PAUL SCHERRER INSTITUT

PSI

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Radio Frequency Systems

“Mini-CAS” course on Mechanical and Materials Engineering for Accelerators, April 9, 2021

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Outlook Presentation

- Introduction
- Overview function RF systems and their generic topology
- Transmissions Lines
- Itroduction to RF (accelerating) structures
- Excursion in the UHP machining for RF

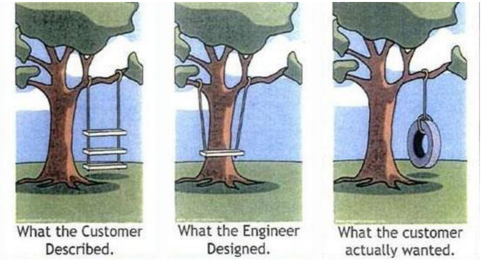
From where I am calling you for the CAS

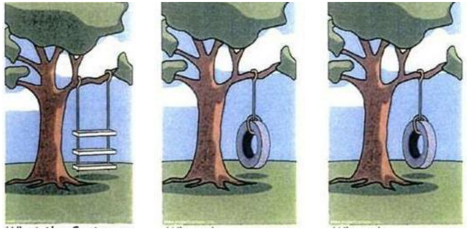
www.psi.ch

← Basel   Germany ↑   Aarau/Bern ↓   Zurich →

Covered by this class

- We will concentrate on classical normal conducting RF systems. We will not cover the particluar 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





What the physicist specified | What the Engineers designed | What the project required

Source image: https://www.webfx.com/blog/web-design/10-tips-for-providing-great-customer-service-to-your-clients/

RF & Engineering: some important aspects to keep in mind

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

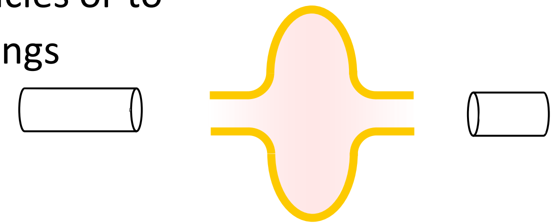
⇒ Significant development and procurement time

Overdesign, reliability and maintenance not always compatible…*

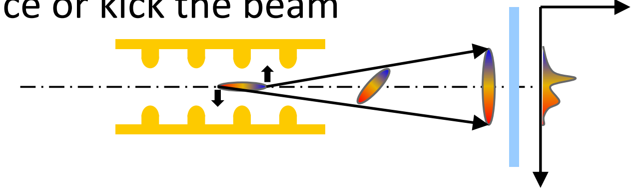
*Image from Web: https://www.hammacher.com/product/eccentrics-wine-steward-eliminator

Function of RF: few quick examples

1. Create a large voltage for the acceleration of charged particles or to compensate the Synchrotron radiation losses in Storage Rings



2. Deflect particle bunches transversally to diagnose the longitudinal phase space or kick the beam



3. Deflect colliding bunches to increase the collision luminosity (Crab cavities: https://home.cern/news/news/accelerators/crab-cavities-colliding-protons-head)

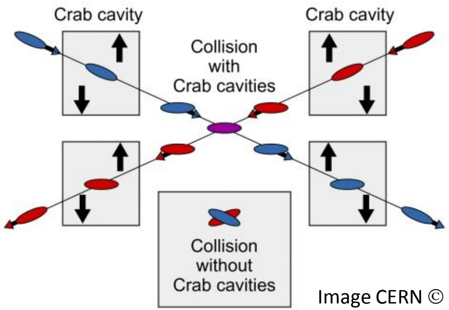
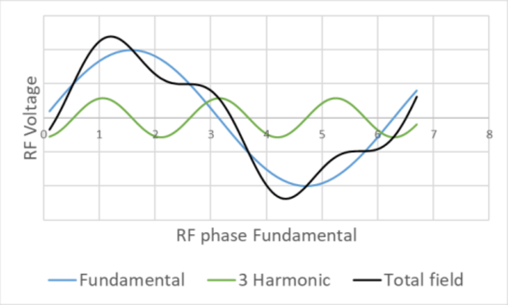


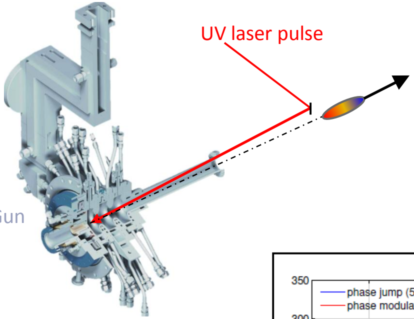
Image CERN ©

Function of RF: few quick examples (cont)

4. RF gymnastic for example for elongating particle bunches in storage rings with the help of Harmonic systems

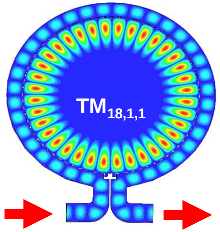


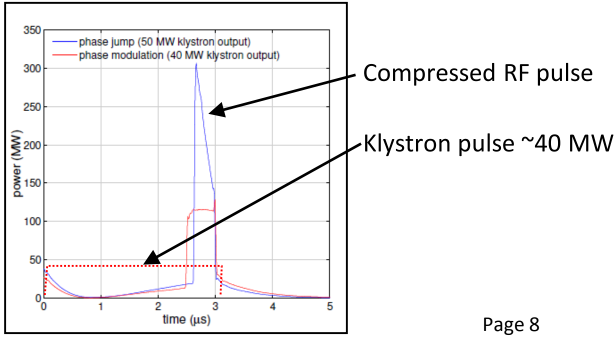
5. Photo-Cathode RF-Gun as high brigthness electron sources typically for FEL facilities



SwissFEL 3 GHz RF Gun

6. Compress RF pulses to achieve higher Peak power from existing pulsed RF surces





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Nomenclature Frequency bands

The CERN Accelerator School

IEEE Standard 521-2002

Standard Radar Frequency Letter-Band Nomenclature

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 Proton & Ion accelerators (HF – S band)

Typical for Electron accelerators (UHF – X band)

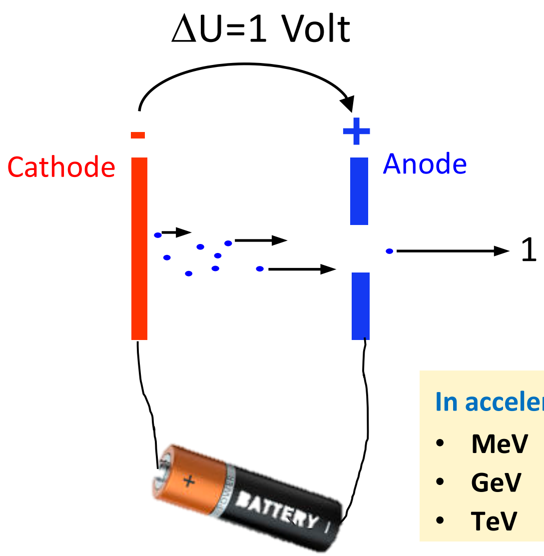
Example S-Band in Linacs: US frequency **2.856 GHz** - European frequency **2.998 GHz** (different standards)

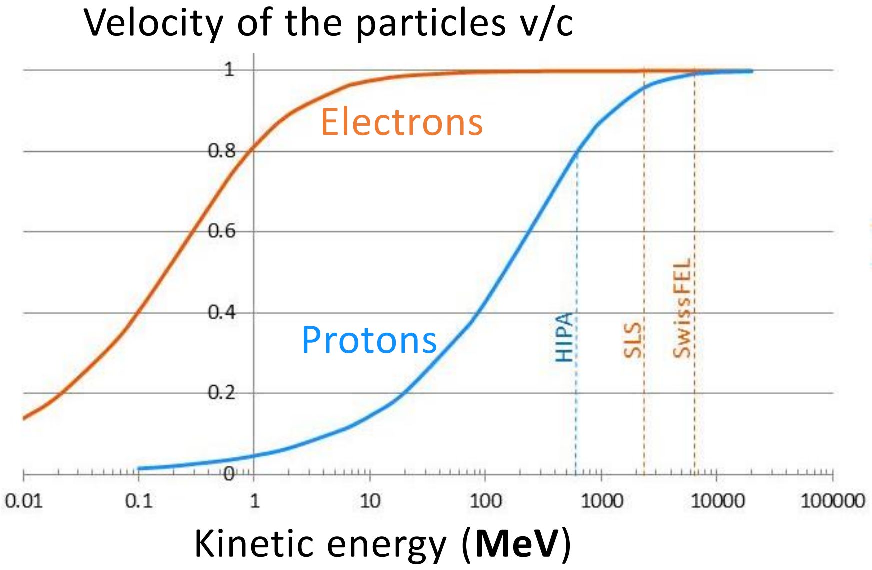
Small parenthesis: definition of eV
(used in next slides)

Just a practical units for particle energy

1 eV = 1.602×10^{-19} J

Refer to the electron/proton charge





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

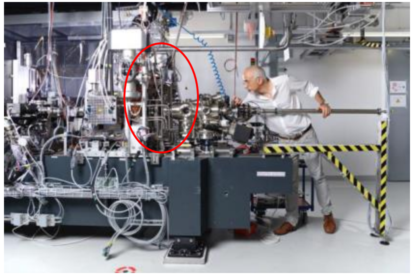
In accelerators we are typically dealing with:

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

RF and DC acceleration

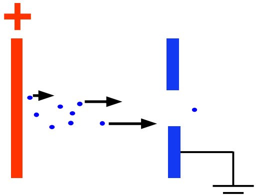
- RF allow reaching higher energy gains than DC Configurations with a more compact topology
- The fields are confined inside the RF structure => The RF structure is grounded

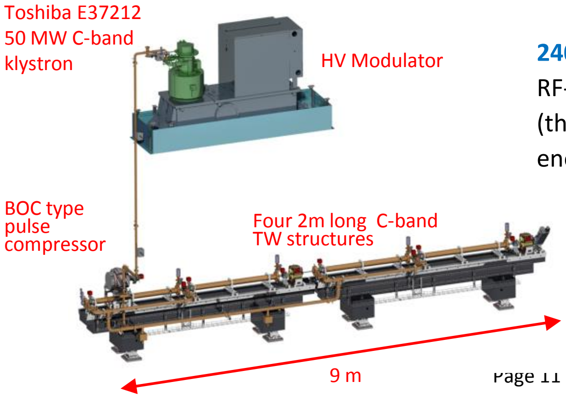
7.1 MeV SwissFEL RF-Gun
Peak gradient 100 MV/m



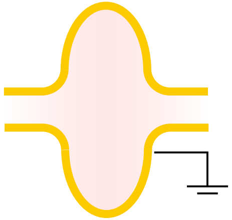
1 MV Cockcroft-Walton: the first stage in the High Intensity Proton Accelerator (HIPA) facility

HV Housing of the ~1 MeV Proton source



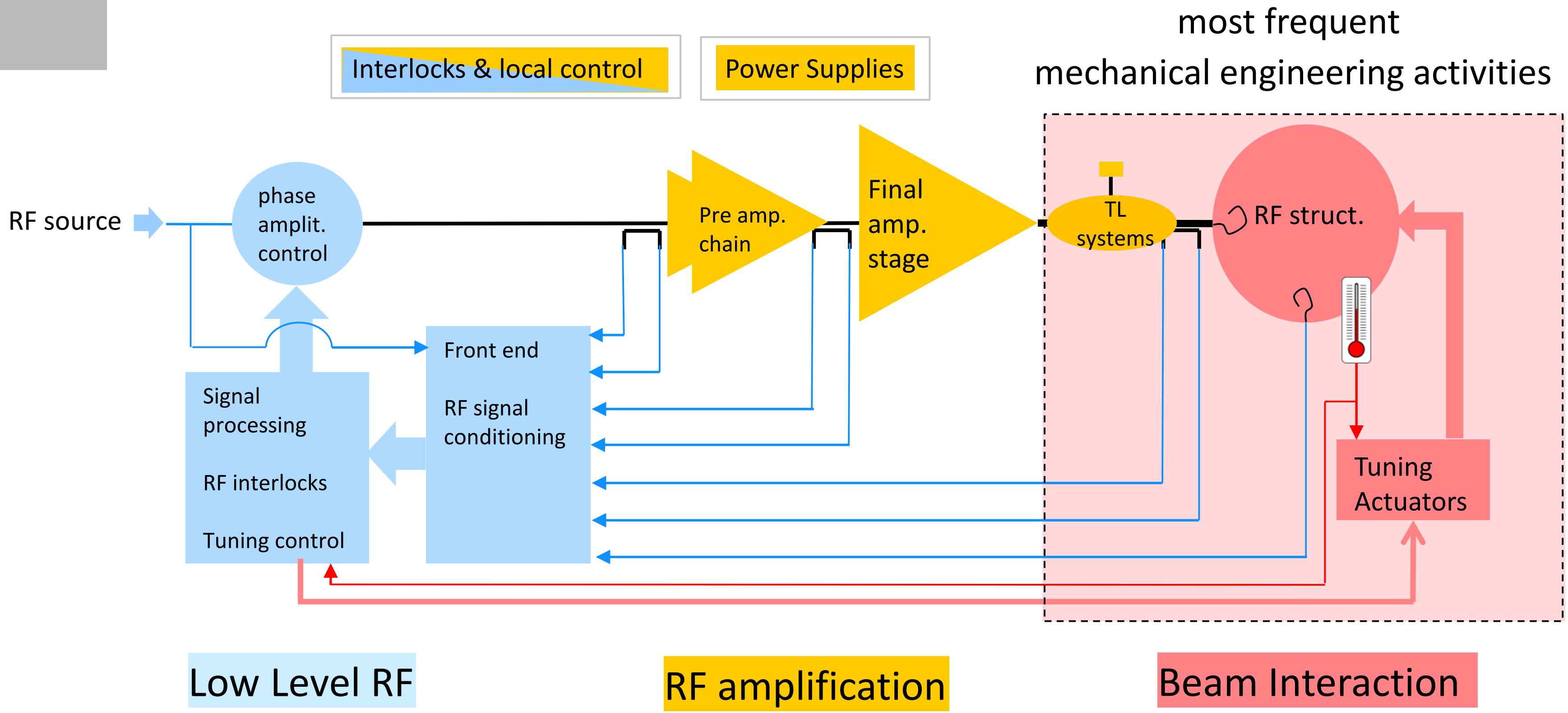


240 MeV energy gain SwissFEL C-Band RF-Module Gradient ~30 MV/m (the cavities would allow >56 MV/m if enough RF power)



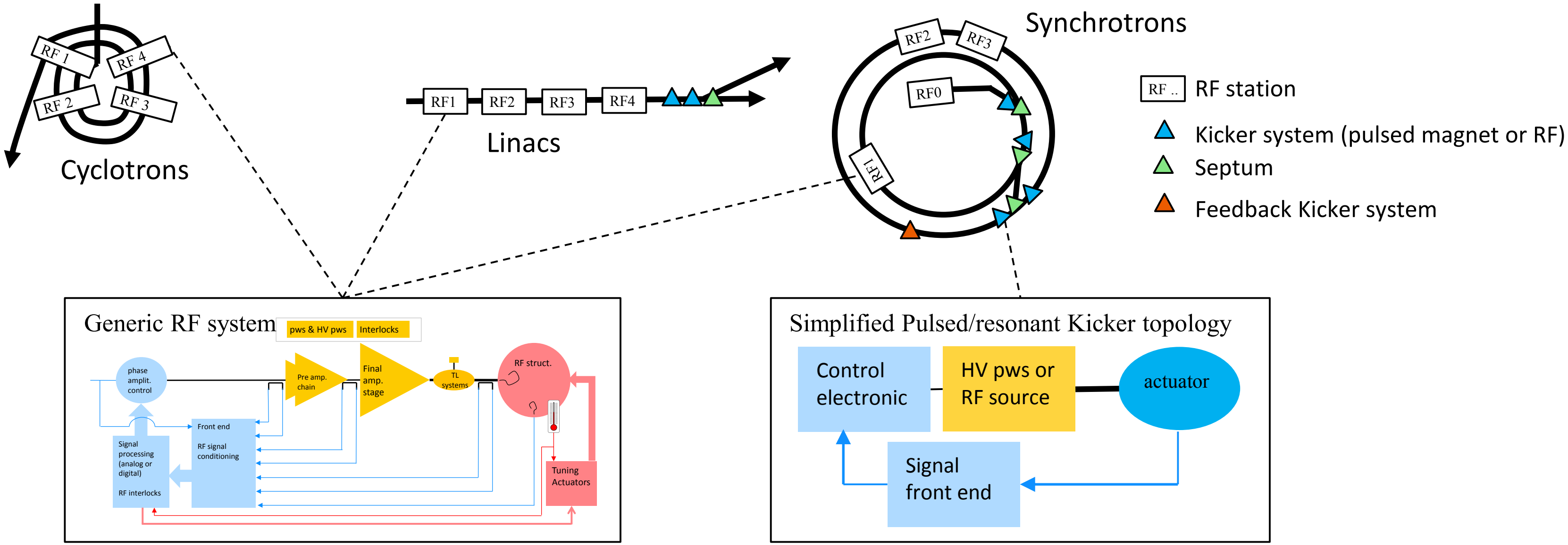
General Topology of an RF System

cw (continuous-wave) or pulsed)



RF in the context of an accelerator

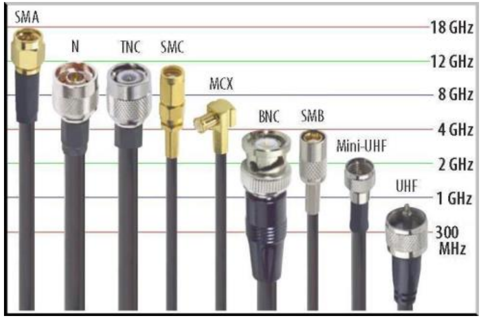
From the operation point of view each RF station or extraction element is seen and handled as a **black-box system** delivering the required accelerating voltage/amplitude and phase stability.



From the RF point of view one RF station is a **complex combination of sub-systems** that must carefully be "matched" to guarantee a stable and reliable user operation.

Transmission line: coaxial

- Very common transmission line for low power signals



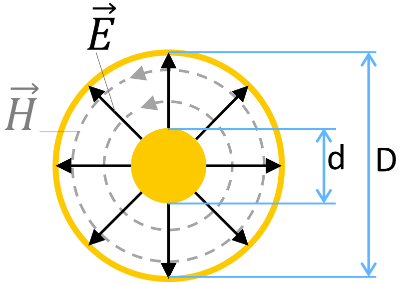
See for example:
https://www.zseries.in/electronics%20lab/cables/coaxial/#.YGrbtu2xVjE

- Impedance of the line

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

$Z = 50\ \Omega \Leftrightarrow D/d=2.302$

$Z = 75\ \Omega \Leftrightarrow D/d=3.493$



- 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

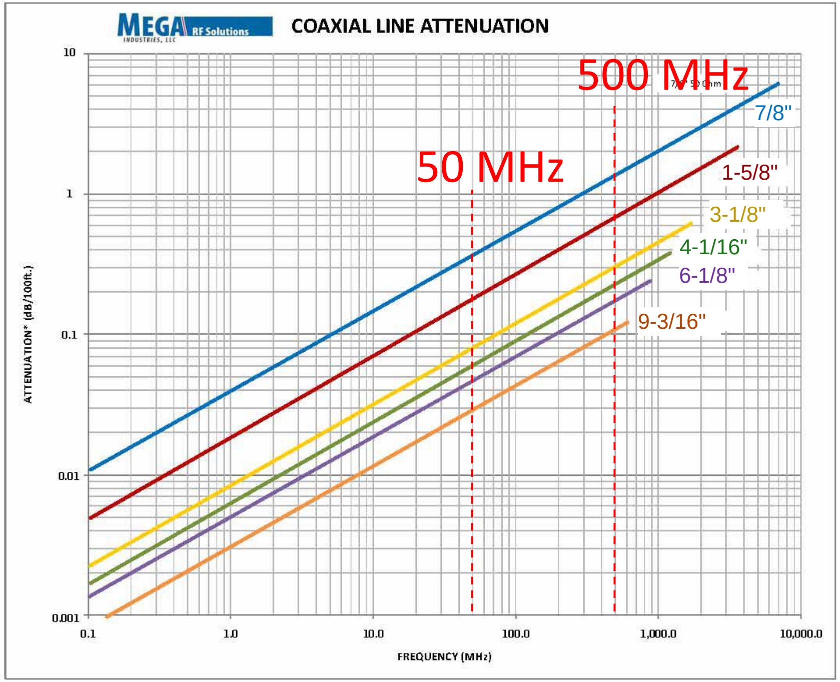
More on coax.see for example: https://cds.cern.ch/record/865921/files/p210.pdf

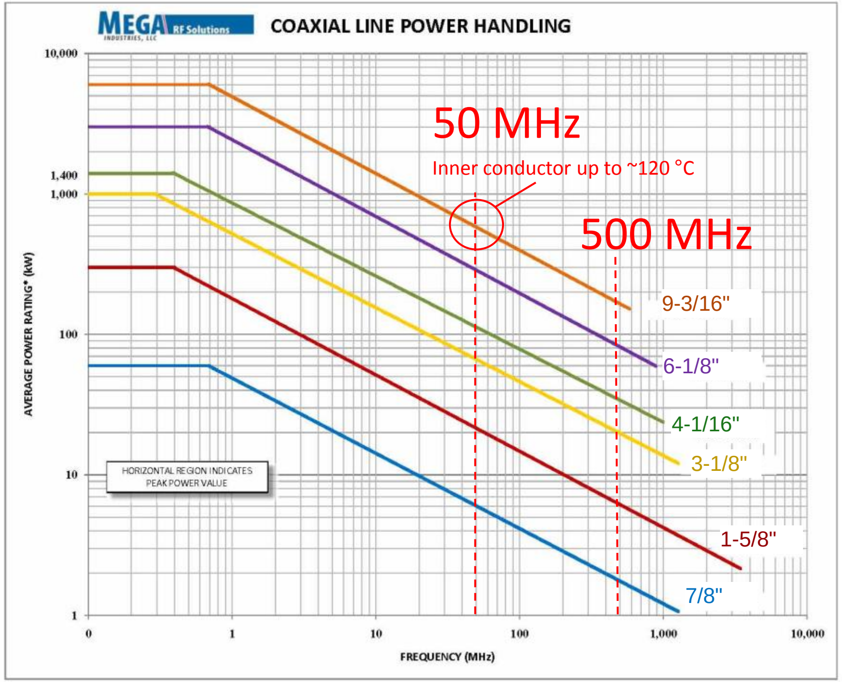
Transmission line: power handling Rigid coax

$$Peak\ Voltage\ \ V_p = E_d \frac{d}{2} ln\left(\frac{D}{d}\right) \quad [\Omega]$$

E_d: insulator breakdown gradient (V/m)

tendency: the higher the frequency, the lower the breakdown strength





Reprint from: https://www.megaind.com/assets/files/catalogs%2FMega-Coaxial-Catalog.pdf

Transmission line: Coax

Important information to keep

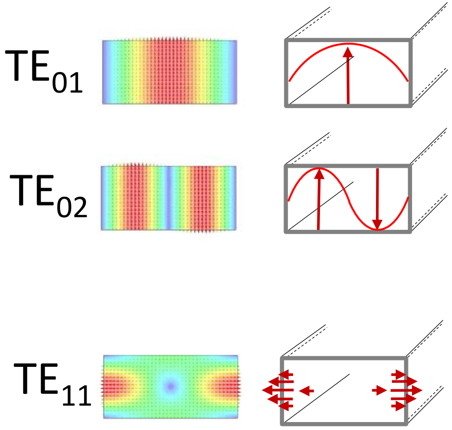
Rigid coax lines are necessary to handle high power
No Cutoff frequency for the TEM Mode. Signals can propagate from DC to high frequencies
Many commercial supplier delivers Rigid coax components, Sizes are standardized but manufacturer have sometime special dimensions.
For accelerator applications 50 Ω lines are commonly used ⇒ ratio outer/inner diameter
The power losses in the coax lines increases with frequency but decreases if increasing the size of the line. The optimization stops when TE Modes starts propagating or the losses are too important (increasing with frequency).
For RF frequencies higher than ~500 MHz rigid coax are not suited for high power (>100 kW)

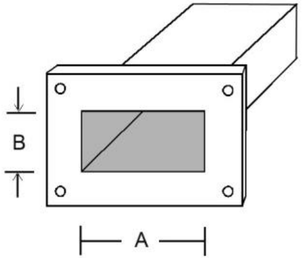
Transmission line: Waveguides

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})





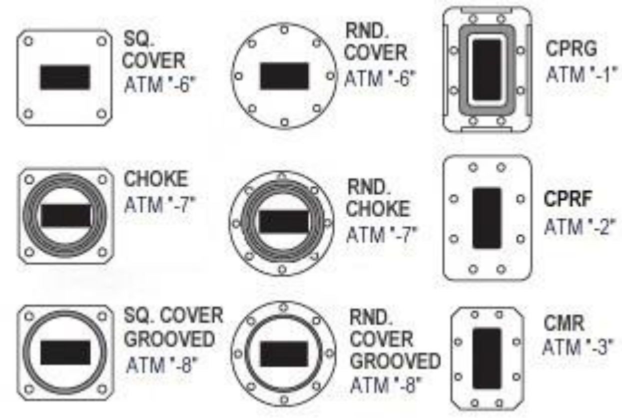
$$f_c(TE_{01}) = \frac{c}{2A}$$

With c being the speed of light

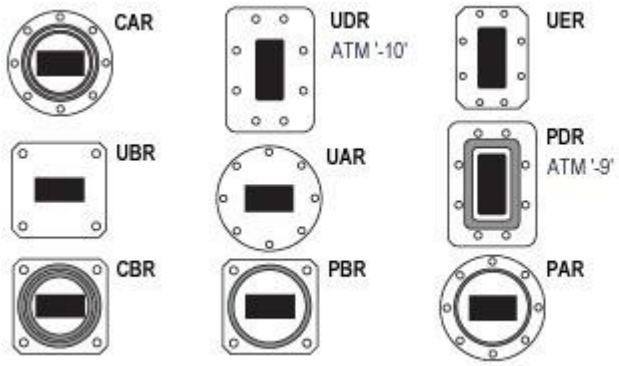
WR Designation	Standard Freq Range (GHz)	Inside dimension A (mm)	Inside dimension B (mm)	Cutoff TE10 (GHz)	Cutoff Next mode (GHZ)	
WR340	2.20 - 3.30	86.360	43.180	1.74	3.47	
WR284	2.60 - 3.95	72.136	34.036	2.08	4.16	S-Band
WR229	3.30 - 4.90	58.166	29.210	2.58	5.15	
WR187	3.95 - 5.85	47.549	22.149	3.15	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 in Internet)

Transmission line: Waveguides
WG Flanges

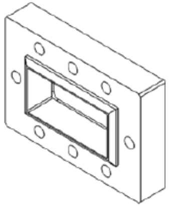


North American EIA Standard Flanges

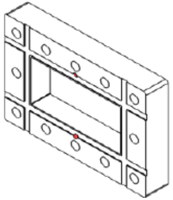


European IEC Standard Flanges

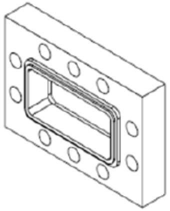
Examples of WR284 Flanges developed by acc. institutes
- **High power**
- **Vacuum compatible**
- **Excellent electrical contacts**



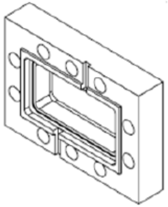
LIL Flange
CERN



DESY Flange



Male SLAC



Female SLAC

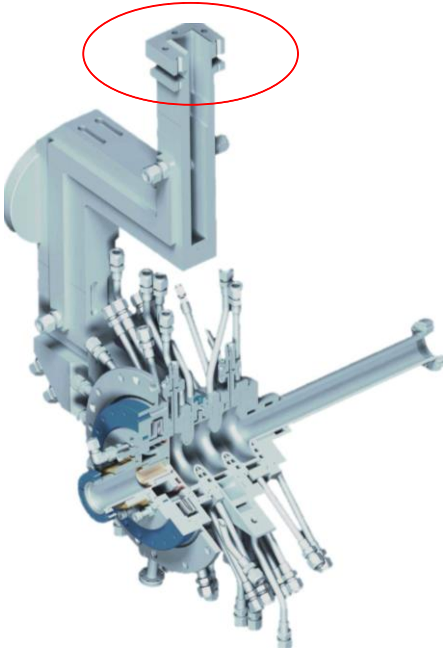
Reprint standard flanges from: https://www.microwave-link.com/microwave/microwave-waveguide-flange/

Transmission line: Waveguides

Important information to keep

Waveguide are standardized industrial products, the operating frequency determines the WG dimensions
In the specified frequency band only the mode with the lowest cutoff frequency (TE01) propagates => well defined polarization of the electric field => no mode conversion/superposition
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 (SF_6) => Flange quality is essential
High power operation in vacuum requires very clean surfaces. An advantage if compatible with 120-150 °C bake-out
The best flanges were designed by acc. Institutes and commercialized => good electrical contact and vacuum compatibility

Interface to WR284 with LIL flange

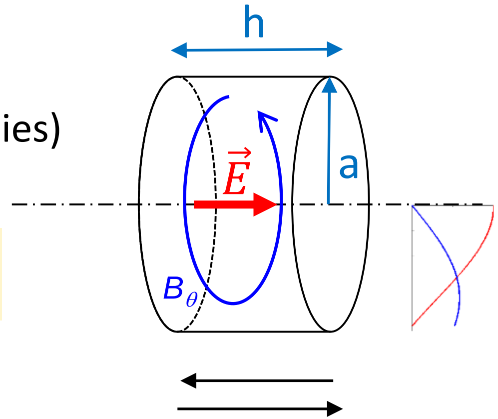


SwissFEL RF-Gun

Basic RF accelerating structures
Pill box cavity

Nice example with analytic solutions => closed cylindrical Waveguide

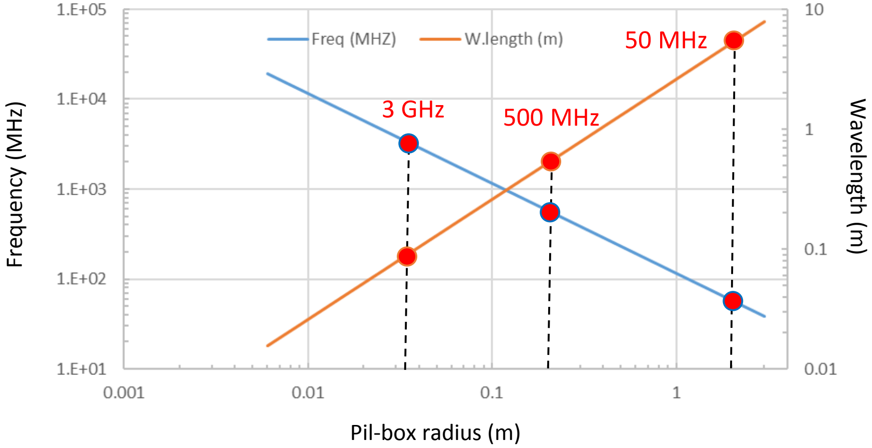
In a cylindrical WG TE and TM modes can propagate (≠ cut off frequencies)



Fundamental mode for accelerating structures TM_{010}

The Resonance frequency is independent of **h**

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



Standing Wave cavity

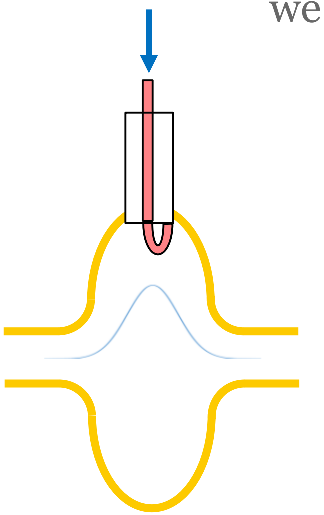
Superposition of two counter-propagating waves

The higher the frequency and the tighter are the mechanical tolerances

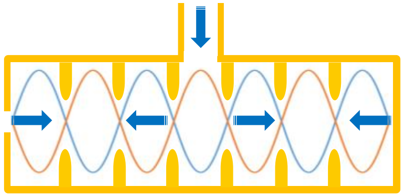
More detail see for example : F. Caspers, M. Wendt; JUAS 2017 RF Engineering, *https://indico.cern.ch/event/569714/contributions/2303930/attachments/1407697/2151655/JUAS2017.pptx*

Some more realistic types of acc. structures

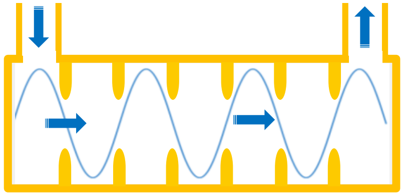
we need apertures for the beam and to power the structure



Standing wave
Elliptical shape



Standing wave
Multi Cells

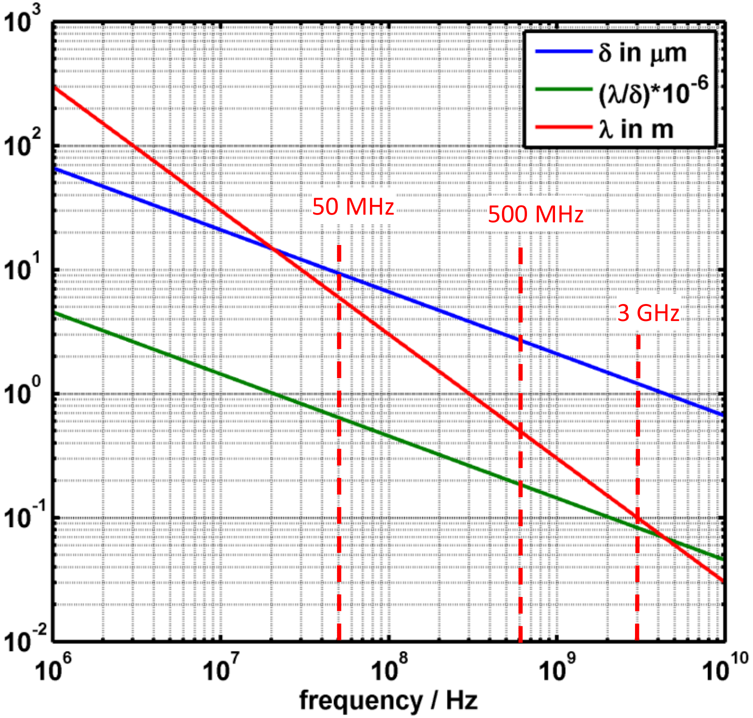


Traveling wave
Multi Cells

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

RF and Wall losses

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



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

$\rho_{copper} = 0.017\ \Omega.mm^2/mm$ resistivity

$\mu_0 = 4\pi \cdot 10^{-7}\ A/N^2$ permeability constant

$\mu_r = 1$ (in Vacuum) relative permeability

$$R_s = \frac{\rho}{\delta} \propto \sqrt{\rho}$$

is the surface resistance (1 mΩ at 1 GHz)

$P_{loss} = \iint_{wall} R_s\ |H_t|\ dA$ 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

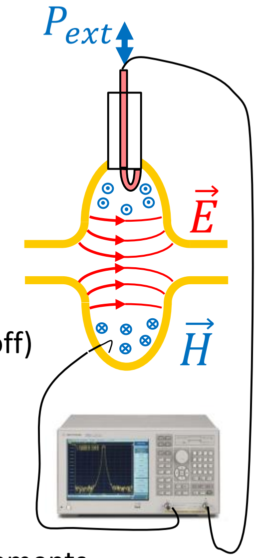
typically between 15000-50000 for copper cavities

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

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

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) ⇒ 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: $R = \frac{|V_{acc}|^2}{2P_{loss}}$

➡ Optimized by the RF designer to minimize the power requirements

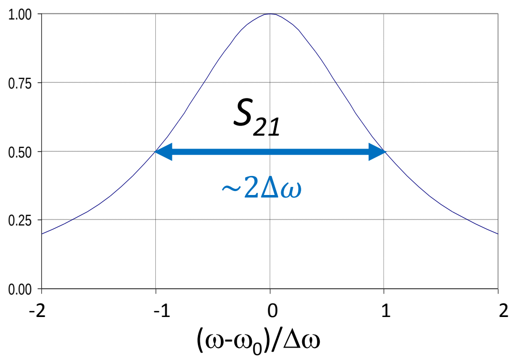
R «upon» Q: $\frac{R}{Q} = \frac{|V_{acc}|^2}{2\omega W_0}$

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



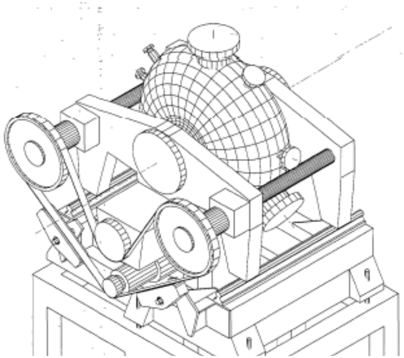
How to adjust the Resonant frequency

Permanent adjustment

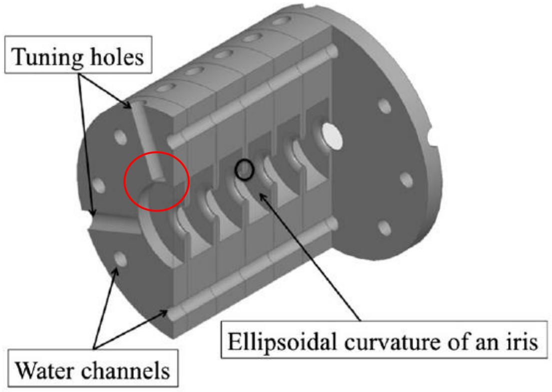
- Inelastic deformation of the cavity wall after manufacture
- Or, very precise manufacturing

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

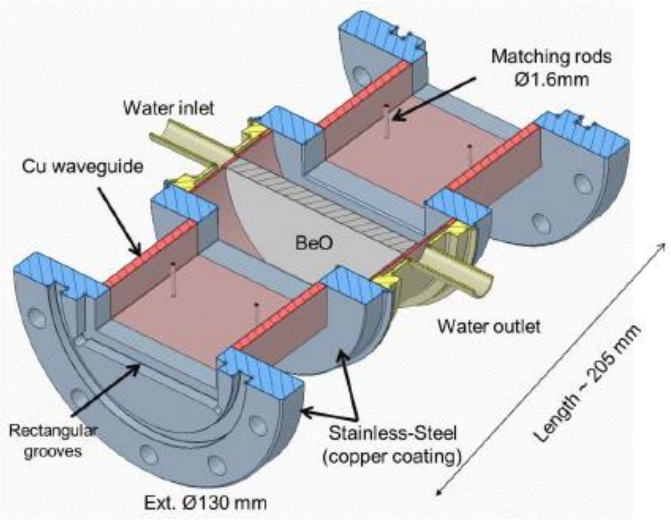
High Freq. : fix tune & temperature

Low freq. : elastic deformation & plungers

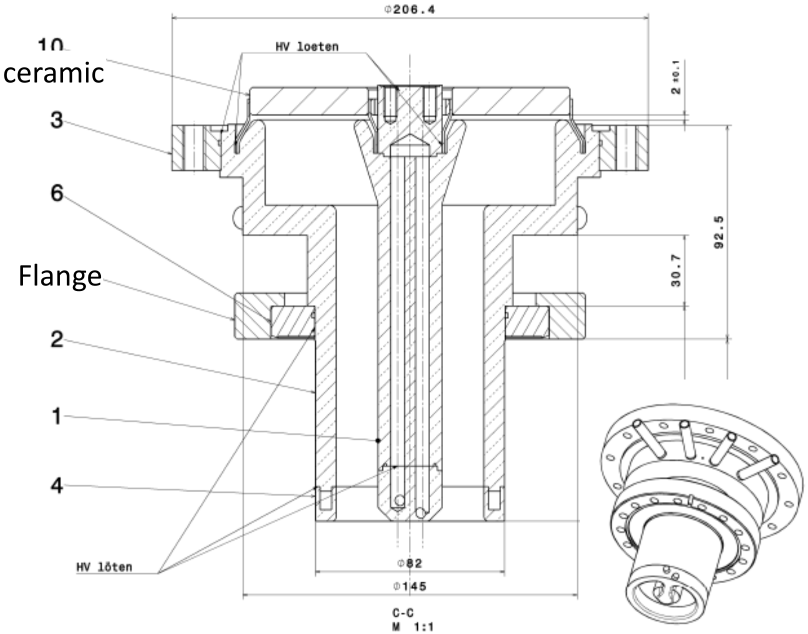
Image reprint: T. Sakurai et al, PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 042003 (2017)

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 & 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 **

120 MV/m peak RF gradient

14 MW; 100 Hz; 3 μs RF pulse

β=2 for fast filling

3.3 kW average power dissipated

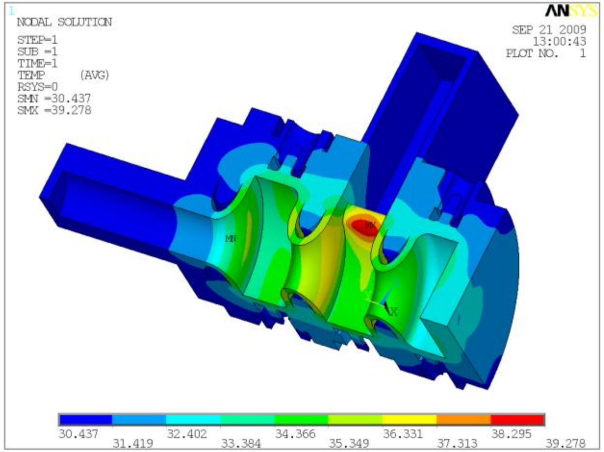
αk: 7500 W/m2K /

Water inlet 30°C

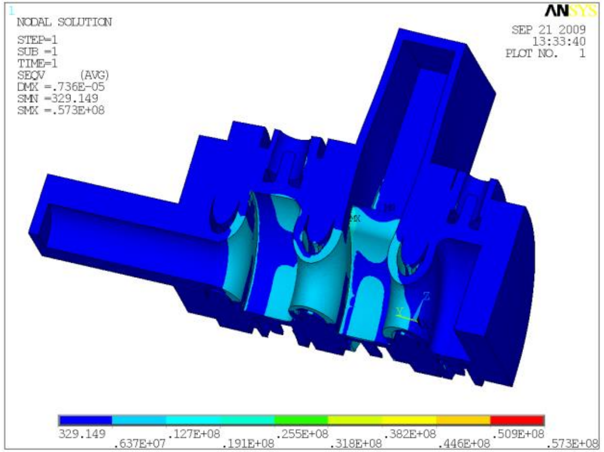
Always very important!

Near collaboration between RF and mechanical engineer

Temperature distribution



Mechanical stresses



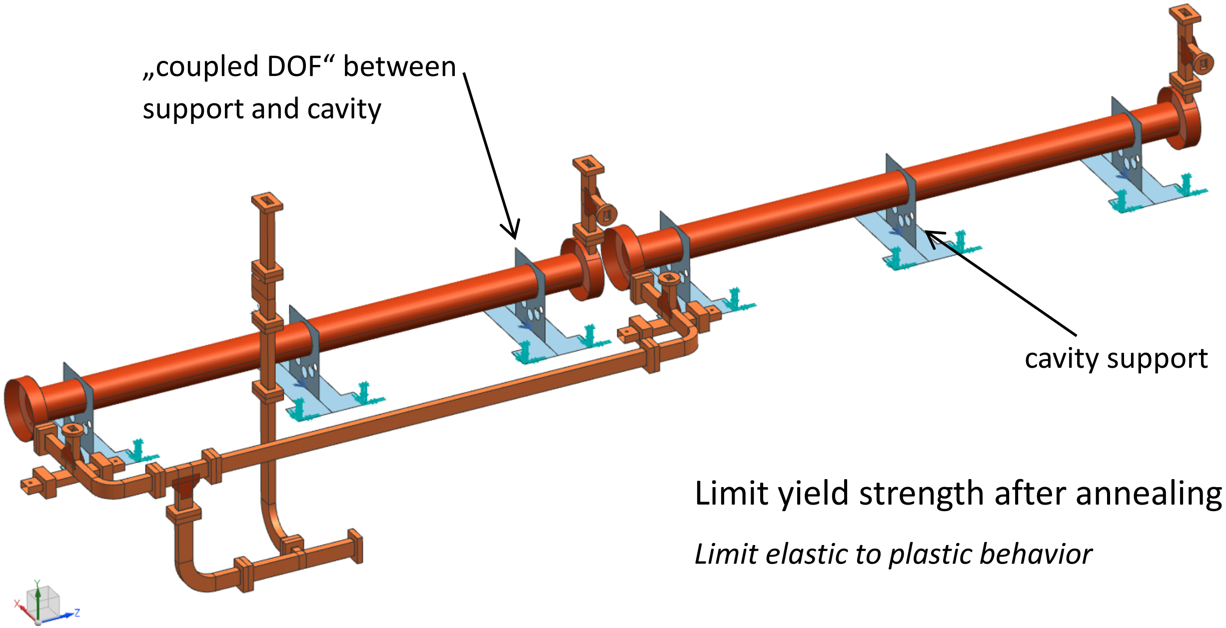
*https://www.ansys.com/

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 **$T_{thermal\ load}$ = 50°C** (operation 30 °C)



Limit yield strength after annealing ~40 MPa

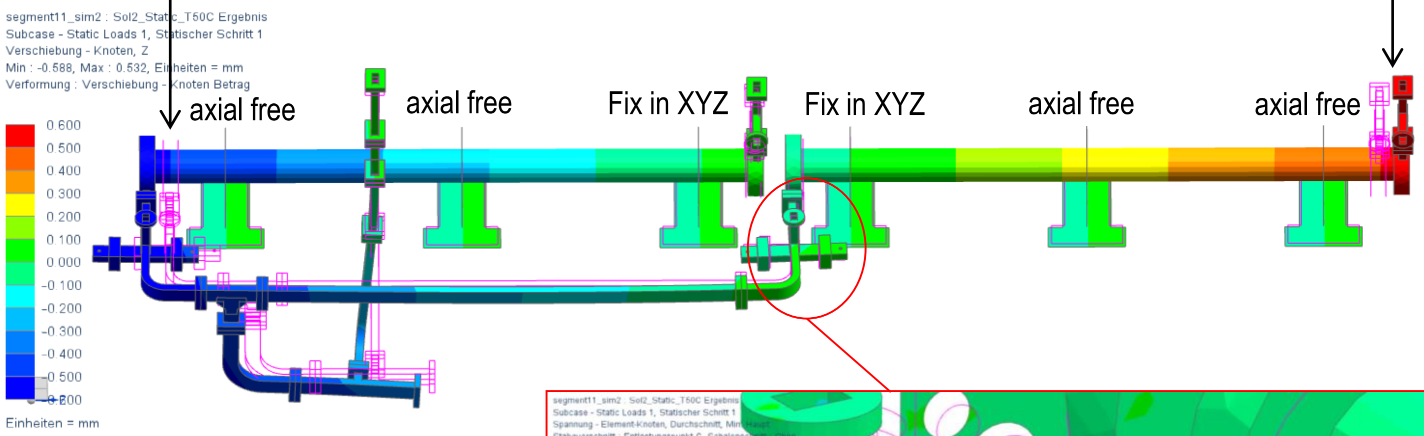
Limit elastic to plastic behavior

Stress analysis SwissFEL C-Band module

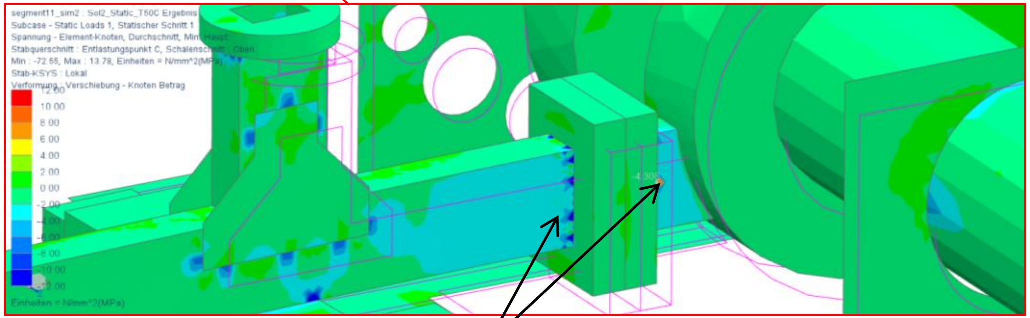
Displacements

$\Delta u_z \approx$ - 0.5 mm

$\Delta u_z \approx$ + 0.5 mm



Stress far from limits



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

Important for the design of the supports

Oxigen Free High Conductivity 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 $\Rightarrow$ 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.

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.

PSI RF structures: frequency Zoo

50 MHz Ring Zyklotron

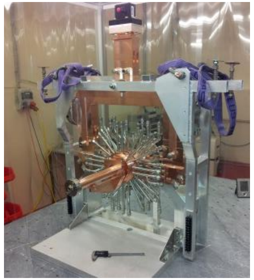
50 MHz Inj. II

150 MHz buncher

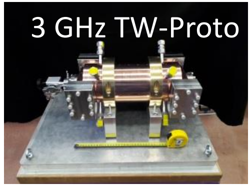
500 MHz Super-buncher

1.5 GHz 2 cell LEG

3 GHz RF-Gun
SwissFEL



Disks for TW-struct.



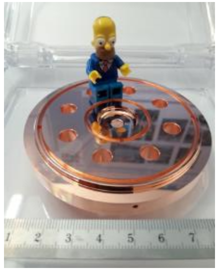
3 GHz TW-Proto

50 MHz ⟷ **12 GHz**

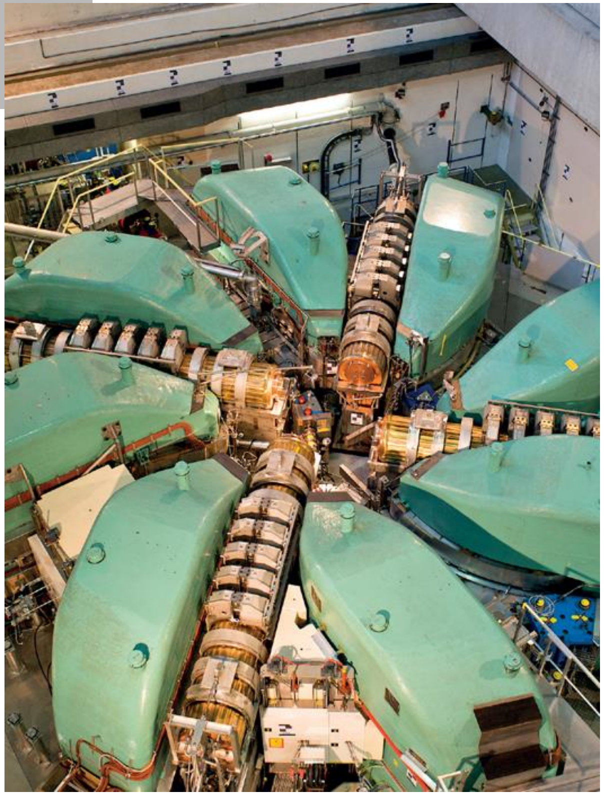
6 GHz TW-SwissFEL
After brazing at PSI

12 GHz Deflector
Assembly In SwissFEL

12 GHz Disc



Examples: High Intensity Proton
Accelerator at PSI, 50 MHz RF System

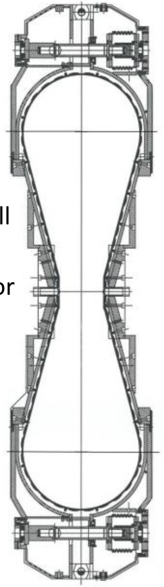


Opening for the beam

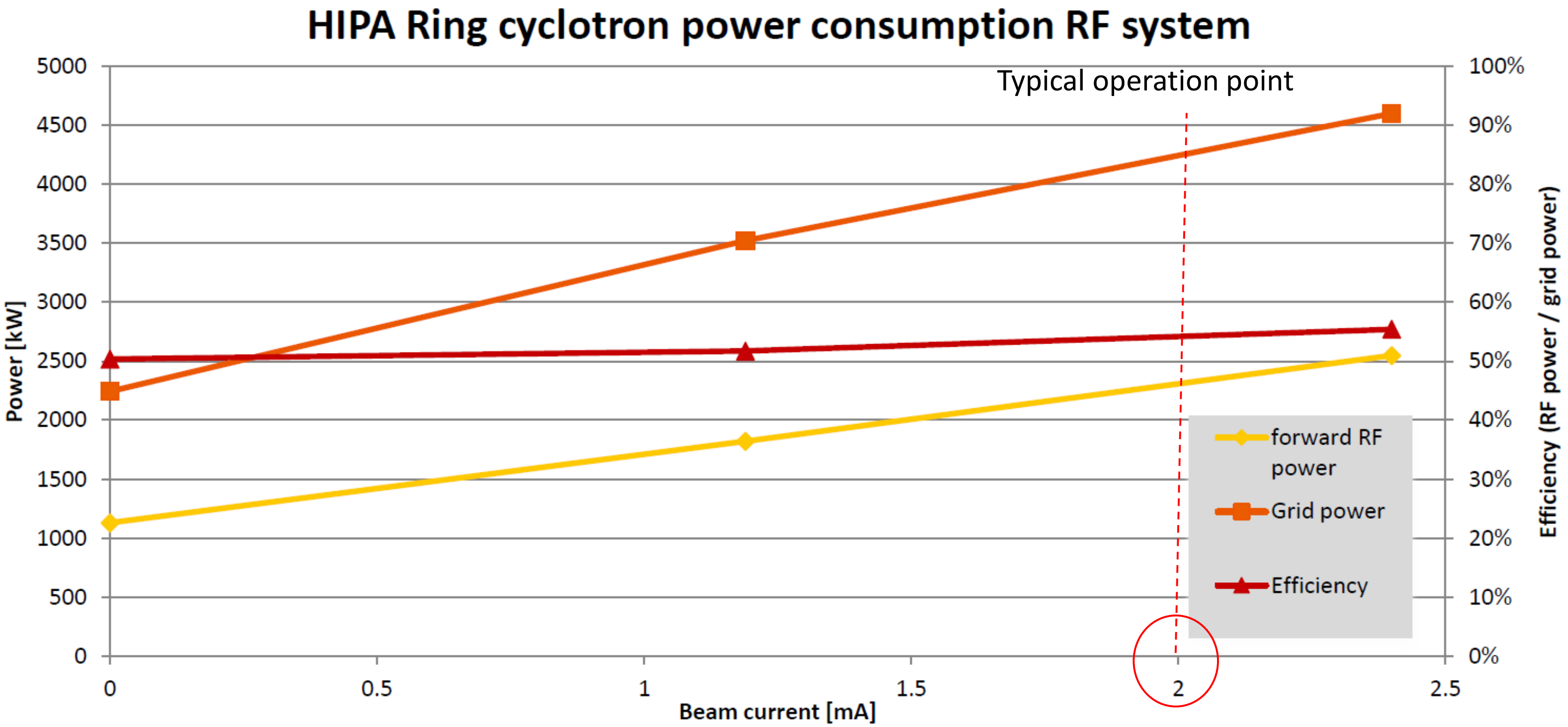
External structure for the frequency tuning by (pneumatic) deformation of the cavity

1 MW Tetrode final amplification stage

- Copper to minimize the wall losses
- Shape to reduce multipactor



HIPA: as we said RF need power



Proton beam power > 1 MW!
Energy 590 MeV

Example: SwisssFEL Injector S-band structures

PSI RF design

- **Constant gradient + constant losses**
- **Dual feed racetrack couplers**

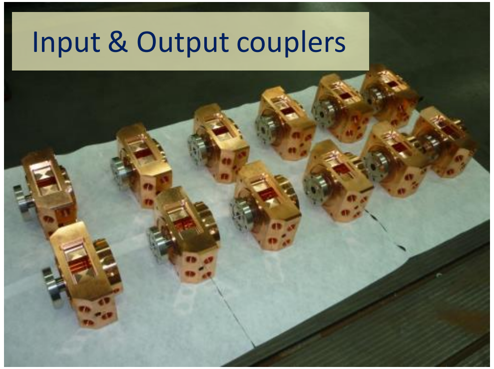
Classical technology with cell to cell dimple tuning after brazing

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

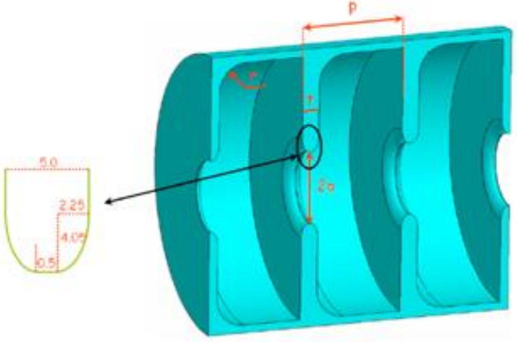
Parameter	Value
Operating frequency	2998.8 MHz
Phase advance per cell	$2\pi/3$
Total number of cells	122
Accelerating gradient	20 MV/m
Maximum pulse repetition frequency	100 Hz
Operating temperature	30°C

	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



Input & Output couplers



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

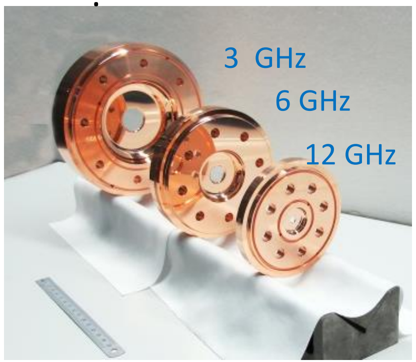
Cavity on the tuning bench at RI

J.-Y. Raguin, "The Swiss FEL S-Band Accelerating Structure: RF Design", Proc. LINAC 2012, Tel-Aviv, Israel, 2012

PAUL SCHERRER INSTITUT

New frontiers with Ultra High Precision machining

The CERN Accelerator School



- 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 (HFFS*, 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

* https://www.ansys.com/products/electronics/ansys-hfss ** https://www.3ds.com/products-services/simulia/products/cst-studio-suite/

UHP Machining and Temperatures

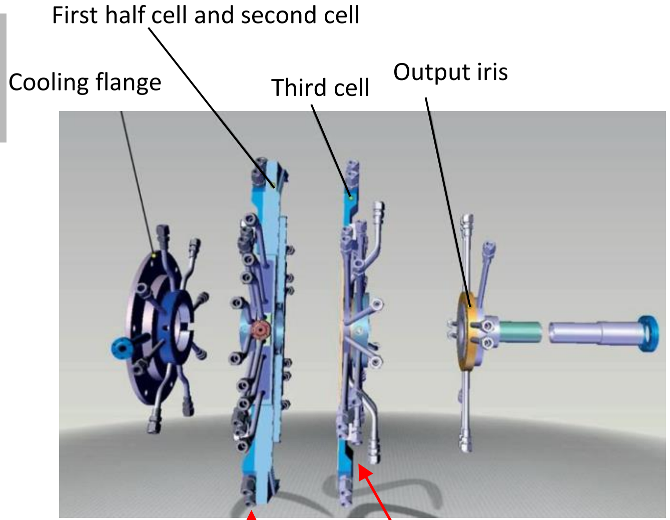
Manufacturing temperature $\neq$ operating temperature of the structure

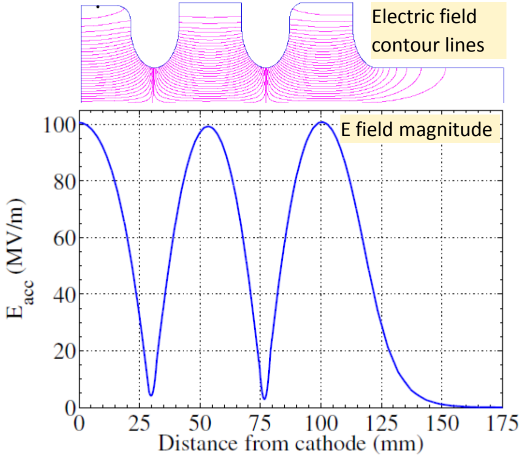
The dimensions on the manufacturing drawings must be adapted taking into account:

- 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: SwissFEL S-Band RF Gun





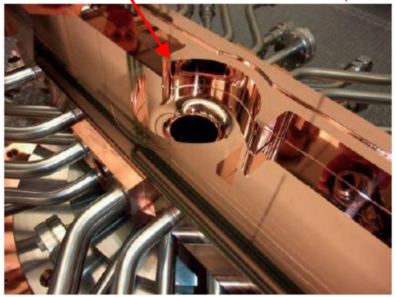
First structure fabricated with UHP techniques at PSI (cells of cavity body).

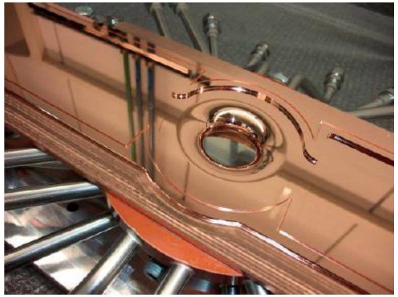
Fabrication on tune according to RF simulations

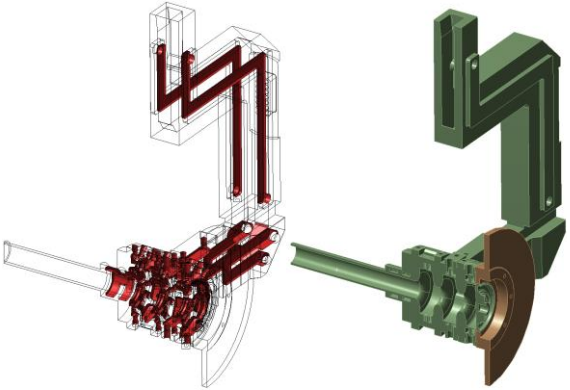
No Correction of tuning and field balance required after final brazing.

Few µm tolerances (outer diameter cells)

Coupling aperture in the second cell

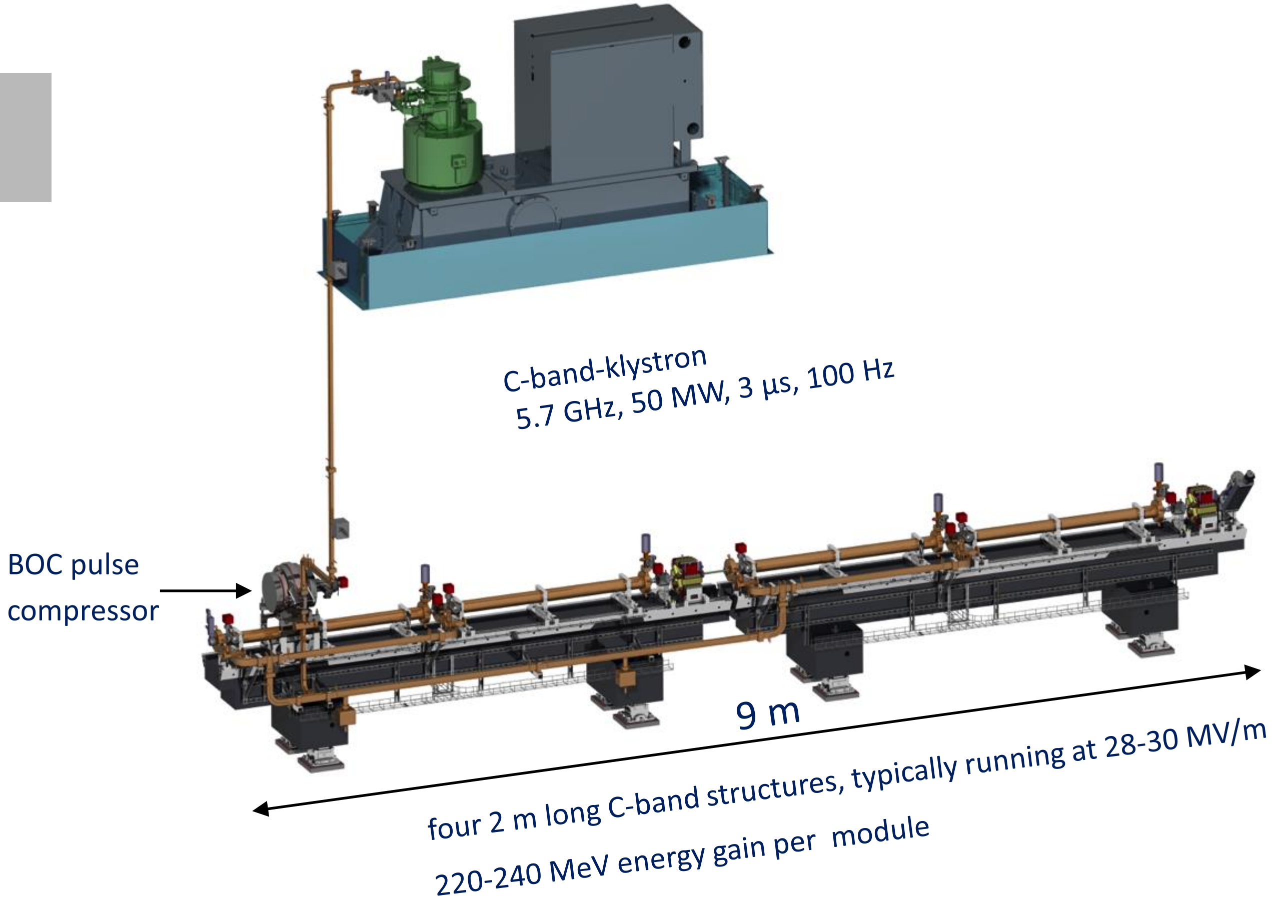






Cooling was dimensioned for 4 kW

UHP example: C-band linac modules



Main LINAC	#
LINAC module	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structure	104
Waveguide splitter	78
Waveguide load	104

UHP

- BOC (less stringent requirements)
- Accelerating structures

PAUL SCHERRER INSTITUT PSI

Some production infrastructure

The CERN Accelerator School

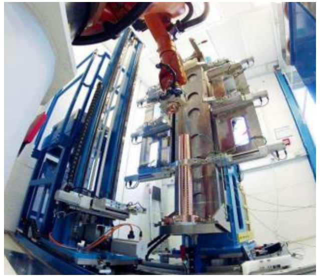
UP-Machine HEMBRUG Slantbed-MIKROTURN-100-CNC
Was used to establish the manufacture procedure at PSI
Later delivered to the industrial partner for mass production

Brazing furnace @ PSI

Metrology: Leitz Infinity: accuracy 0.3 μm.

7 sequential cleaning baths with automatized cup handling

Handling tools



Automatized stacking with robot

UHP example: SwissFEL C-Band structures

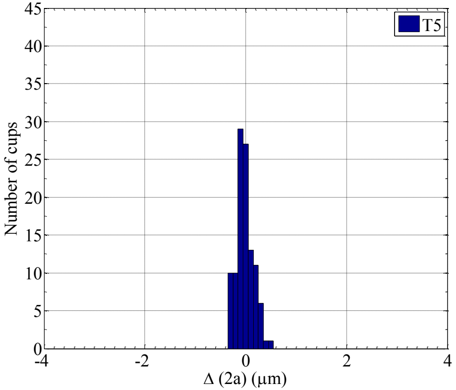
Structure ready to be brazed

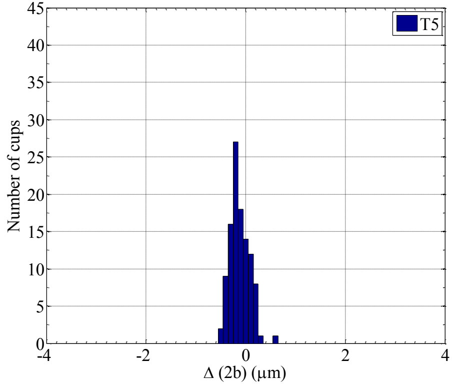
- Structures are machined “on tune”, no provisions for dimple tuning!
- Cup manufacturing with micron precision (VDL ETG Switzerland)
- Coupler manufacturing at VDL ETG
- Stacked by robot at PSI
- Vacuum-brazed at PSI
- Production rate: 1-2 / week
- Production finished August 2016

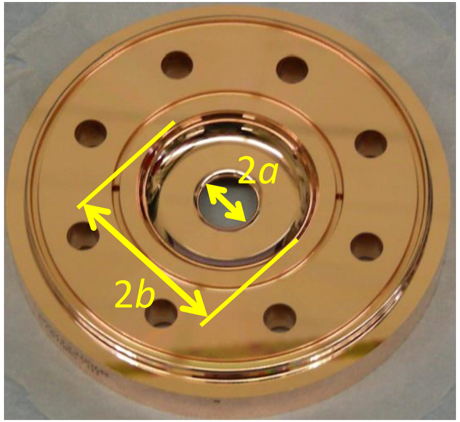
- **High power results for first structure:**
  - → Conditioned to 52 MV / m (limited by Power availability)
  - → Break-down rate at 52 MV / m $\approx 2 \times 10^{-6}$
  - → At nominal 28MV/m, break-down rate negligible (well below the specified threshold of 10^{-8})

R. Zennaro et al., “Measurement and High Power Test of the First C-Band Accelerating Structure for SwissFEL”, Proceedings of LINAC2014, Geneva, Switzerland

C-band structures: ultra-precision machining

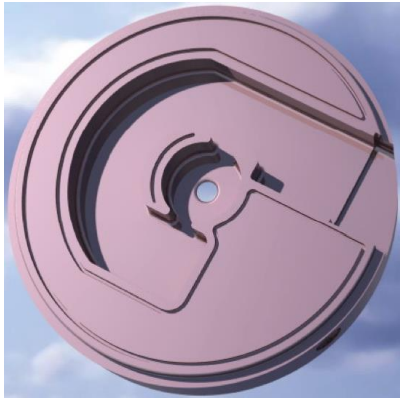


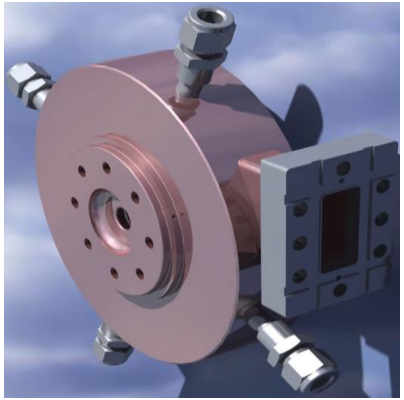




Regular cell

J coupler cell

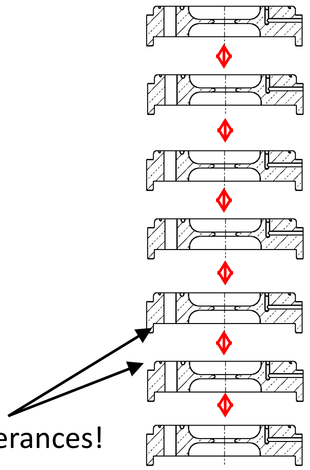




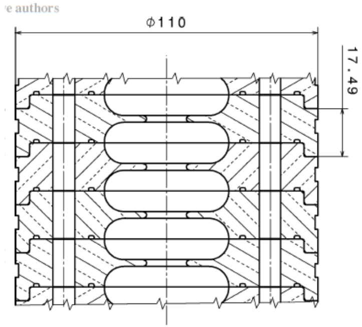
Typical examples of metrology on a structure:
top histogram iris diameter, bottom histogram iris cell diameter

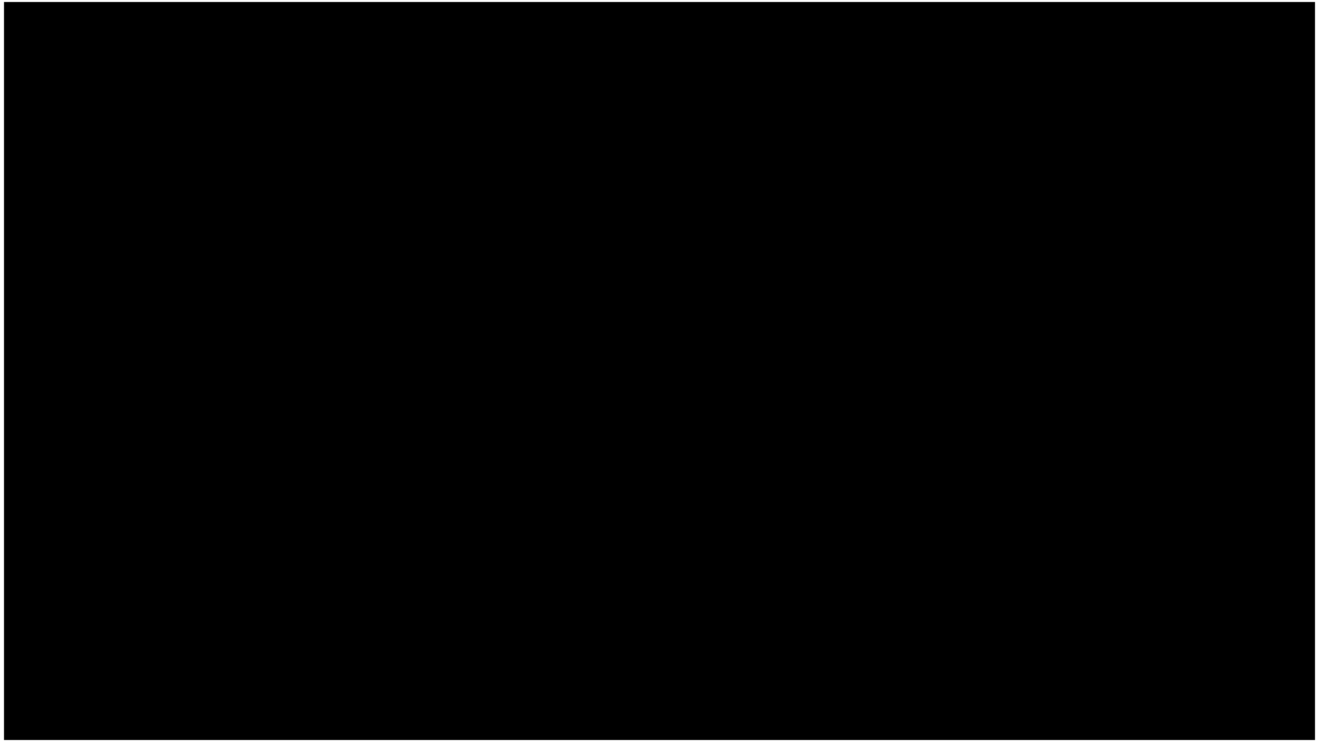
U. Ellenberger et al., Proceedings of FEL2013, New York, NY, USA, Basel, Switzerland

UHP & tricks for cup stacking



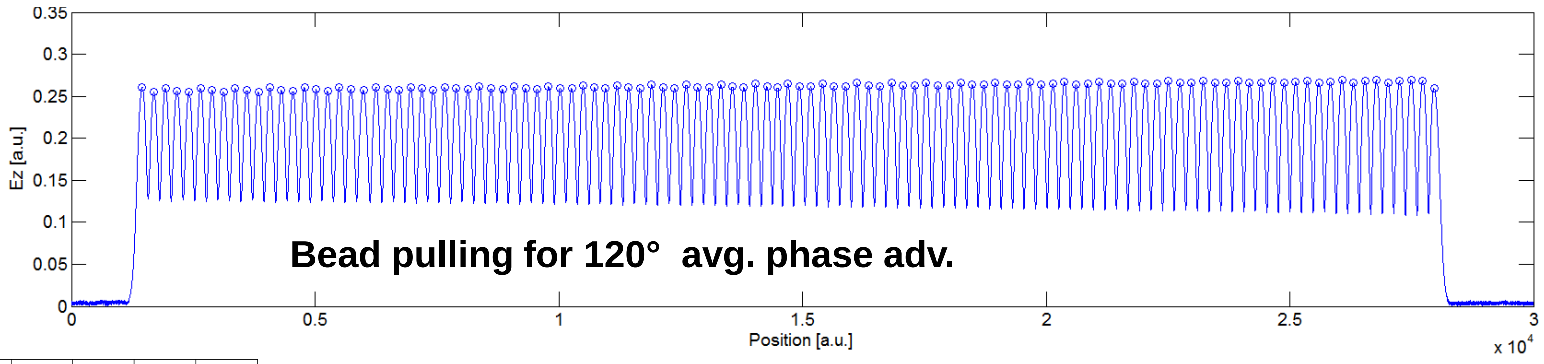
Zero tolerances!

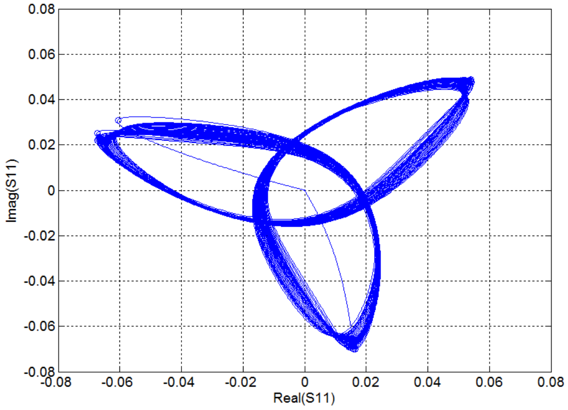




C-band structures: typical bead-pull results

VSWR = 1.06

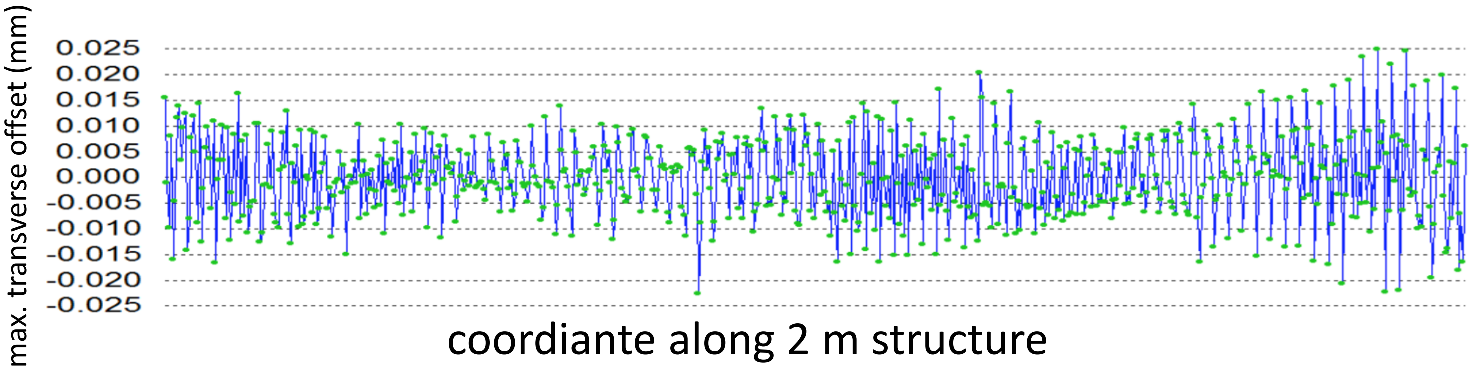


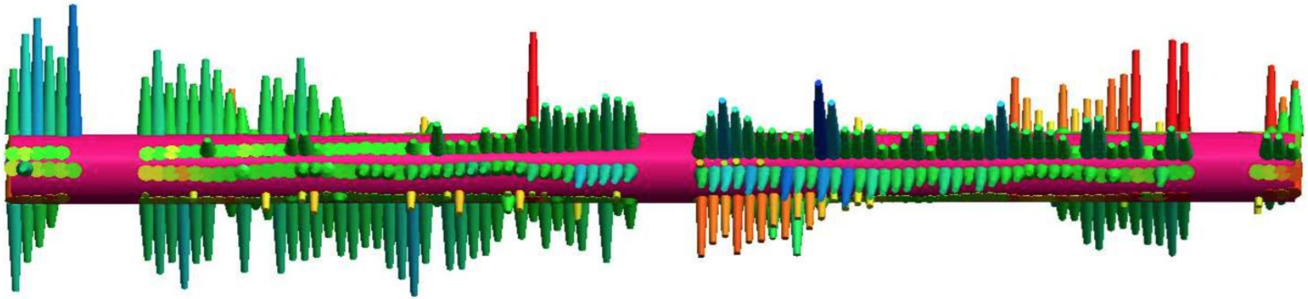


RMS phase error typically < 1 deg

I shall be noted that during the brazing process the structure expands longitudinally ~20 mm
After cooling down the tolerances are preserved and the cavity is on tune!

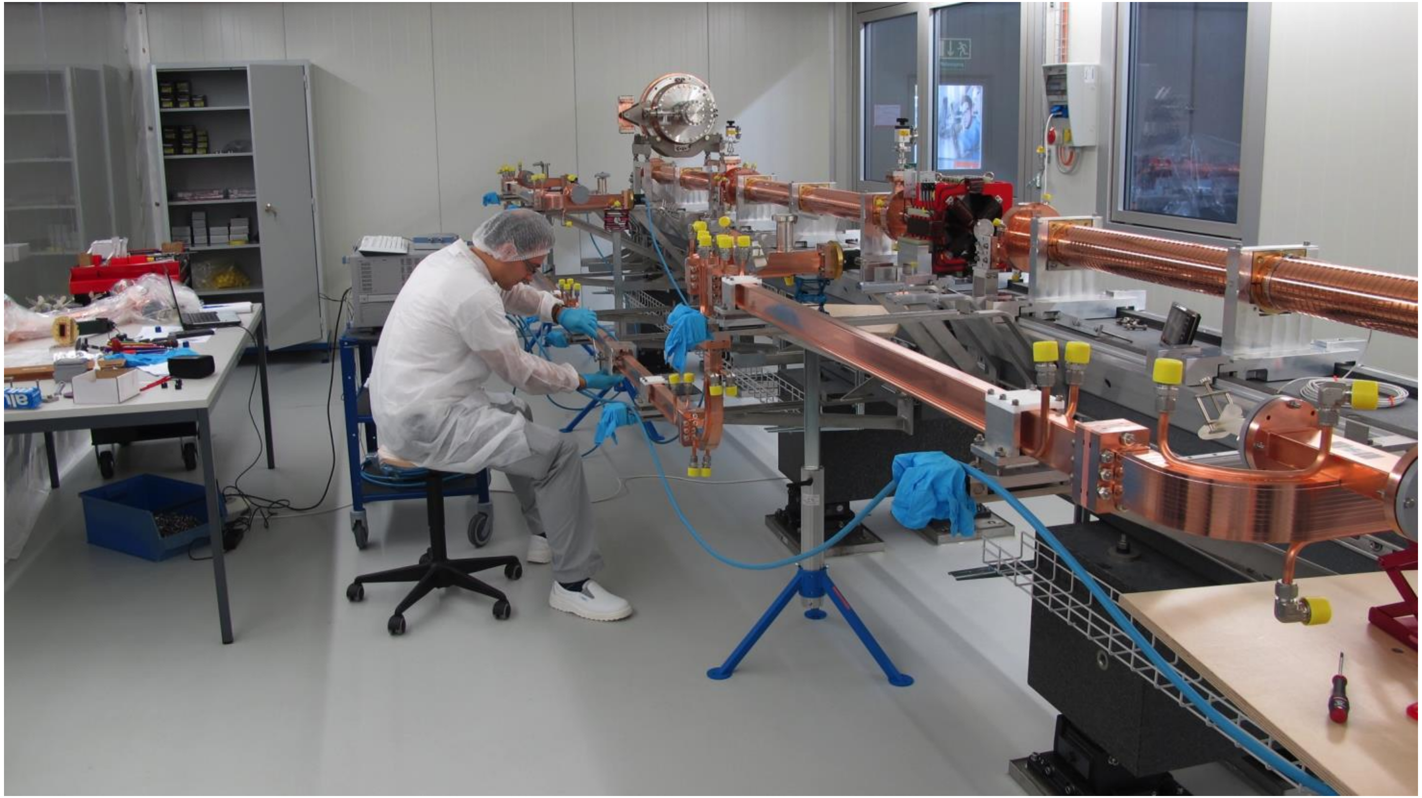
C-band structures: typical straightness



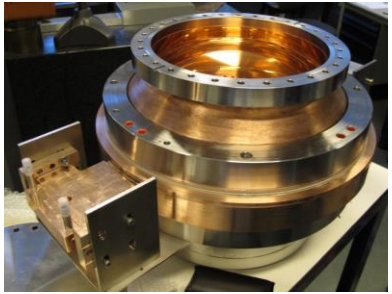


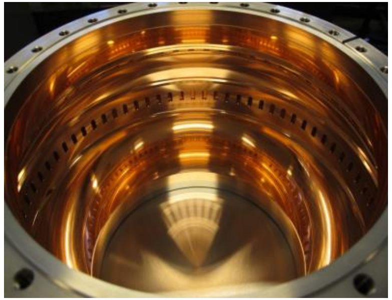
→ Max. deviation from straight trajectory typically < 20 µm

C-Band module: Preassembly and tuning of the waveguide train



SwissFEL C-Band RF pulse compressors





RF design:

- ✓ intrinsic high $Q_0 > 200000$
- ✓ β=10

Adapted from the original design for S-Band of

I. Syratchev (CERN).

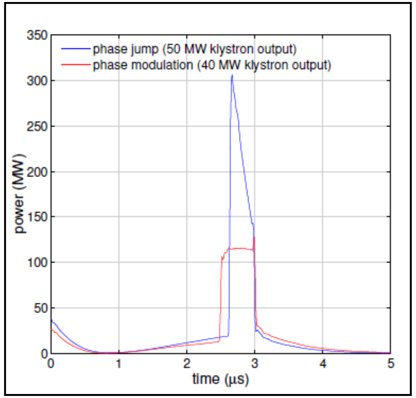
Mechanical design:

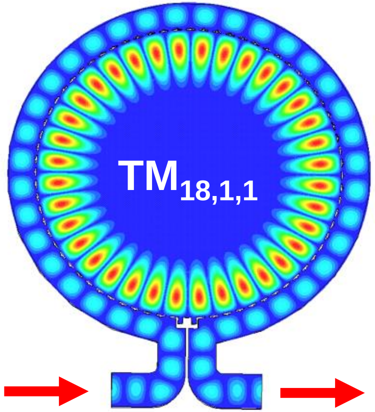
Simple and robust design:

- ✓ Inner body from a single piece
- ✓ Two brazing steps
- ✓ Machined on tune

Production:

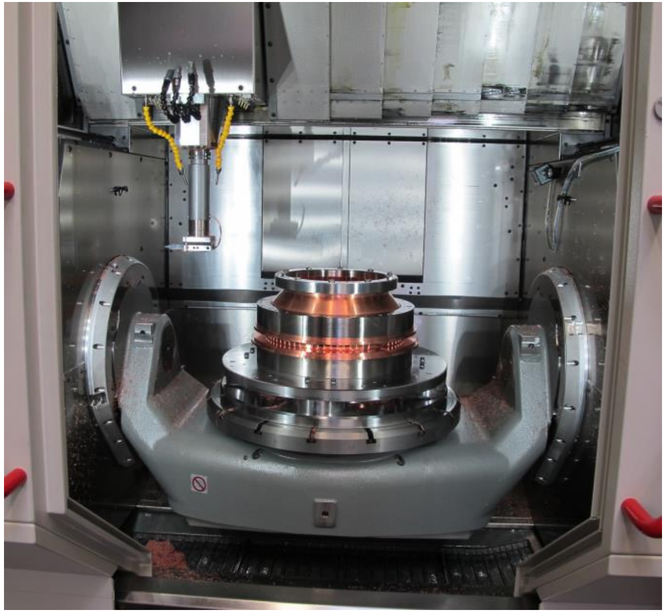
- ✓ 100% in house





- R. Zennaro et al., "C-band RF pulse compressor for the SwissFEL", Proc. IPAC 2013, Shanghai
- U. Ellenberger et al., "The SwissFEL C-Band RF Pulse Compressor: Manufacturing and Proof of Precision by RF Measurements", FEL 2014, Basel
- A. Citterio et al., "C-band Load Development for the High Power Test of the SwissFEL RF Pulse Compressor", LINAC 2014, Geneva
- I. V. Syratchev, "RF pulse compressor systems for CTF3", Proc. 5-th MDK Workshop, Geneva, June 2001.

BOC production @ PSI



Hermle C42 U: 5 axis machine for BOC production at PSI

The chosen RF mode (size of the cavity) allow for more relaxed tolerances ±10μm

Mechanical stress was an issue => very thin wall in the coupling ring 1.8 mm

Impression in the SwissFEL tunnel

350 m of Linac

Conclusion

A very near exchange between RF and mechanical engineers is essential for an efficient development work $\Rightarrow$ iterative process.
Very important to reach a common understanding of both mechanical and RF constraints to avoid loosing time with nearly unfeasible designs.

A core group with a mechanical engineer and experienced draft mans must be permanetly integrated within the RF team to:

- build and maintain the necessary engineering know-how in the field of RF (learn from the past experience)
- ensure an efficient communication with the workshop and extern 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.

Wir schaffen Wissen – heute für morgen

My thanks go to

- you all for listening
- the RF section at PSI
- the PSI Workshop
- The very fruitful exchanges with numerous colleagues from other institutions

Some references

(1) CAS: **RF for Accelerators, 08 - 17 June 2010, Ebeltoft, Denmark**
https://cas.web.cern.ch/schools/ebeltoft-2010

(2) CAS: **RF Engineering, 01 - 10 May 2000, Seeheim, Germany**
https://cas.web.cern.ch/schools/seeheim-2000

(3) CAS: **RF Engineering for Particle Accelerators, 01 - 10 September 1991, Oxford, UK**
https://cas.web.cern.ch/schools/oxford-1991