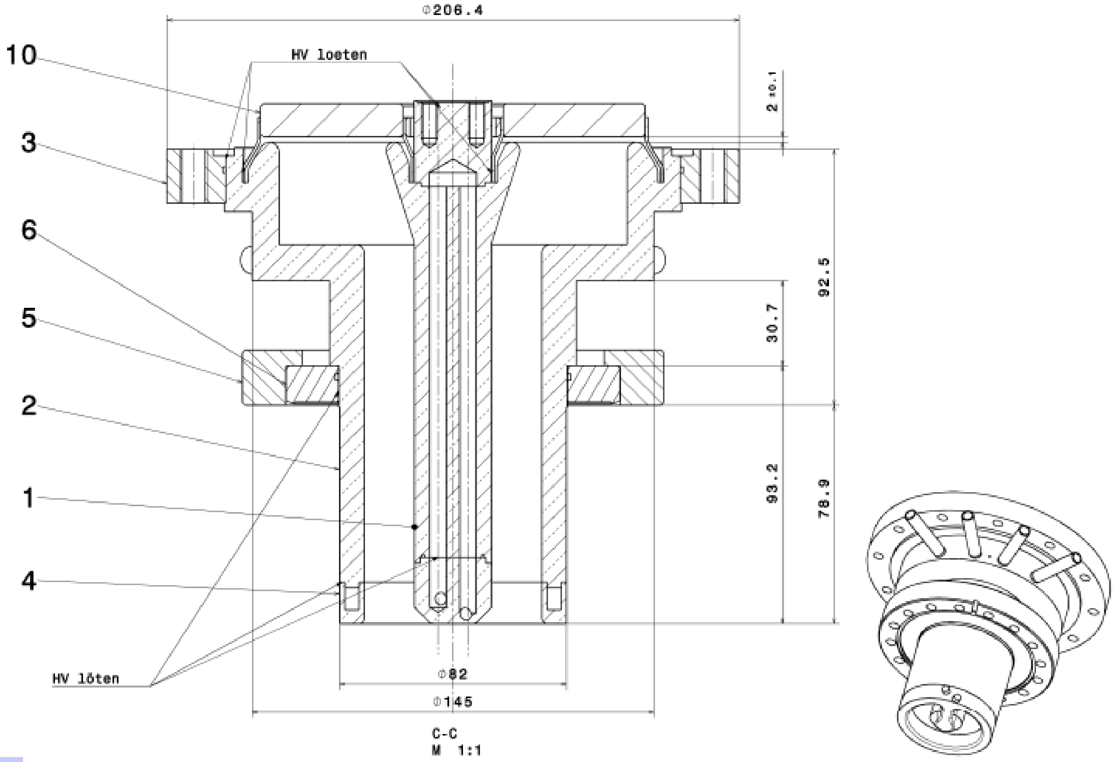
SwissFEL RF-Gun

Couplers and Windows: Examples

Wave guide window *



500 MHz Coaxial coupler SLS



A metallic thin coating on the vacuum side of the ceramic is commonly used to suppress multipactor and avoid accumulation of charges ⇒ prevents discharges

* *Reprint window from: Julien Hillairet, et al.. Design and Tests of 500kW RF Windows for the ITER LHCD System. Fusion Engineering and Design, Elsevier, 2015*

Thermal Analysis

Thermal analysis & RF design

For high power applications (large wall losses) a detailed thermal analysis is required to refine both RF and mechanical design in order to:

- avoid hot spots & deformations, detuning of the structures) and damages
- optimize cooling channels

Multi-physics simulations are therefore required (for example using ANSYS*)

Example SwissFEL RF-Gun **

100 MV/m peak RF gradient

14 MW; 100 Hz; 3 µs RF pulse

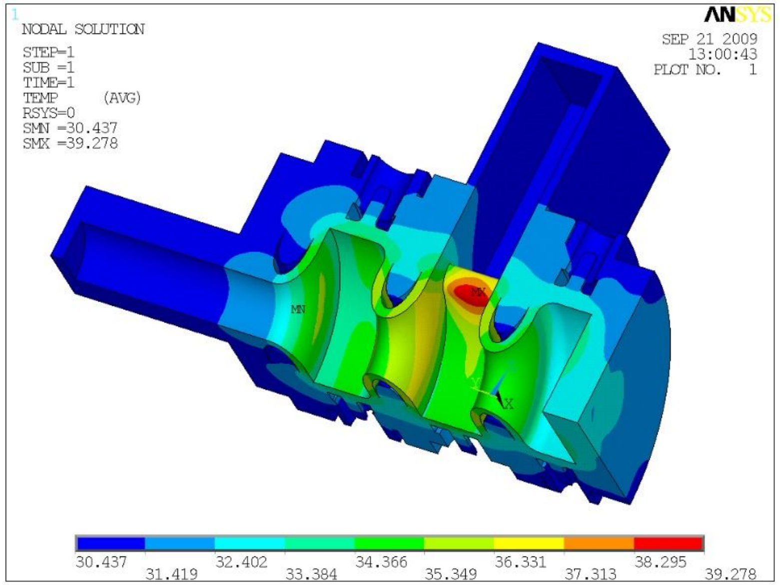
β=2 for fast filling

3.3 kW average power dissipated

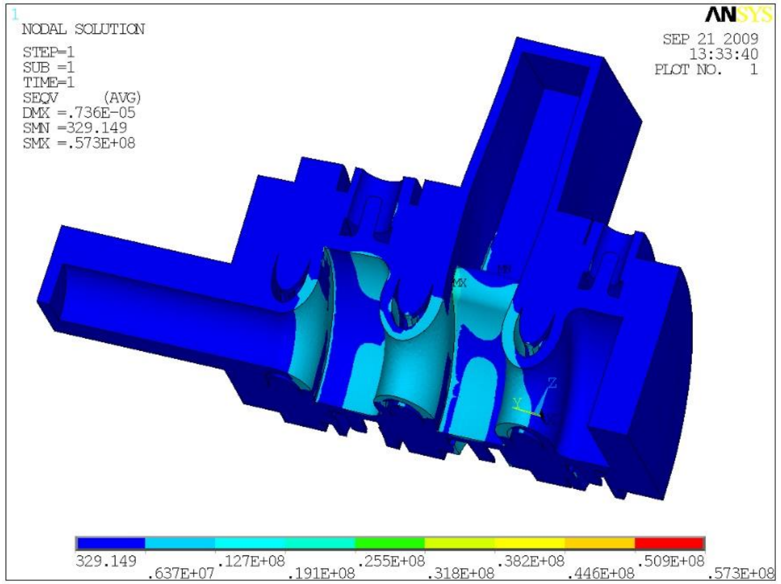
αk: 7500 W/m2K for Water inlet 30°C

Always very important!
Near collaboration between RF and mechanical engineer

Temperature distribution*



Mechanical stresses*



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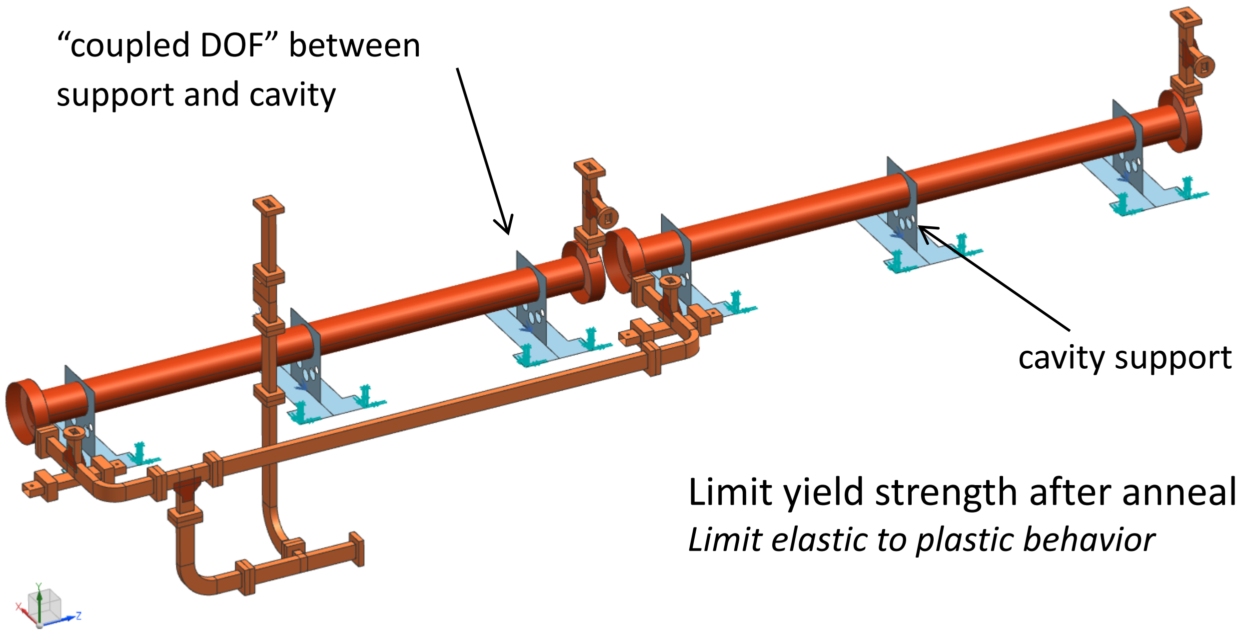
*https://www.ansys.com/

** For more details on the RF-Gun design: J.-Y. Raguin et al, Proceedings of LINAC2012, Tel-Aviv, Israel

Stress analysis SwissFEL C-Band module

FEA boundary conditions for stress estimation due to thermal eleongations

- All cavity supports translational+rotational fixed in XYZ direction (3 point bearing)
- Each cavity is supported by 1 fixation in XYZ + 2 fixations in XY (with „Coupled DOF“)
- All structures have temperatures of **T_{initial} = 25°C** and **$T_{\text{thermal load}}$ = 50°C** (operation 30 °C)



“coupled DOF” between support and cavity

cavity support

Limit yield strength after annealing ~40 MPa

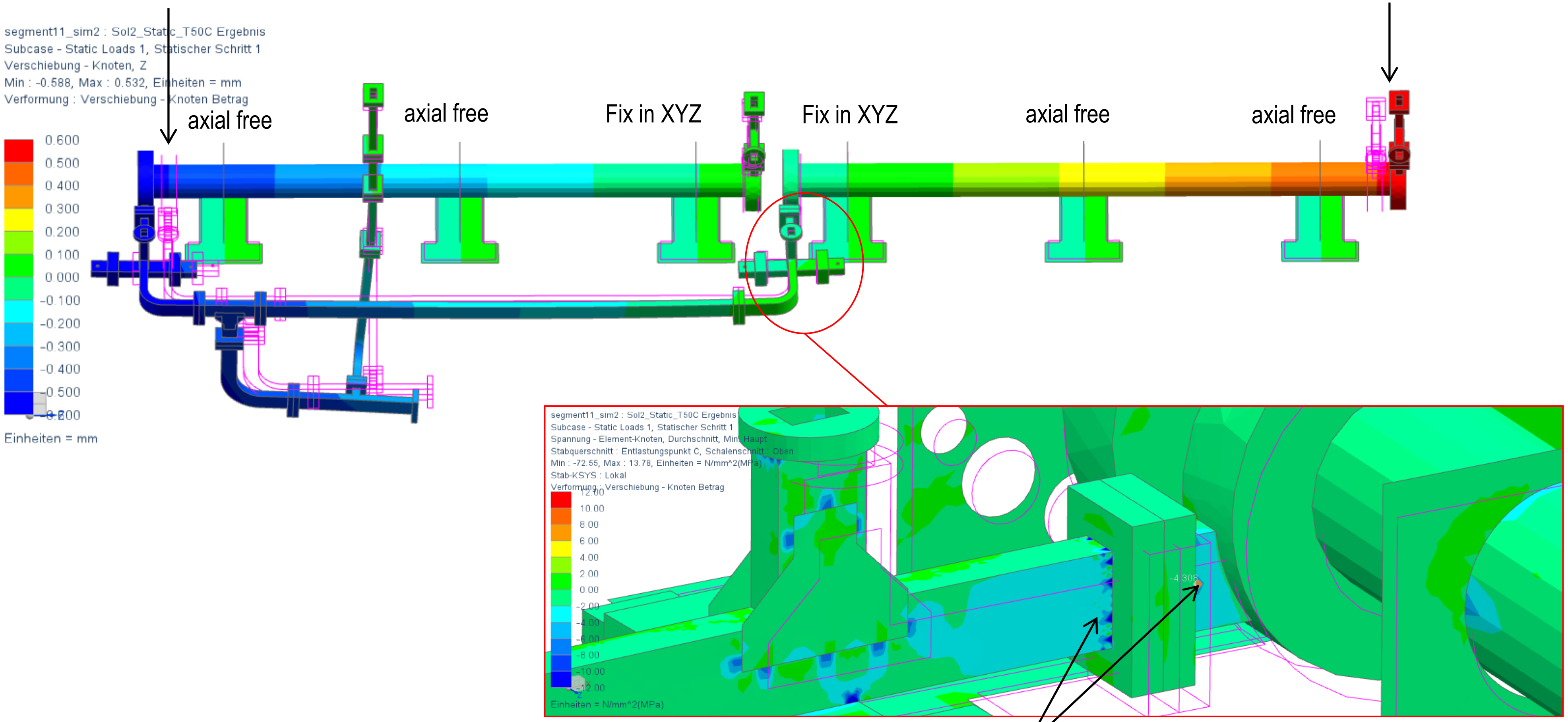
Limit elastic to plastic behavior

Stress analysis SwissFEL C-Band module

Displacements

$\Delta u_z \approx$ - 0.5 mm

$\Delta u_z \approx$ + 0.5 mm



```
segment11_sim2 : Sol2_Static_T50C Ergebnis
Subcase - Static Loads 1, Statischer Schritt 1
Verschiebung - Knoten, Z
Min : -0.588, Max : 0.532, Einheiten = mm
Verformung : Verschiebung - Knoten Betrag
```

```
segment11_sim2 : Sol2_Static_T50C Ergebnis
Subcase - Static Loads 1, Statischer Schritt 1
Spannung - Element-Knoten, Durchschnitt, Min. Haupt
Stabquerschnitt : Entlastungspunkt C, Schalenschnitt : Oben
Min : -72.55, Max : 13.78, Einheiten = N/mm^2(MPa)
Stab-KSYS : Lokal
Verformung : Verschiebung - Knoten Betrag
```

$\sigma_{max,\ bending} \approx$ 4.5 MPa

Ultrahigh Precision Machining

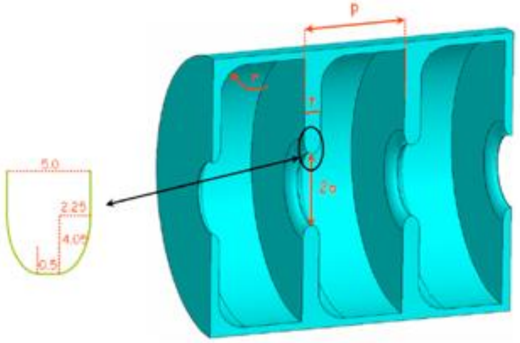
‘Typical’ Ultrahigh Precision: SwissFEL Injector S-band structu

PSI RF design

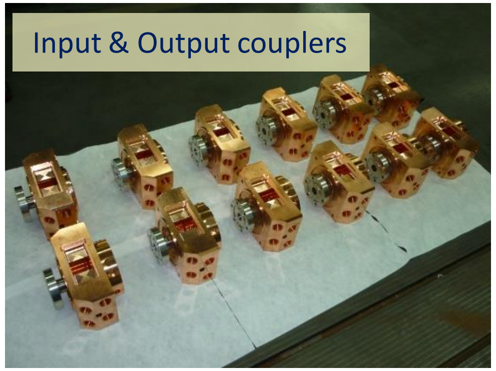
- Constant gradient + constant losses
- Dual feed racetrack couplers

Classical technology with cell to cell dimple tuning after brazing

Manufacturing incl. machining, brazing & tuning by Research Instruments (2008-09)



Geometry of 3 regular cells
(120 regular cells + 2 coupling cells)



Parameter	Value
Operating frequency	2998.8 MHz
Phase advance per cell	$2\pi/3$
Total number of cells	122
Accelerating gradient	20 MV/m
Maximum pulse repetition frequency	100 Hz
Operating temperature	30°C

	v_g/c (%)	r/Q (kΩ/m)	Q
First cell	2.91	3.85	11688
Middle cell	1.87	4.23	11640
Last cell	0.79	4.81	11589

Coupler cell with waveguide

New frontiers with Ultra High Precision machining

This make sense for structures at high frequencies operating at fixe tune

The idea is to manufacture on tune => i.e. the exact dimensions of the structures as simulated by the RF engineers

Prerequisite

- Very high level of confidence in the RF design simulation tools (HFSS*, CST**, …).
- Relay on UHP machining with tolerances in the µm range (qualify commercial partner for large series)
- In house expertise for the mechanical design and production process (need time to be established)
- In house expertise (and possibly the oven) for the brazing process

Advantages

- Structure ready for use direct after brazing.
- Avoid «long» tuning process with possible contamination of the structure surfaces
- Very low roughness of the surfaces – typically **Ra <15 nm**

} Good for high gradient applications

UHP Machining and Temperatures

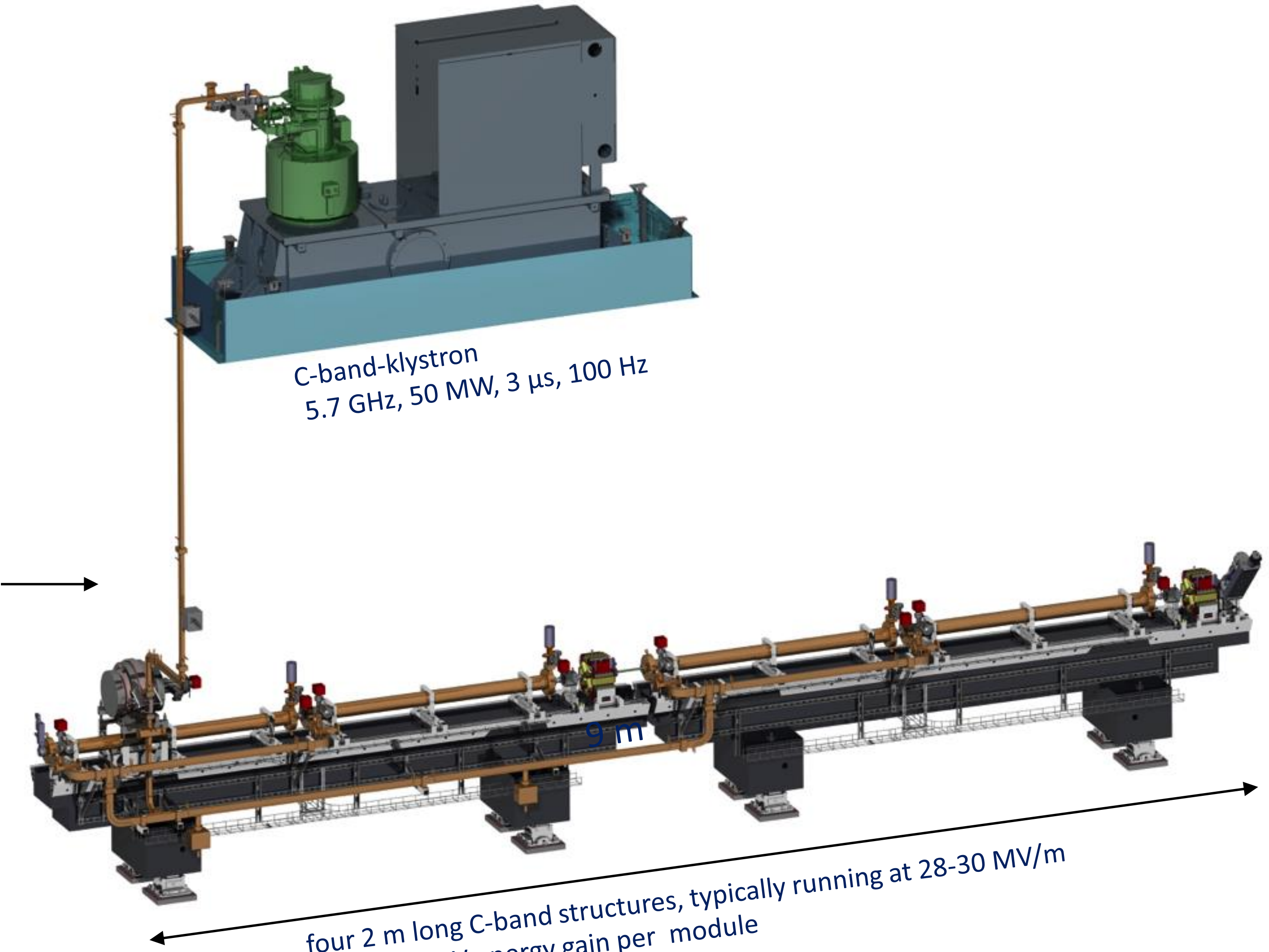
Manufacturing temperature $\neq$ operating temperature of the structure.

The dimensions on the manufacturing drawings must be adapted taking into account:

- The temperature of the UHP workshop environment (temperature stabilized)
- The final operating temperature of the cavity

Seems trivial but remember we want to achieve precisions in few µm range

UHP example: C-band linac modules



C-band-klystron
5.7 GHz, 50 MW, 3 µs, 100 Hz

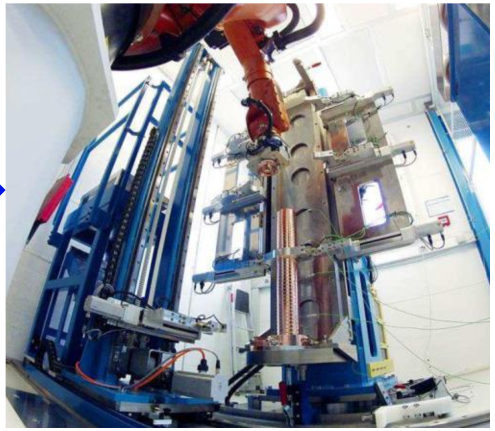
BOC pulse
compressor

four 2 m long C-band structures, typically running at 28-30 MV/m
220-240 MeV energy gain per module

Some production infrastructure

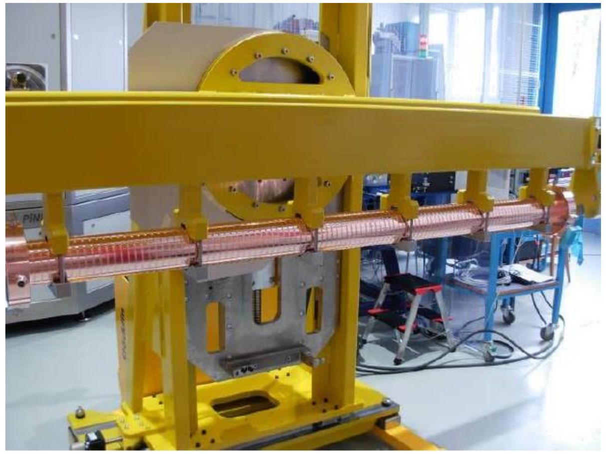
UP-Machine HEMBRUG Slantbed-MIKROTURN-100-CNC. Was used to establish the manufacture procedure at PSI. Later delivered to the industrial partner for mass production

7 sequential cleaning baths with automatized cup handling



Automatized stacking with robot

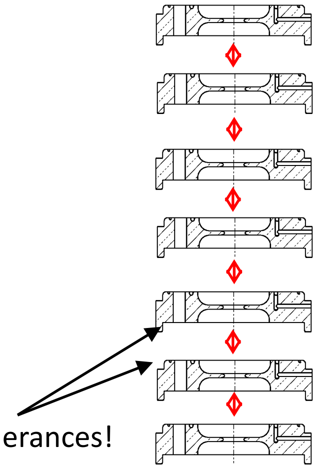
Brazing furnace @ PSI

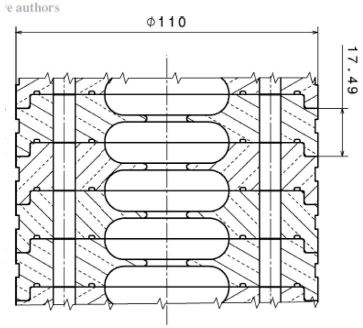


Handling tools

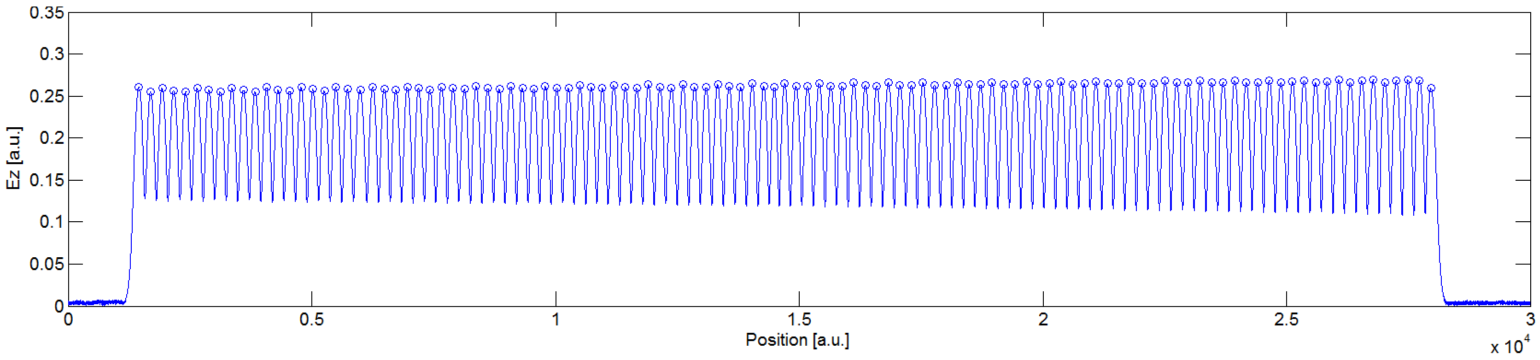
Metrology: Leitz Infinity: accuracy 0.3 mm.

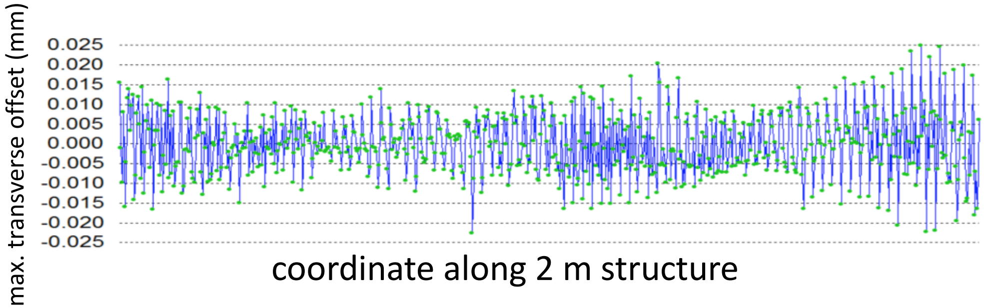
C-band structures: Assembly Procedure

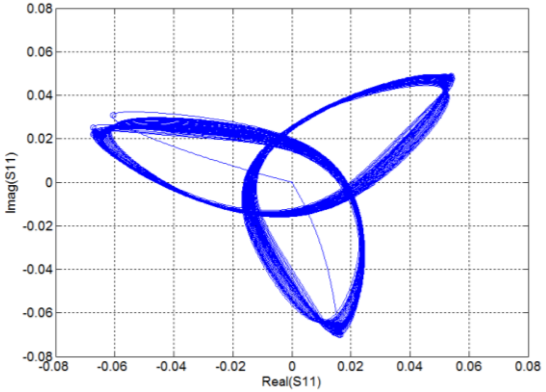

Zero tolerances!



C-band structures: typical straightness







End Result! SwissFEL

Closing Remarks

Closing Remarks

Close collaboration between RF and mechanical engineers is key to efficient work and it is important to work iteratively.

Important to discuss the constraints with the RF engineer to ensure the design remains feasible to build.

It is important to have a mechanical engineer within the RF design group to build the necessary knowledge in the field of RF and ensure efficient communication with the workshop and external suppliers.

The progress with the RF simulation tools and UHP machining allows extreme precise design and fabrication on tune. Prototyping phase to validate the design may be avoided or strongly reduced.

Acknowledgements

I would like to thank those that contributed to these slides

- Dr. Marco Pedrozzi and Dr. Paolo Craievich for their support in developing the slides.
- The RF Section at PSI who design these RF systems that I've shown you today.
- The CAS team for the invitation.

And thanks to you for your attention.

PSI

Any Questions?