The MYRRHA Project

and a few detours via current Linac developments at IAP Frankfurt

NED2024

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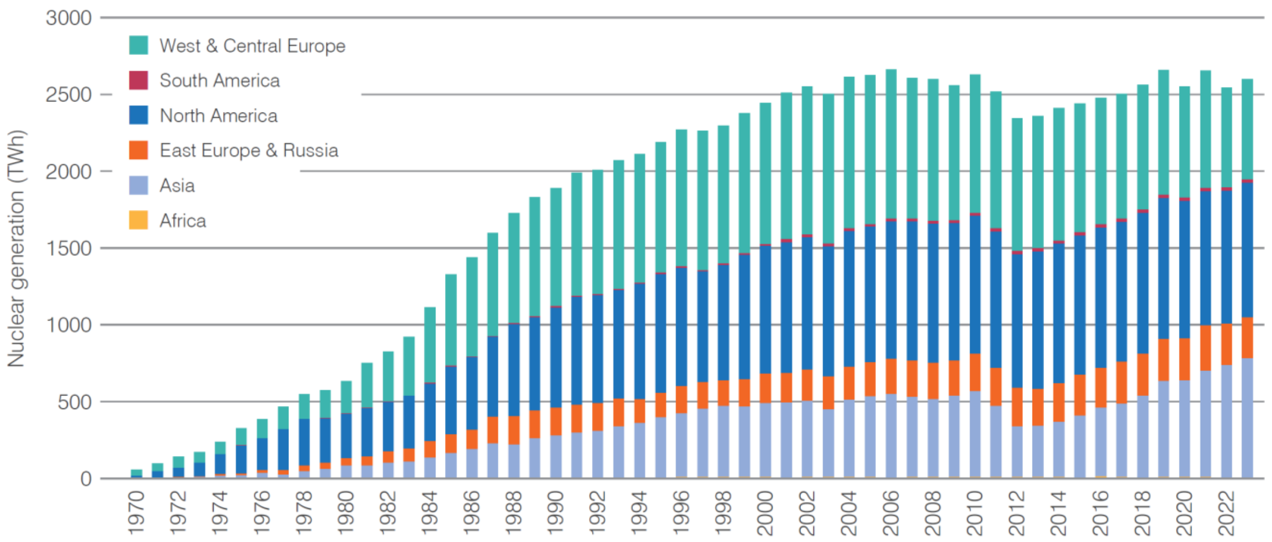
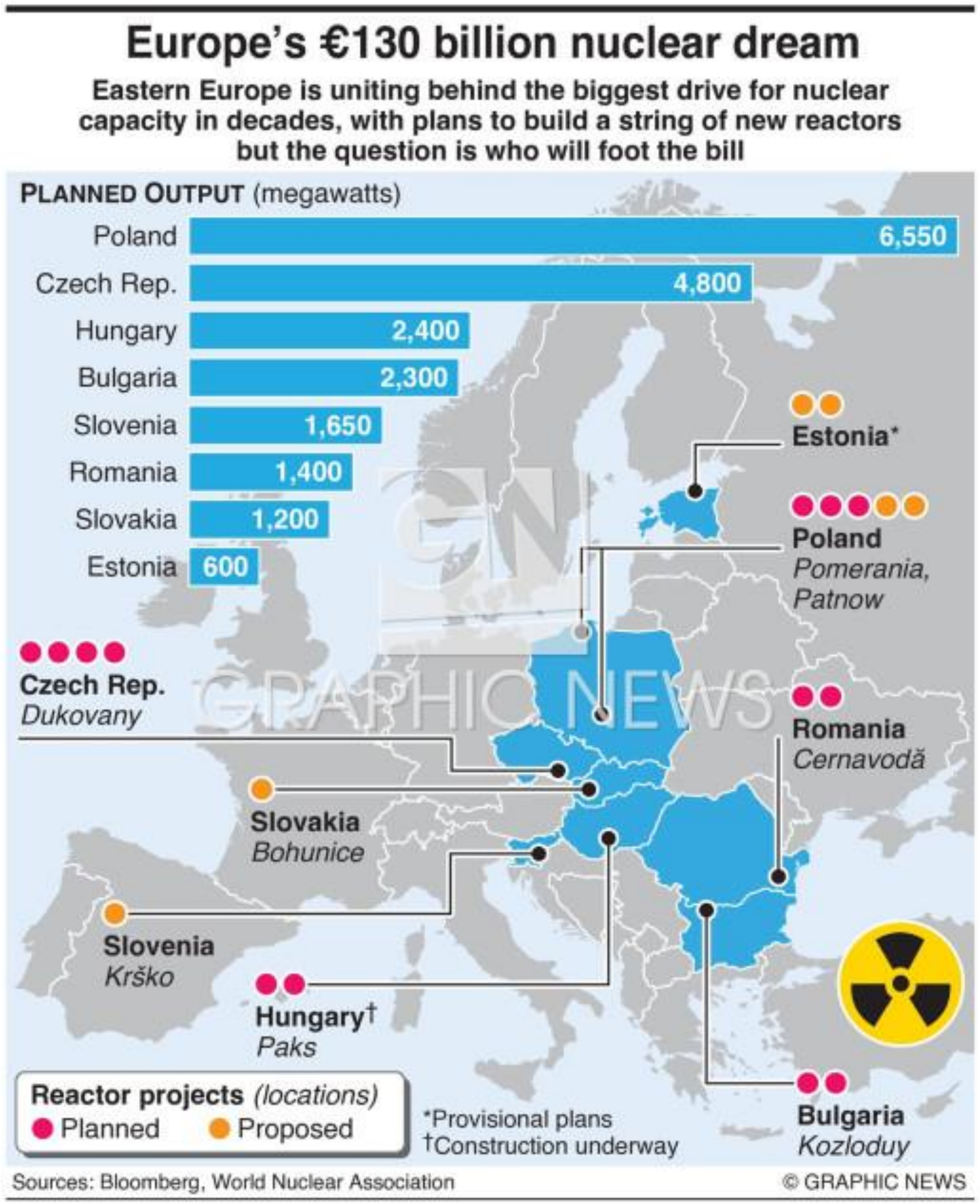
Introduction

'Some day, son, all this (nuclear waste) will be yours!' Cartoon: Katauskes via Greens MPs on Flickr (CC BY-NC-ND).
Taken from: https://theecologist.org/sites/default/files/styles/inline_l/public/NG_media/402277.jpg?itok=lfXcQo99, 24.11.2024

Introduction



Source: World Nuclear Association and IAEA Power Reactor Information Service (PRIS)



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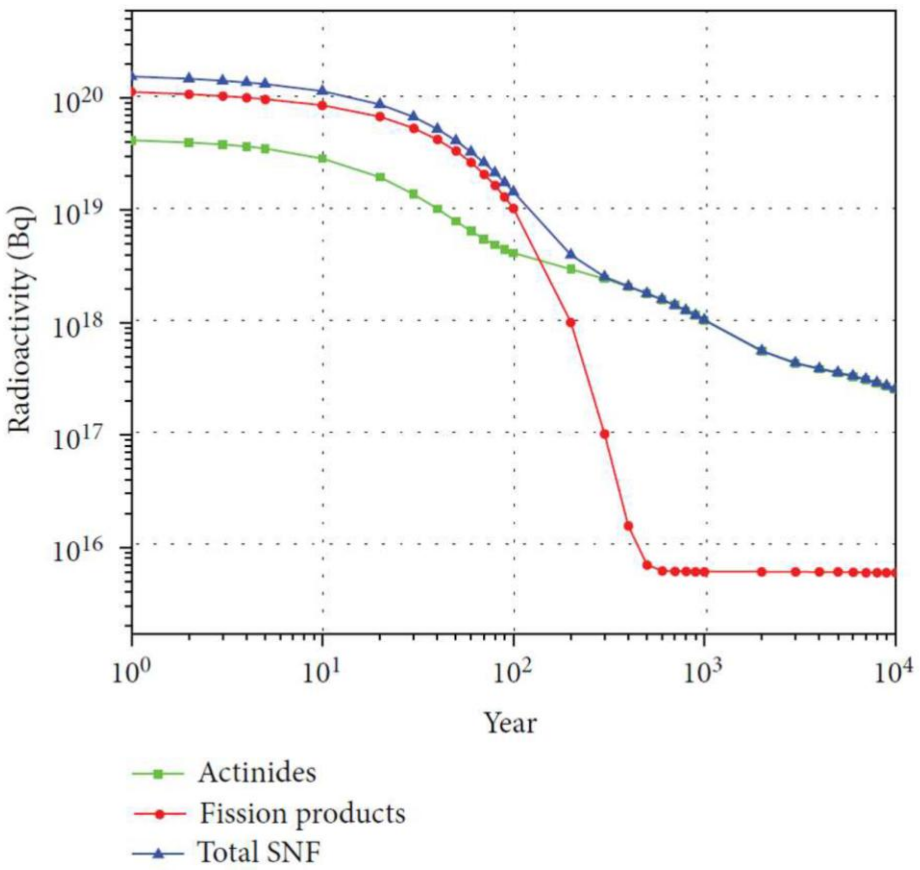

A. SCHWENK-FERRERO: *German Spent Nuclear Fuel Legacy: Characteristics and High-Level Waste Management Issues.* Science and Technology of Nuclear Installations, Vol. 2013, 2013, http://dx.doi.org/10.1155/2013/293792

20th Century Fox

ELEMENT	kg
U	930,7
Plutonium	11,1
Minore Aktinide	
Np-237	0,79
Am	0,99
Cm	0,1
Langlebige Spaltprodukte	
I-129	0,26
Tc-99	1,23
Zr-93	1,12
Cs-135	0,6
Kurzlebige Spaltprodukte	
Cs-137	1
Sr-90	0,6
Stabile Isotope	
Lanthaniden	15,87
andere Stabile	35,64

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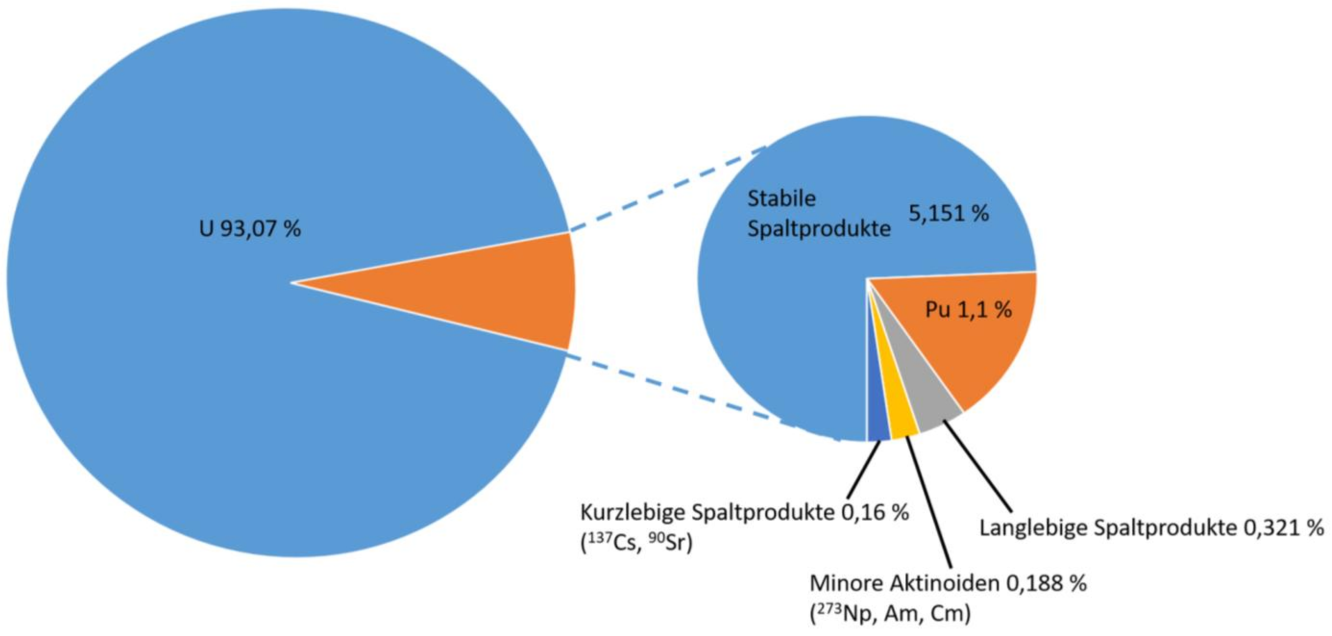
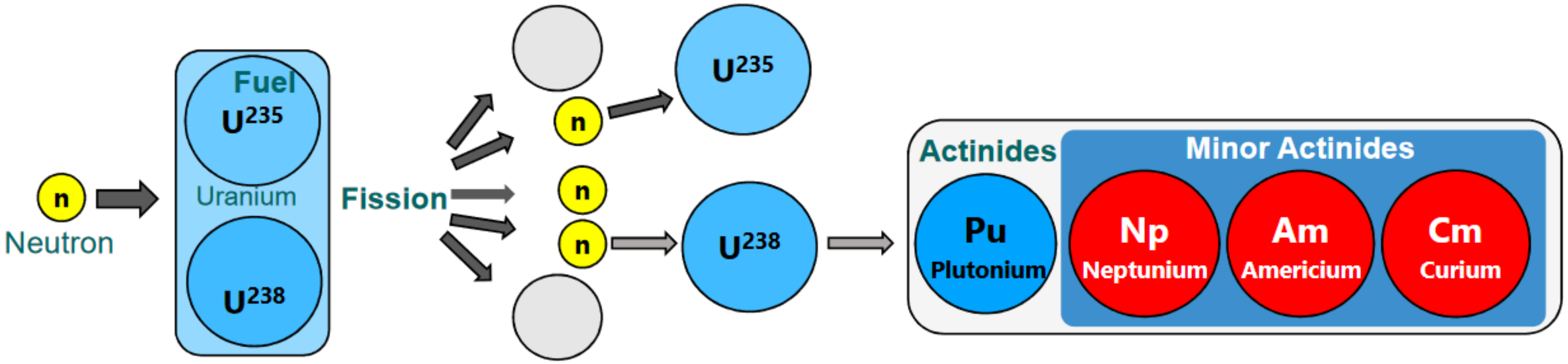
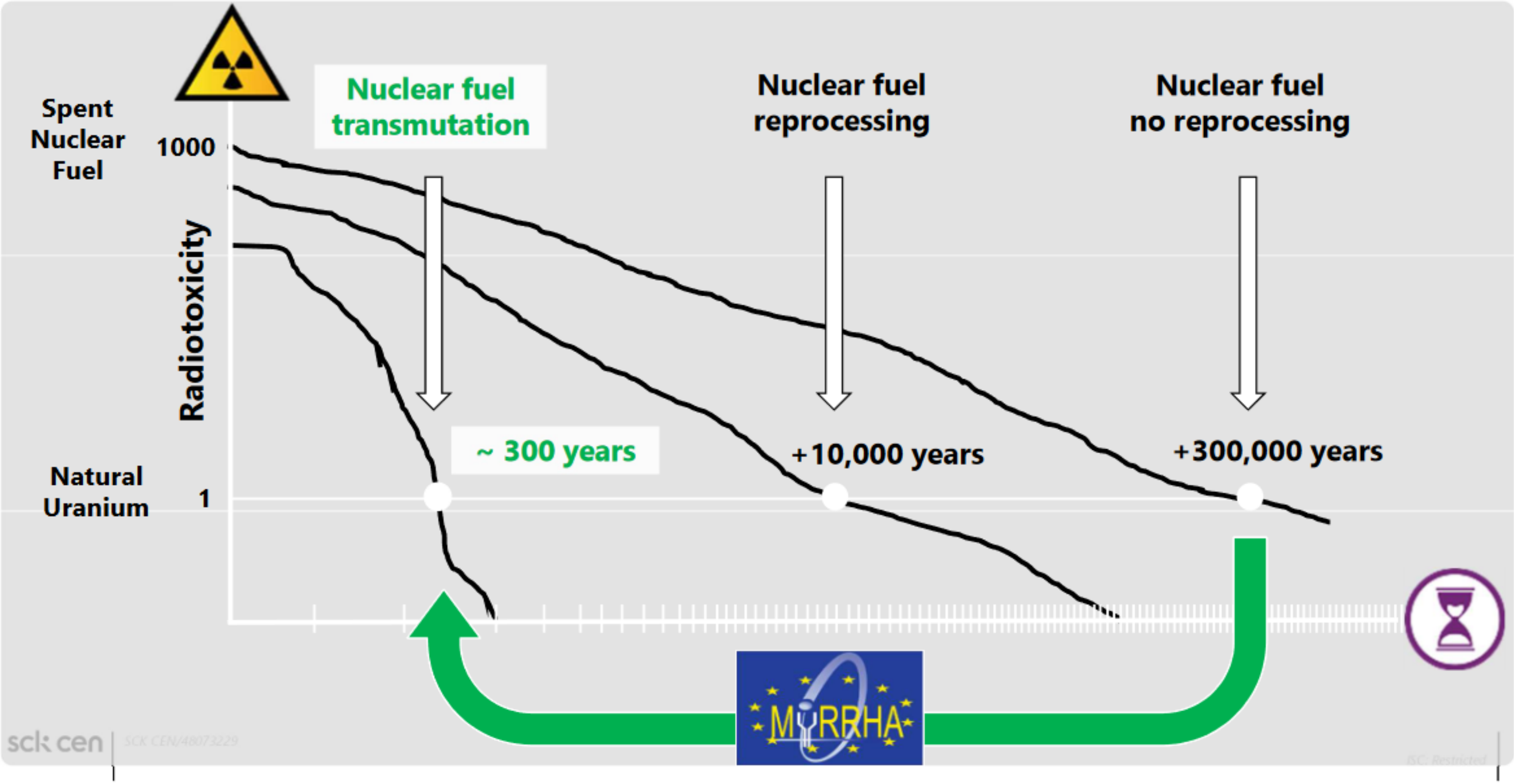


O.RENN (HRSG.): *Partitionierung und Transmutation. Forschung - Entwicklung – Gesellschaftliche Implikationen (acatech STUDIE).* Herbert Utz Verlag, München, 2014.



C. Angulo, MYRRHA A New Large Research Infrastructure in Belgium for Applications in Nuclear Energy and Nuclear Physics, Talk at the FlipPhysics Workshop, 2022,https://www.google.com/url?sa=i&url=https%3A%2F%2Findico.ific.uv.es%2Fevent%2F6372%2Fcontributions%2F17464%2Fattachments%2F9905%2F13624%2F4_Angulo.pdf&psig=AOvVaw1drmyYsV7NfTAqKwO5BumE&ust=1732635420596000&source=images&cd=vfe&opi=89978449&ved=0CBgQ3YkBahcKEwi4q_yS6PeJAxUAAAAAHQAAAAAQBA



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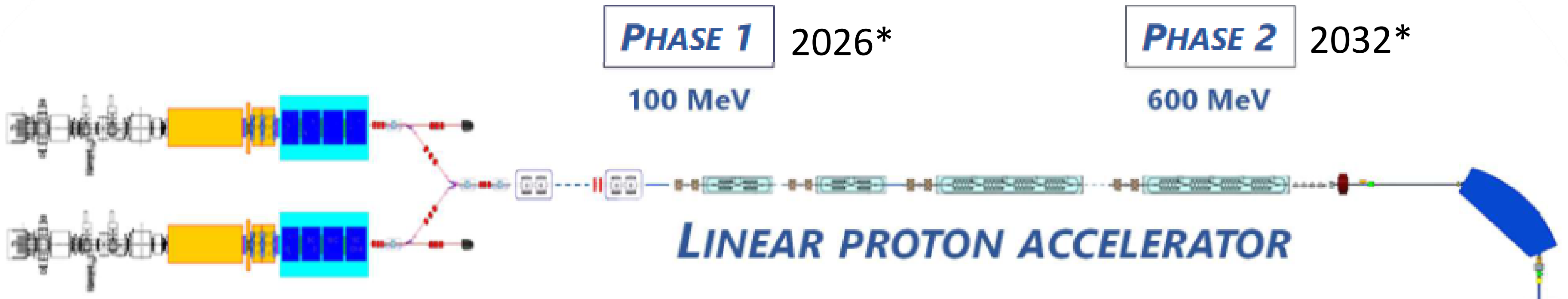
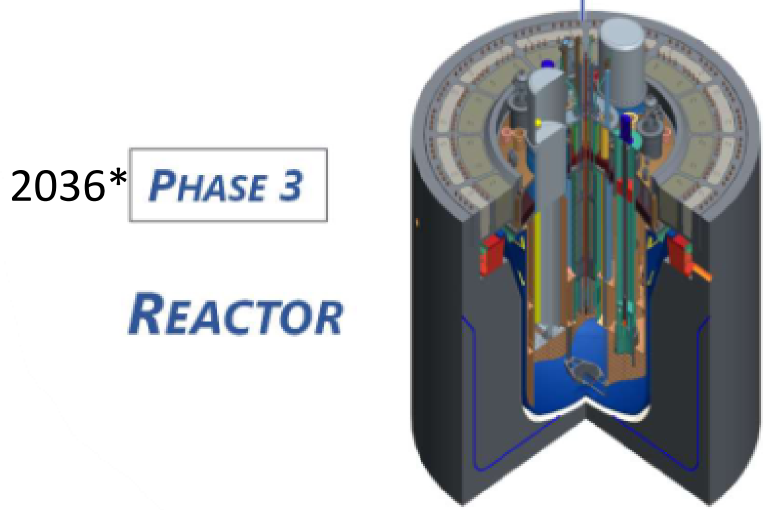
MYRRHA – **M**ulti-purpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications





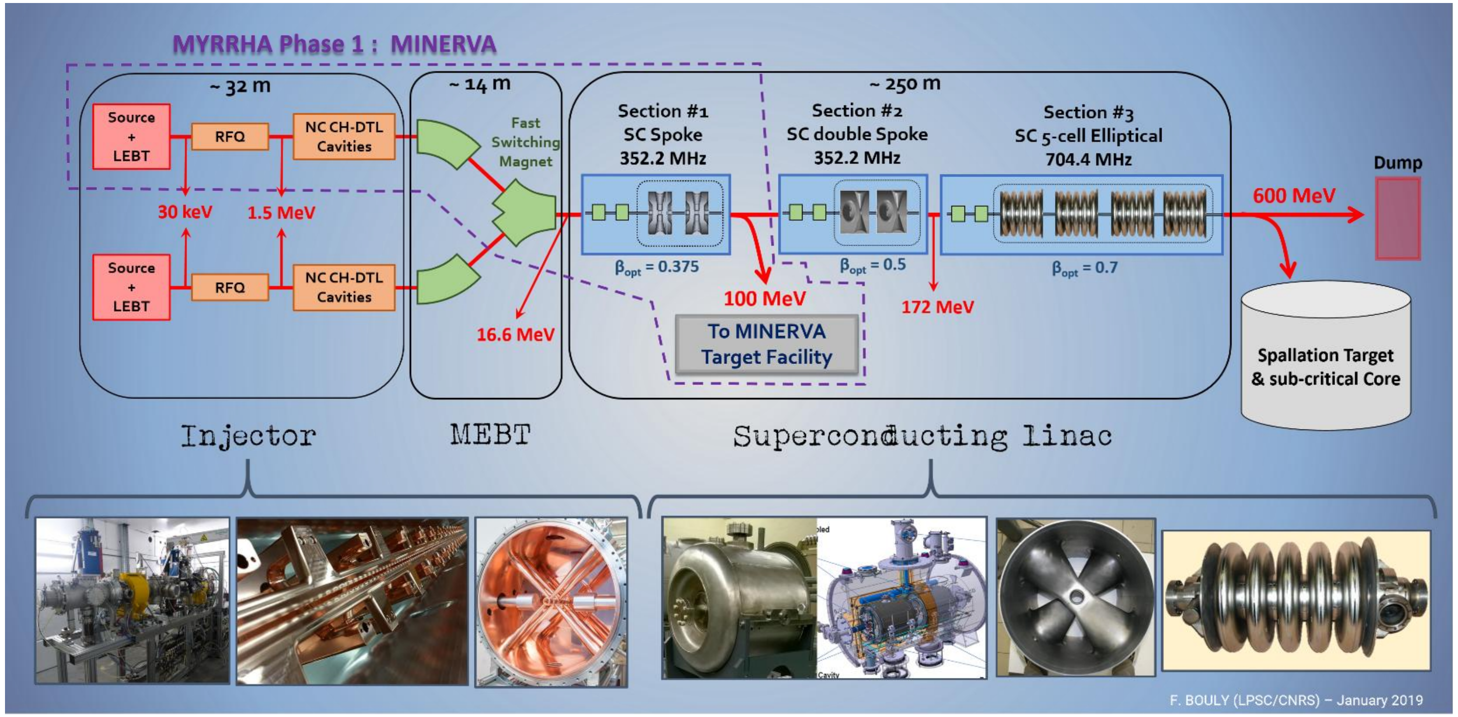
particles	protons	N/A
energy	600	MeV
current	4	mA
beam power	2.4	MW
duty factor	100	%
beam stability	energy ±1%, current ±2% position ±10%, size ±10%	N/A
MTBF	250	h

What should MYRRHA do?

- Demonstrate the ADS at pre-industrial scale
- Demonstrate Transmutation
- Use as a multipurpose and flexible irradiation facility

*planned

MYRRHA – Multi-purpose hYbrid Research Reactor for High-tech Applications



F.Bouly et al.: Superconducting LINAC Design Upgrade in View of the 100MeV MYRRHA Phase I. Proceedings of IPAC2019 (pp. 837-840, MOPTS003), Melbourne, Australia, 2019, https://doi.org/10.18429/JACoW-IPAC2019-MOPTS003

Parts of MYRRHA:

- **LINAC** – **LIN**ear **AC**celerator
- **PTF** – **P**roton **T**arget **F**acility
- **FPF** – **F**ull **P**ower **F**acility
- undercritical Reaktor

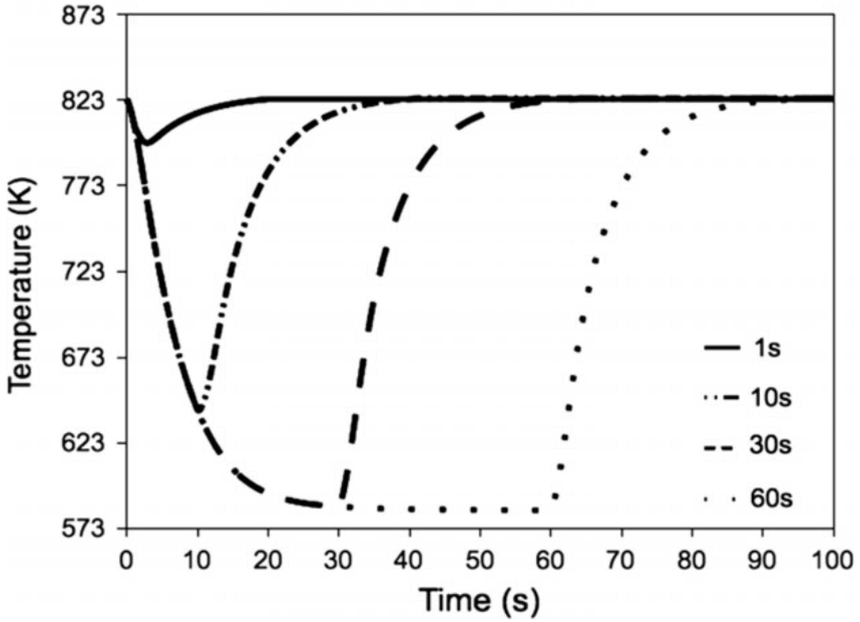
- **Sustainable fission energy:** demonstrate the physics and technology of an Accelerator Driven System (ADS) for transmuting long-lived radioactive waste
- **Sustainable energy:** development of a fast-spectrum reactor and fusion technology
- **Enabling technologies for renewable energies:** production of neutron irradiated silicon
- **Health care:** production of radioisotopes for nuclear medicin (e.g. Mo-99)
- **Science:** production of radioisotopes for fundamental and applied science via the Isotope Separation On-Line method at ISOL@MYRRHA

Nuclear-physics applications of MYRRHA
Lucia Popescu
EPJ Web of Conferences 66 10011 (2014)
DOI: 10.1051/epjconf/20146610011

„…number of beam trips longer than 3 s remains under 10 during a 3-months operational period of the Myrrha reactor…“ [1]

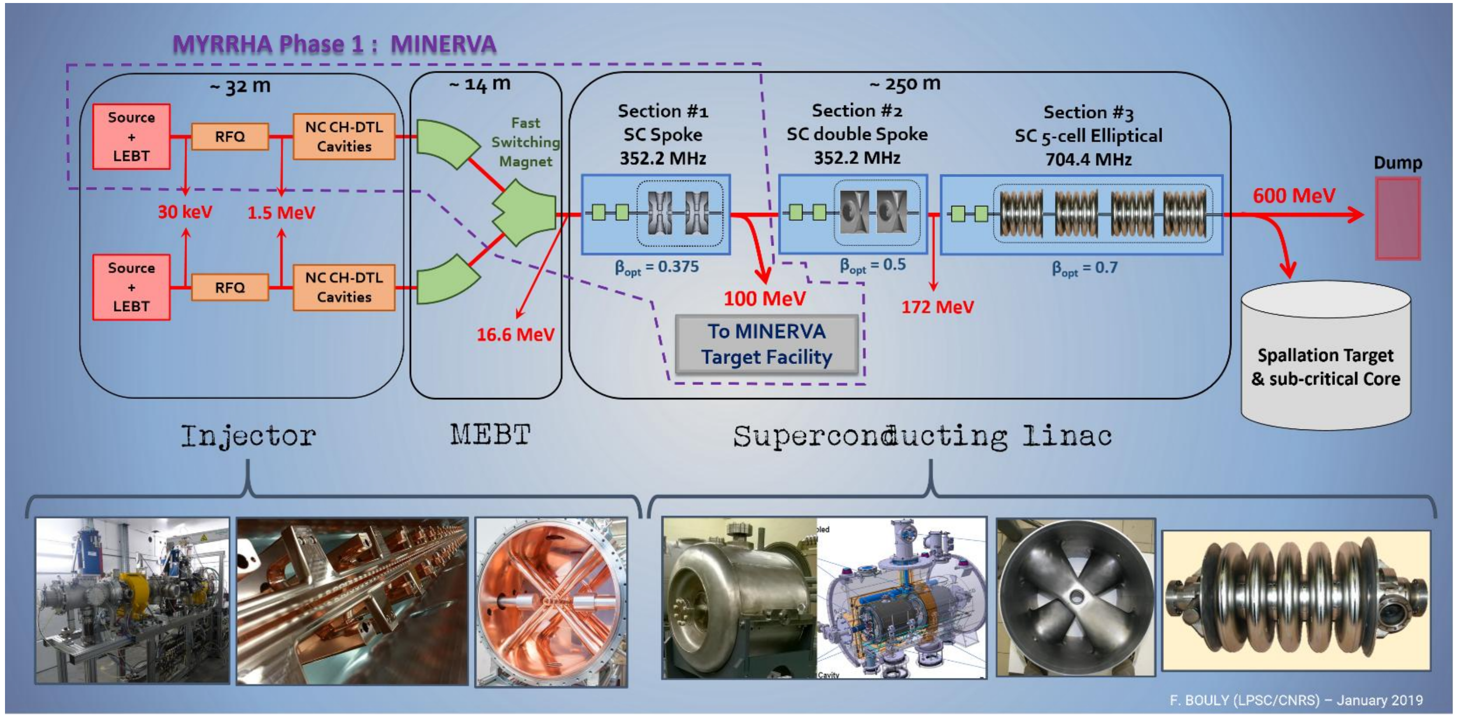
MTBF > 250 h

- use of components far from their limits
  - e.g. the voltages of the cavities in the injector
- Redundancy
  - Parallel scheme in the injector
  - Serial scheme in the superconducting part
- Repairability
  - e.g. use of similar components



[1] D. Vandeplassche, J.-L. Biarrotte, H. Klein, H. Podlech, „The MYRRHA Linear Accelerator“, in *Proc. 2nd International Particle Accelerator Conf. (IPAC11)*, San Sebastian, Spain, Sep. 2011, paper WEPS090, pp. 2718-2720

MYRRHA – **M**ulti-purpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications



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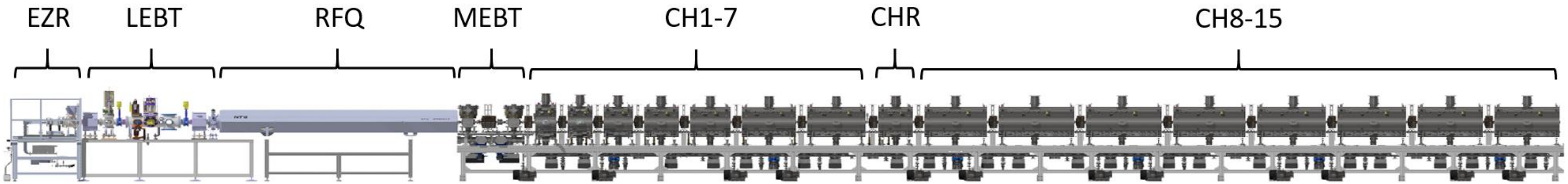
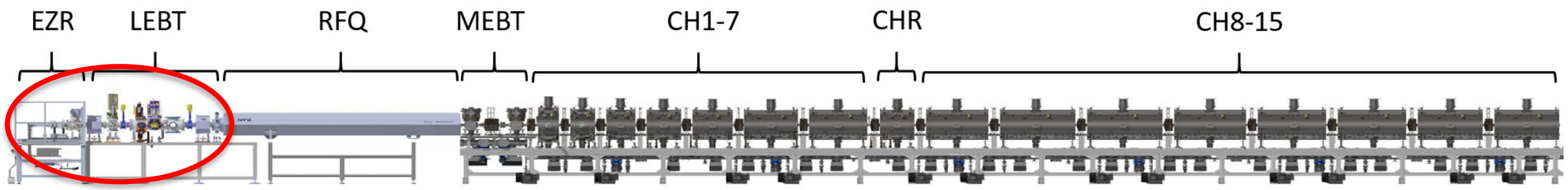


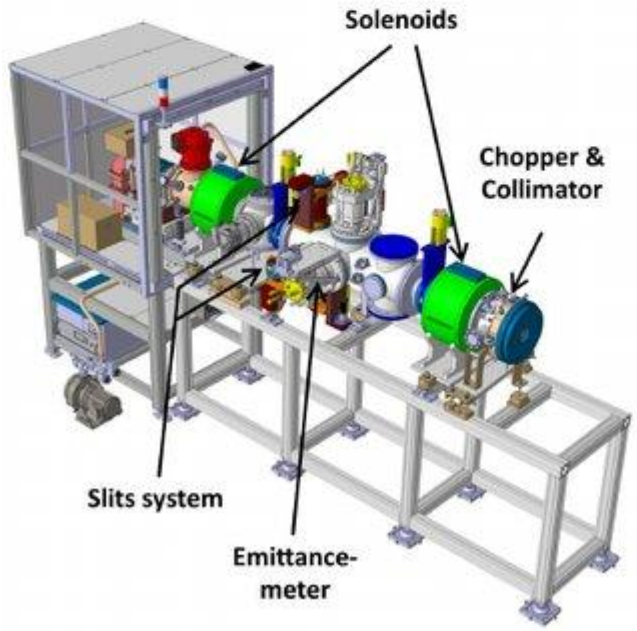
The MYRRHA Injector



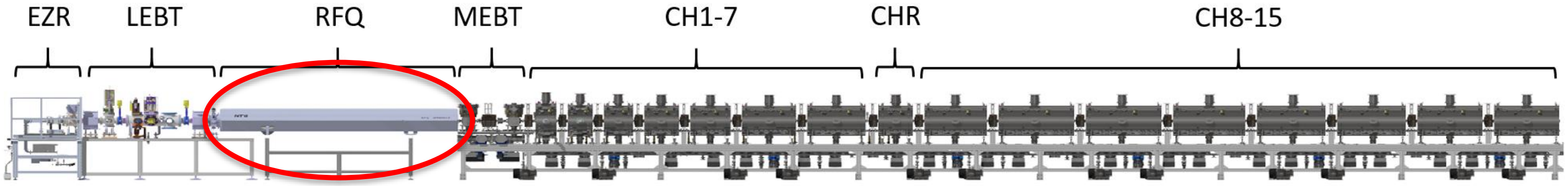
Electron Cyclotron Resonance (ECR) ion source at 2.45 GHz

Low Energy Beam Transport (LEBT)
- Beam diagnostics (emittance meter, faraday cup…)
- Solenoids for focussing

The job of the LEBT is to maximize the proton beam quality injected into the RFQ

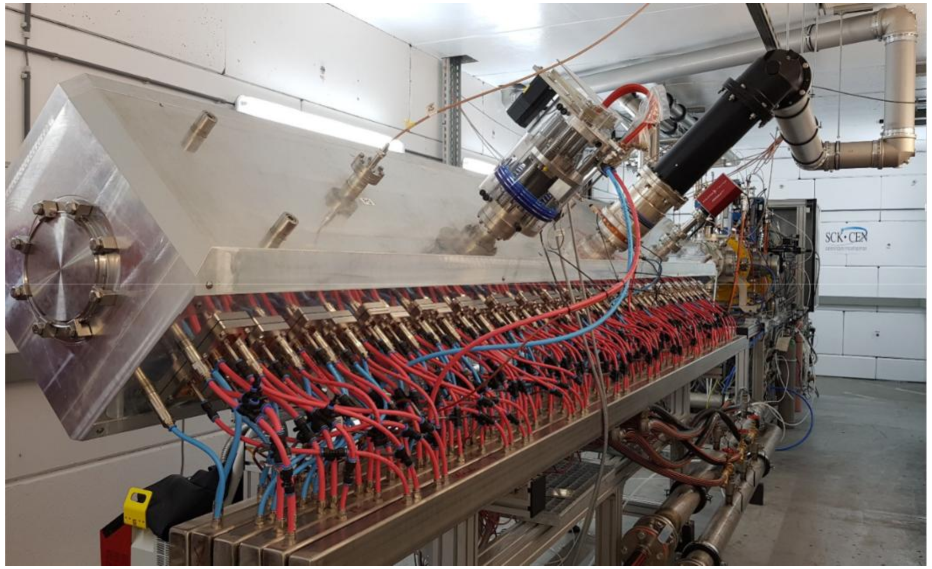


Überblick
Linearbeschleuniger (LINAC)



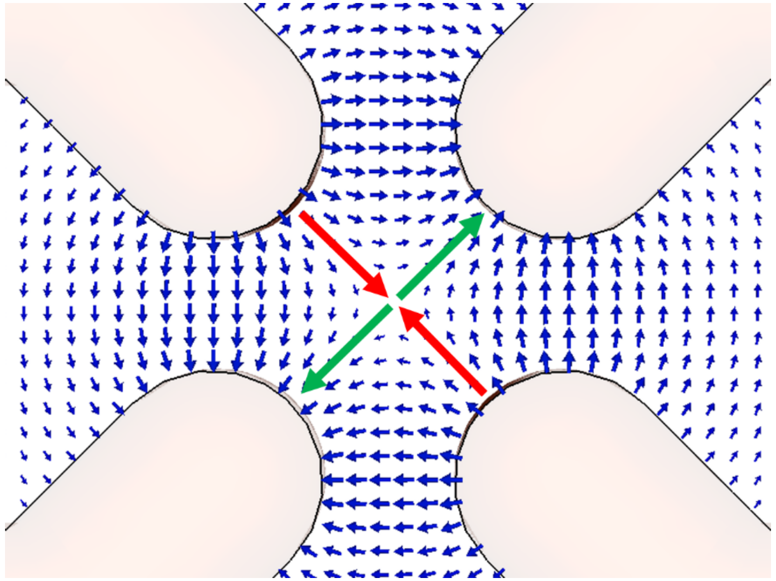
"First accelerating structure"

- Focusing
- Bunching
- Accelerate



Parameter	MHYRRA	Unit
RF Structure	4.Rod	---
Frequency	176.1	MHz
Beam current	4	mA
Duty factor	100	%
E_{in}	30	keV
E_{out}	1.5	MeV
RF Power	108	kW
Voltage	44	kV
Length	4	m

Simulated values

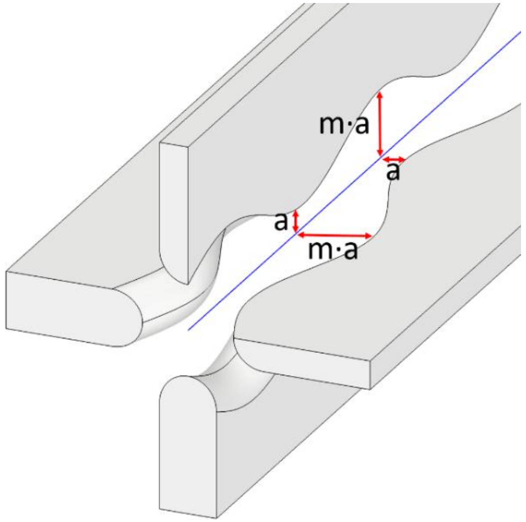


Transverse electric quadrupole field

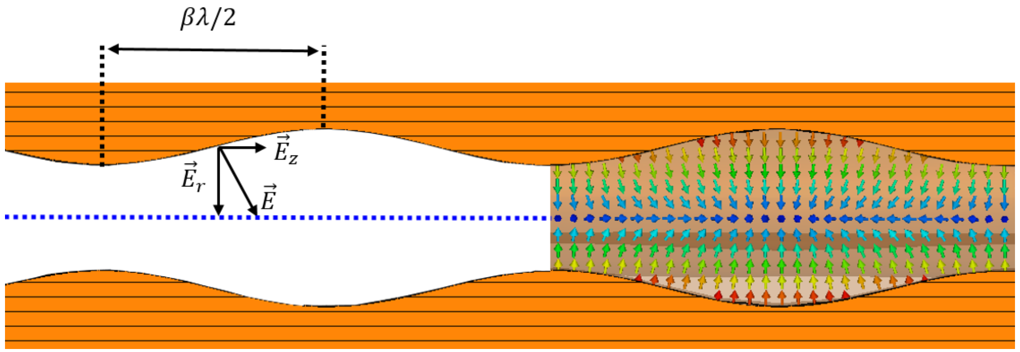
(1) Transversal Focusing

(2) Longitudinal bunching

(3) Acceleration



Modulation of the quadrupole electrodes



Field components due to electrode modulation

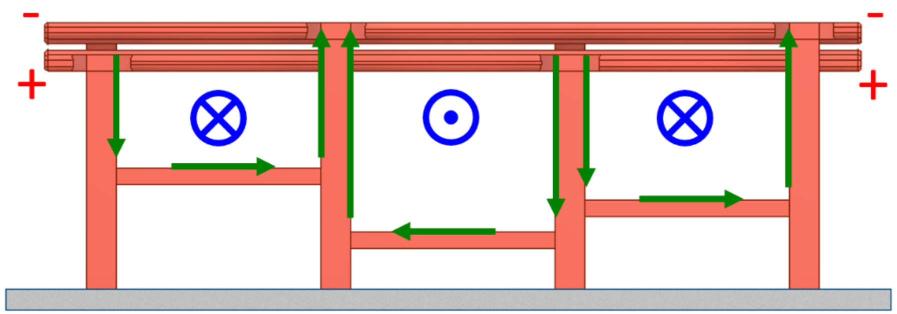
Can be realised as:

<u>Cavity Resonator</u>

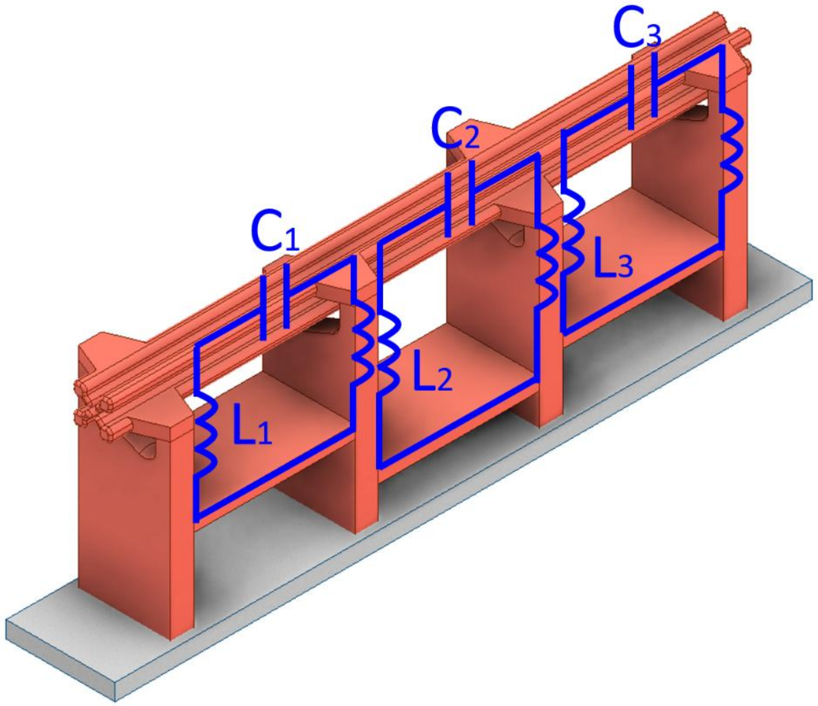
- 4-Vane ($TE_{21(0)}$-Mode)
- Interdigital H-Moden (IH) ($TE_{11(0)}$-Mode)

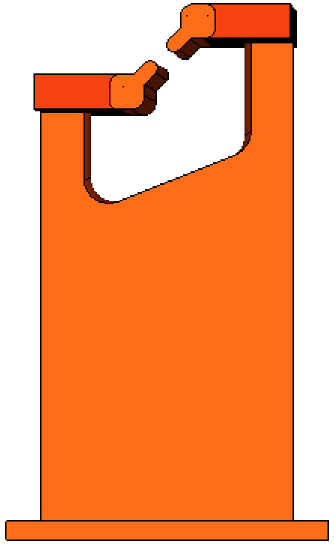
<u>Line Resonator</u>

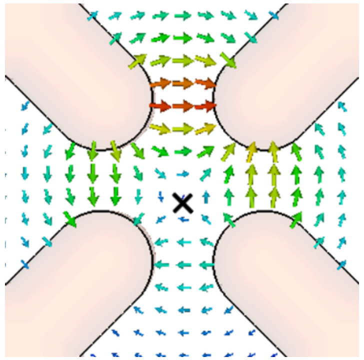
- 4-Rod-RFQ
- Ladder-RFQ
- Spiral-RFQ
- Split-Ring-RFQ



Resonatorstruktur des 4-Rod-RFQ



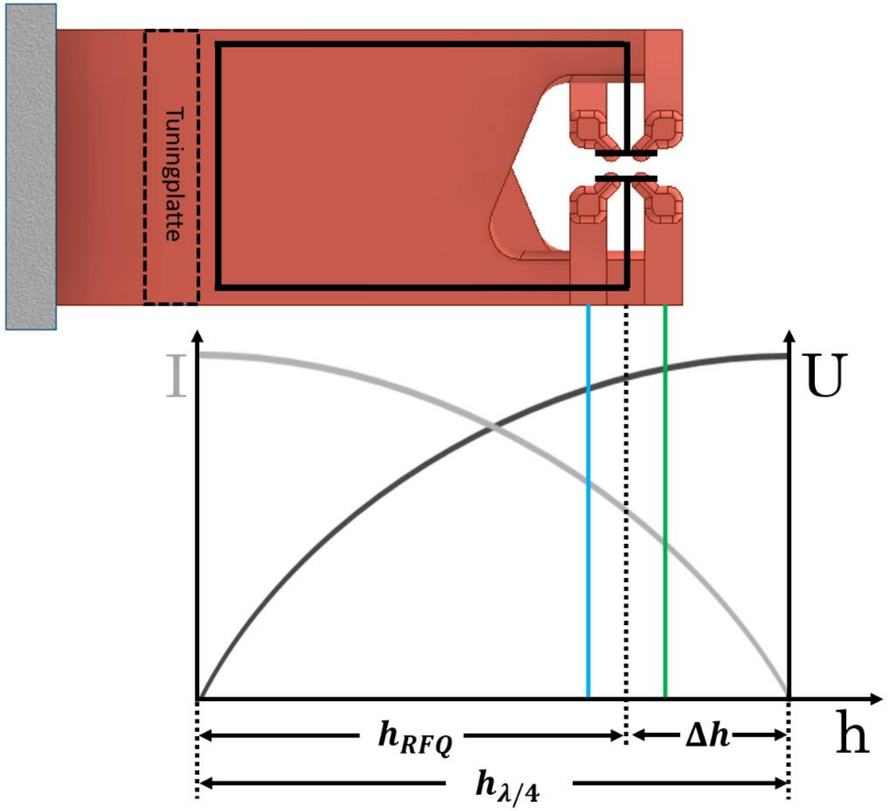




Asymmetric quadrupole field due to the dipole

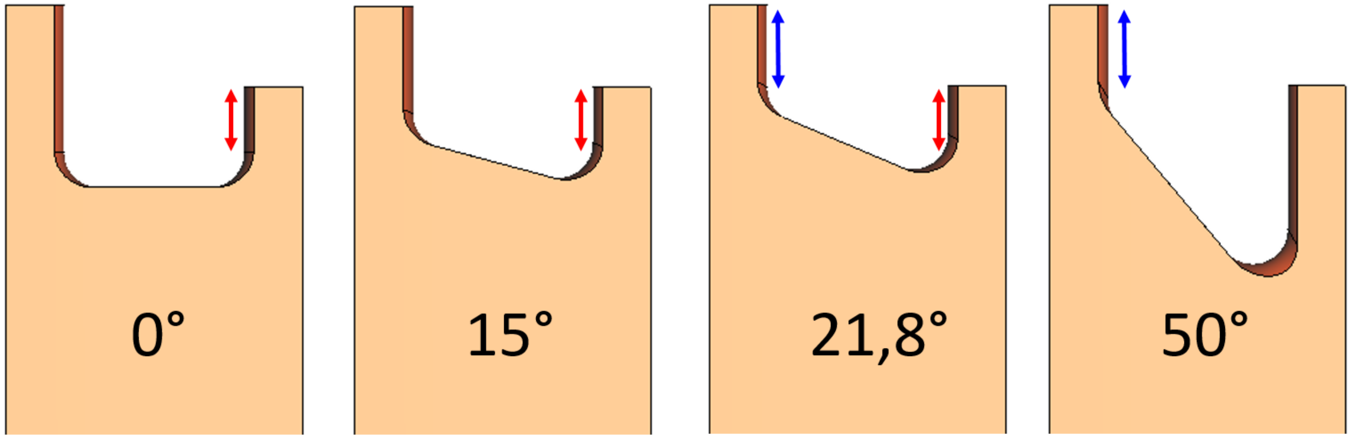
$$\mathrm{Def}_{\mathrm{oben}} = \frac{|U_{\mathrm{oben}}| - |U_{\mathrm{unten}}|}{|U_{\mathrm{oben}}|}$$

$$\mathrm{Def}_{\mathrm{Mittel}} = \frac{|U_{\mathrm{oben}}| - |U_{\mathrm{unten}}|}{\frac{|U_{\mathrm{oben}}|+|U_{\mathrm{unten}}|}{2}}$$



Comparison of the voltage and current distribution of an RFQ stem with a theoretical λ/4 resonator

The 4-Rod-RFQ



$$\mathrm{Def}_{\mathrm{oben}} = \frac{|U_{\mathrm{oben}}| - |U_{\mathrm{unten}}|}{|U_{\mathrm{oben}}|}$$

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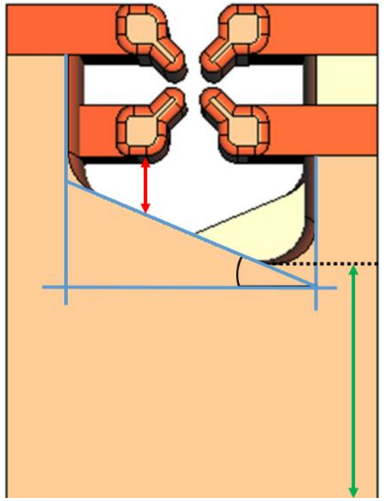
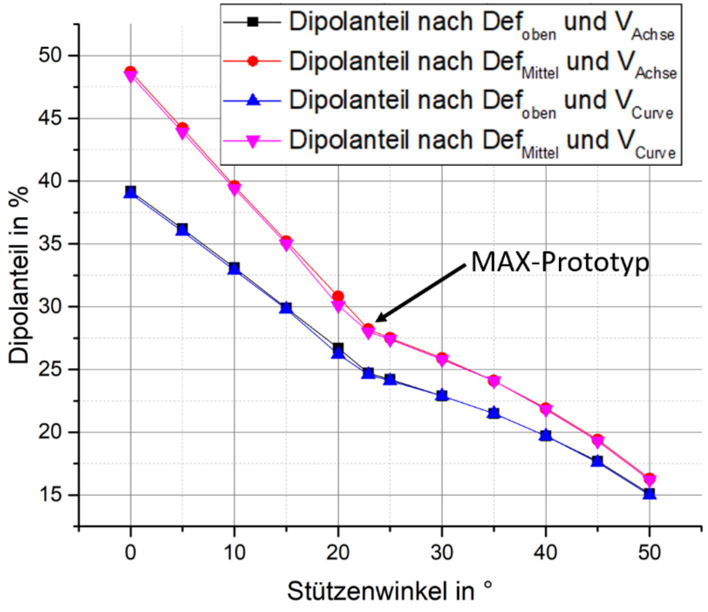
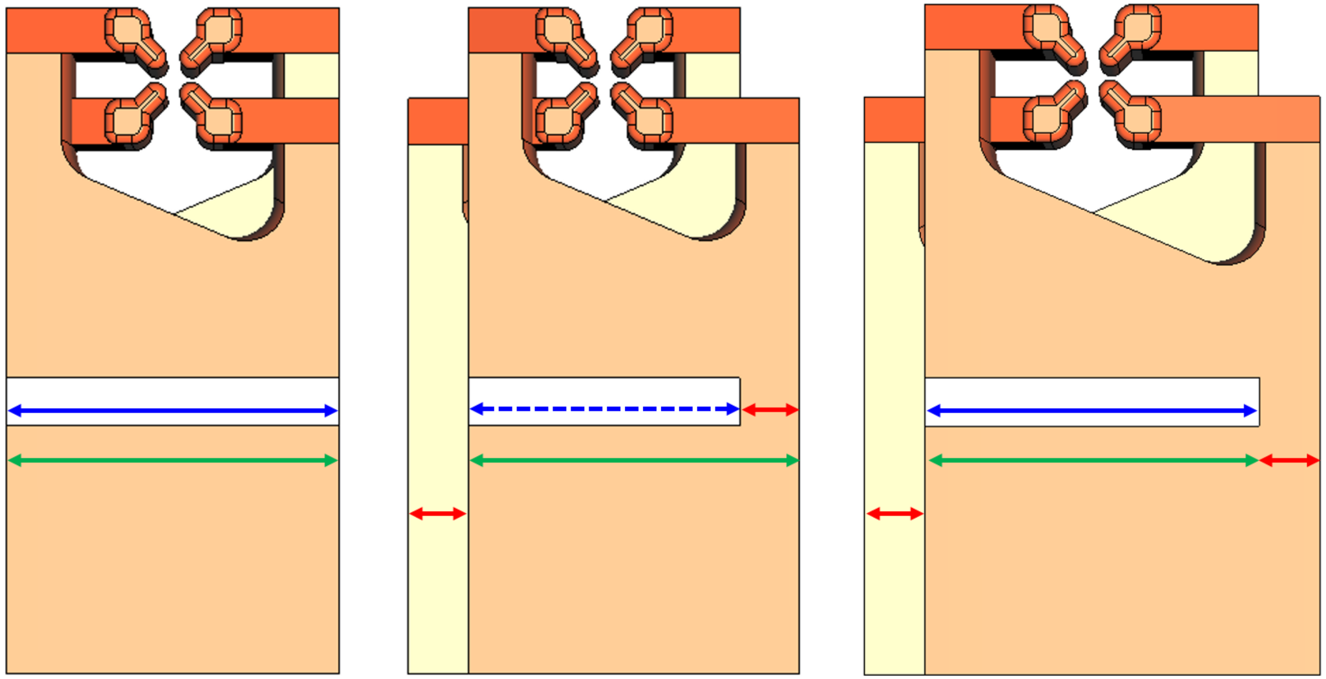


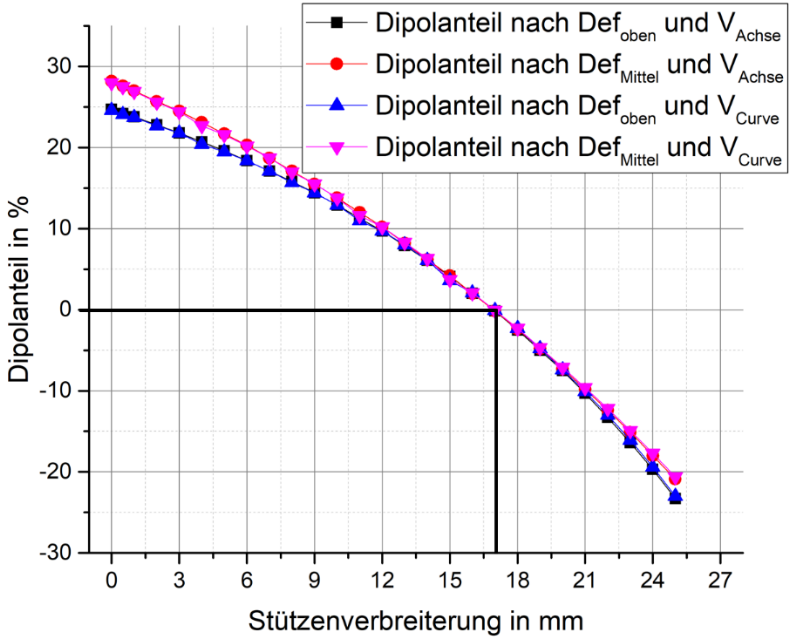


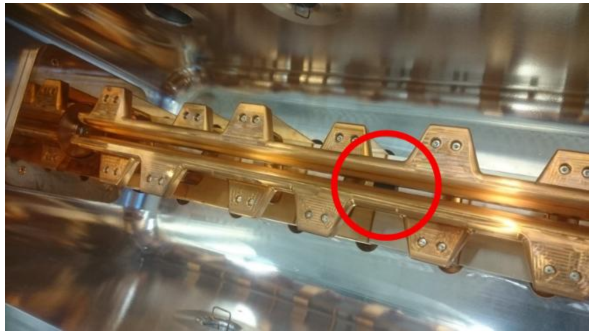


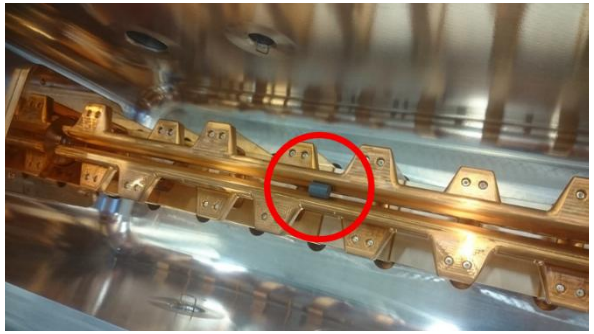
$$\mathrm{Def}_{\mathrm{oben}} = \frac{|U_{\mathrm{oben}}| - |U_{\mathrm{unten}}|}{|U_{\mathrm{oben}}|}$$

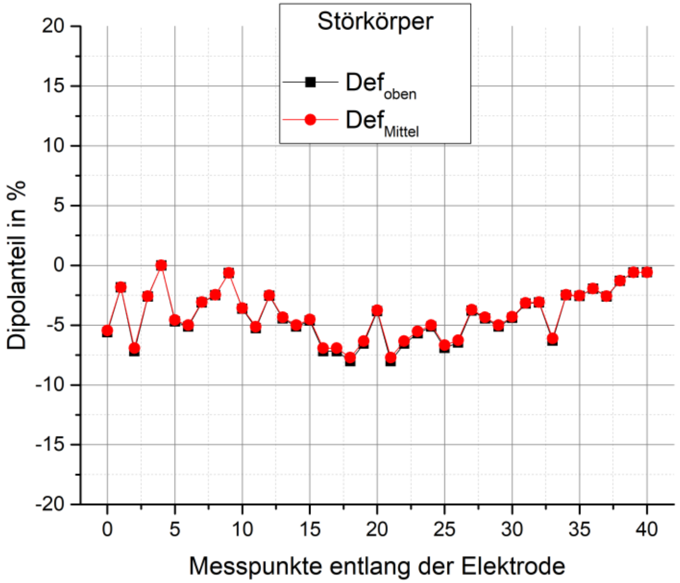
$$\mathrm{Def}_{\mathrm{Mittel}} = \frac{|U_{\mathrm{oben}}| - |U_{\mathrm{unten}}|}{\frac{|U_{\mathrm{oben}}|+|U_{\mathrm{unten}}|}{2}}$$

simulierte Größe	MYRRHA-RFQ-Simulationsmodell
Dipol nach Def_{oben} und V_{Achse}	-3,3 %
Dipol nach Def_{Mittel} und V_{Achse}	-3,2 %
Dipol nach Def_{oben} und V_{Curve}	-2,8 %
Dipol nach Def_{Mittel} und V_{Curve}	-2,7 %





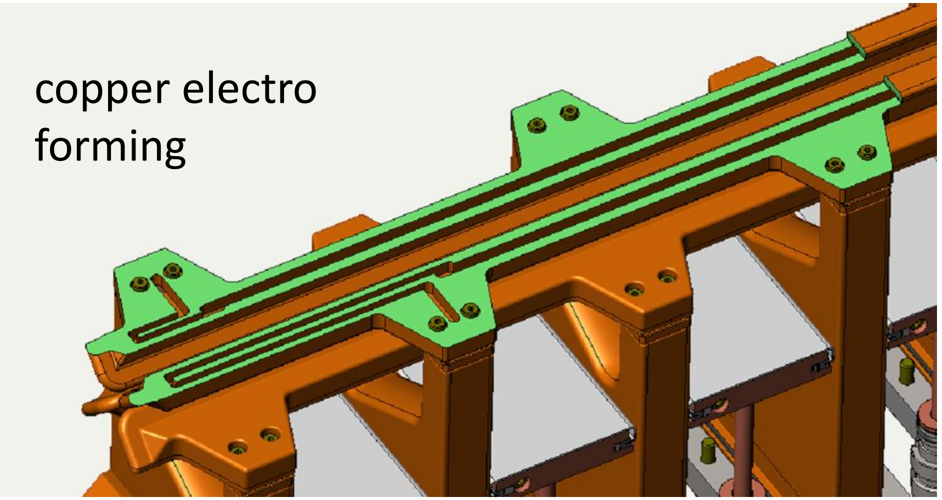


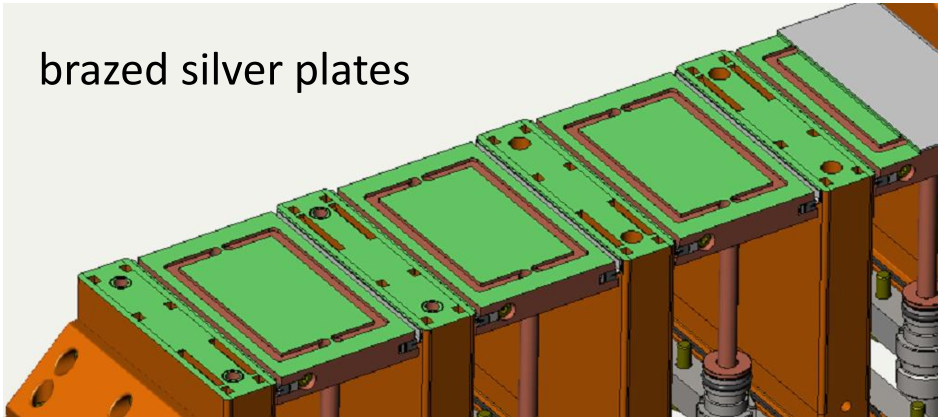


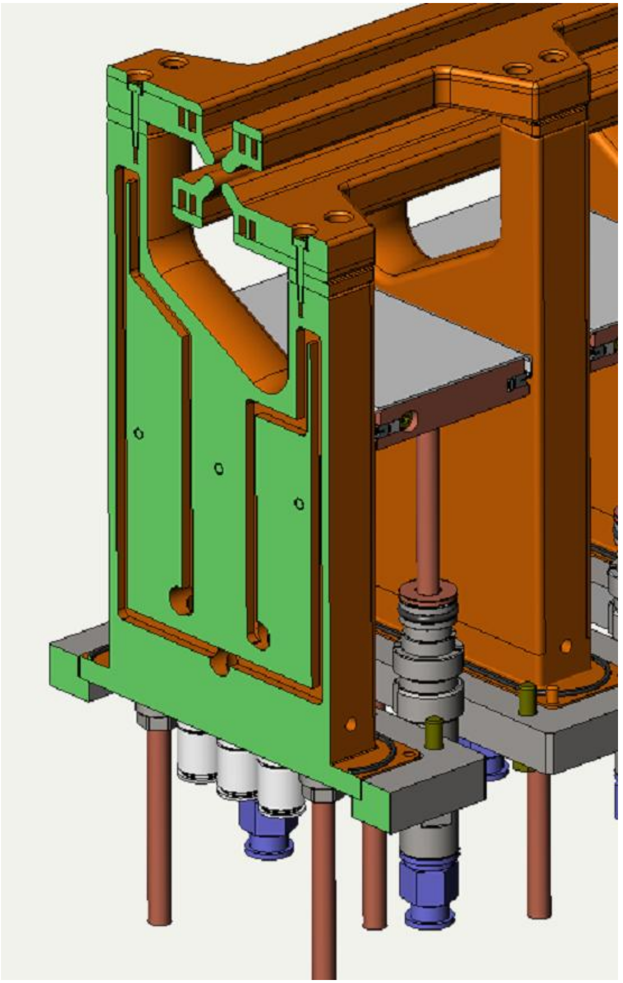
	Dipol gemessen	Dipol Sim. V_{Achse}	Dipol Sim. V_{Curve}
Dipol nach Def_{oben}	-4,2 %	-3,3 %	-2,8 %
Dipol nach Def_{Mittel}	-4,1 %	-3,2 %	-2,7 %

- Limitations in the design of internal cooling channels
- Tension in the assembly due to clamped tuning plates
- Shunt impedance /Q-factor worse than simulations predict (~ 75-80 %)
  - Due to contact resistance of multiple connected parts
- Usage of o-rings instead (could we have a „better“ vacuum?)

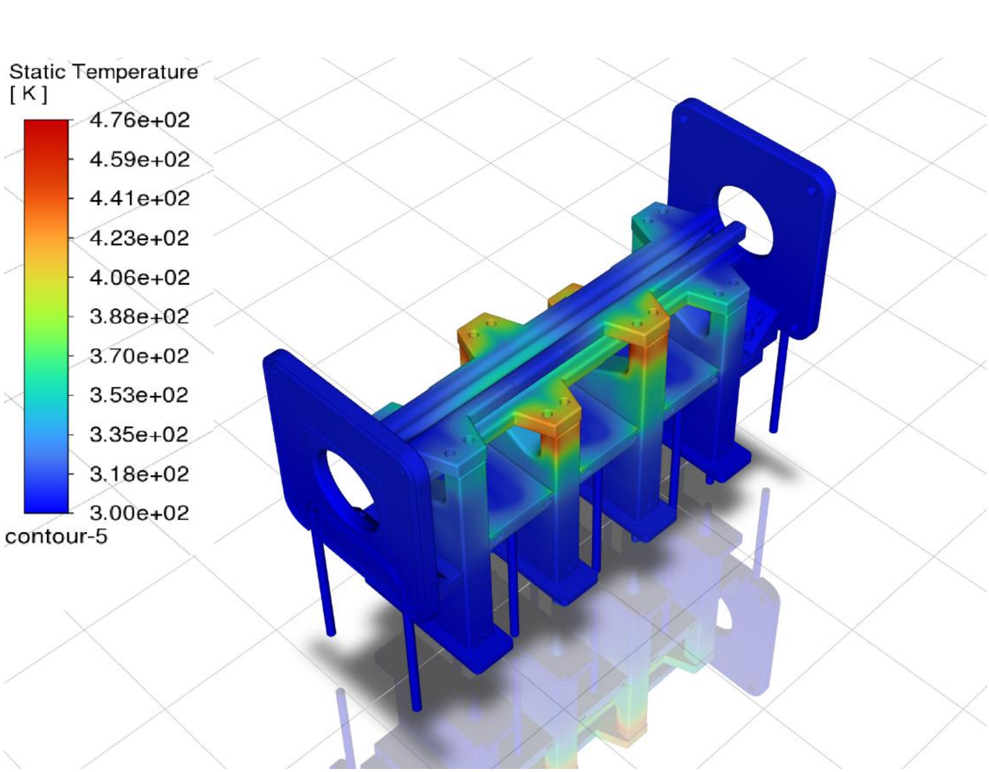
Cooling System on Main Parts of the RFQ

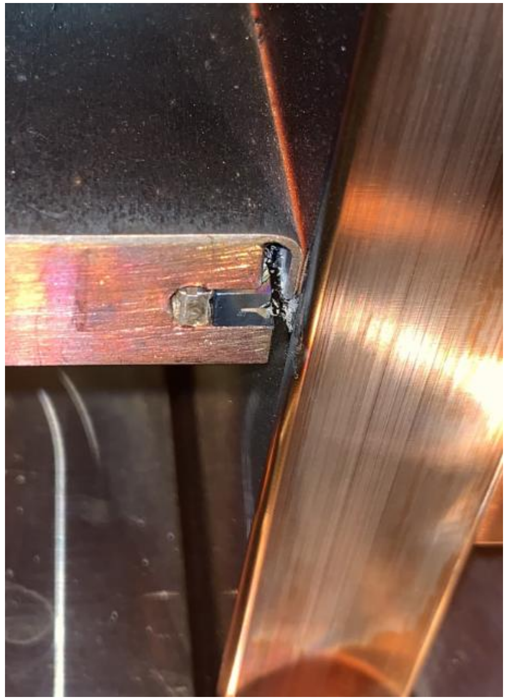






Current Problems / Challenges of the 4-Rod-RFQ





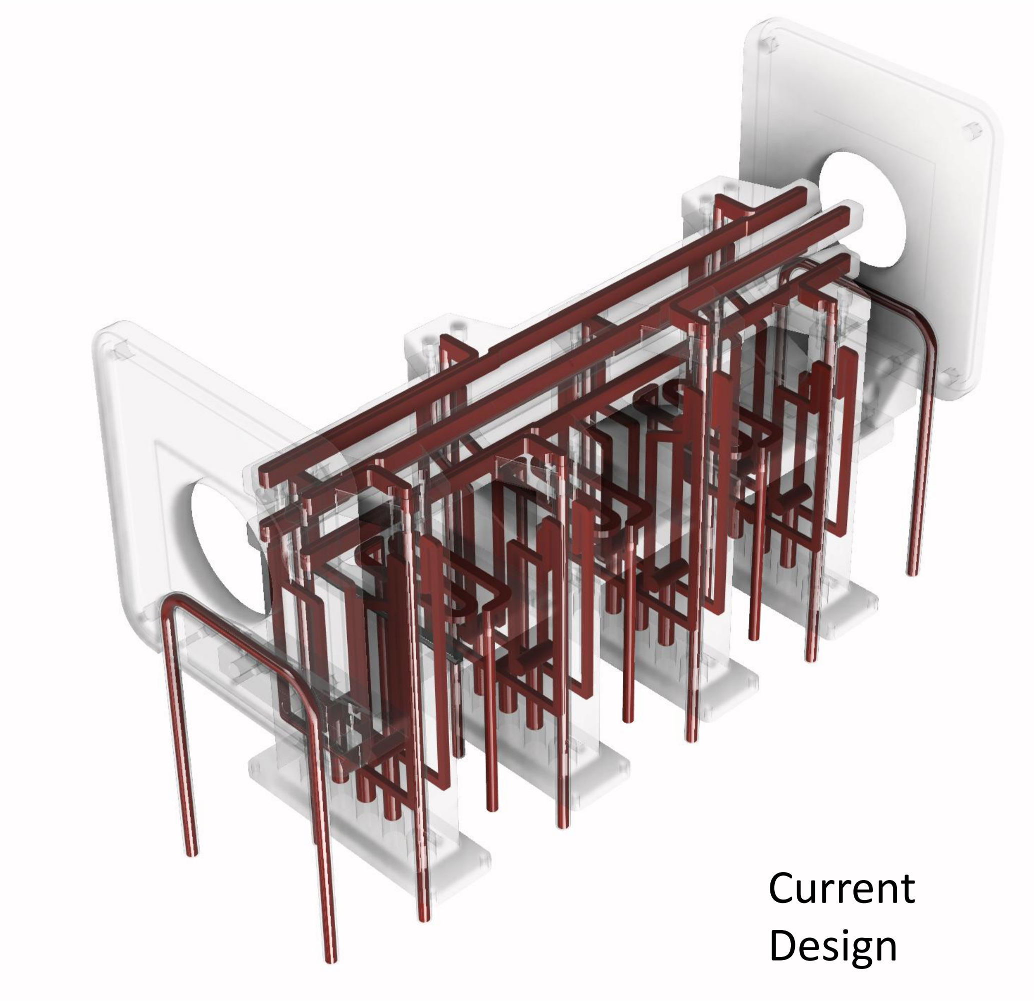
Thermal oxidation
occured during operation
→High surface temperatures

P_F=127,5 kW/m

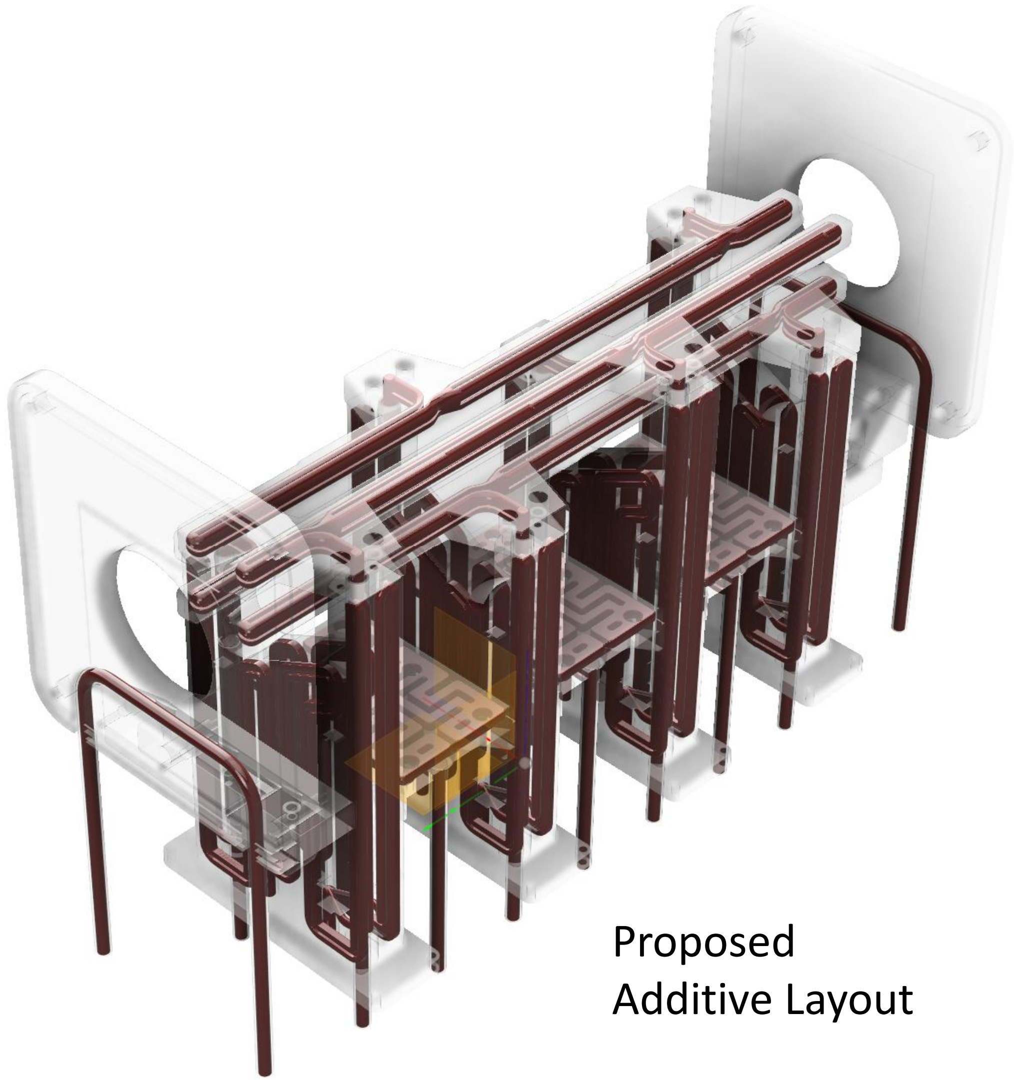
Tuning plates welded to the Stems
→ High contact resistance
→ Limited cooling in this area

Damage occured at a multiple of the design power!

Current Problems / Challenges of the 4-Rod-RFQ



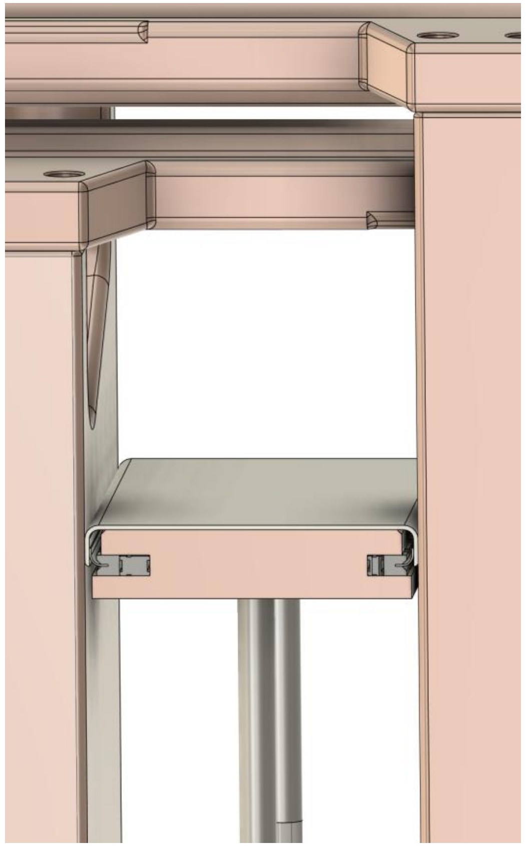
Current Design



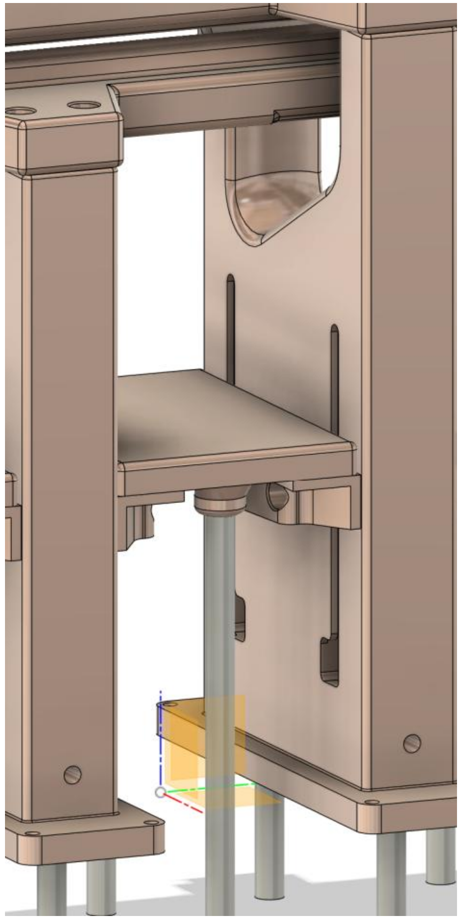
Proposed Additive Layout

- ➢ Limitations in the design of internal cooling channels
- ➢ Tension in the assembly due to clamped tuning plates
- ➢ Shunt impedance /Q-factor worse than simulations predict (~ 75-80 %)
  - Due to contact resistance of multiple connected parts
- ➢ Usage of o-rings instead (could we have a „better“ vacuum?)

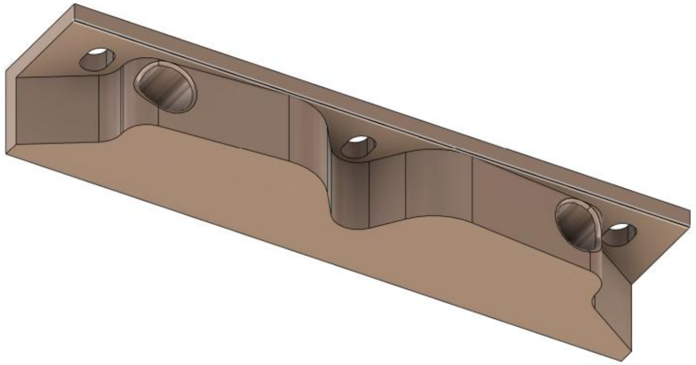
Attachment of the tuning plates



Old design
Silver plate and
clamping system



New design
T-Slots and solid copper
holder screwed from below

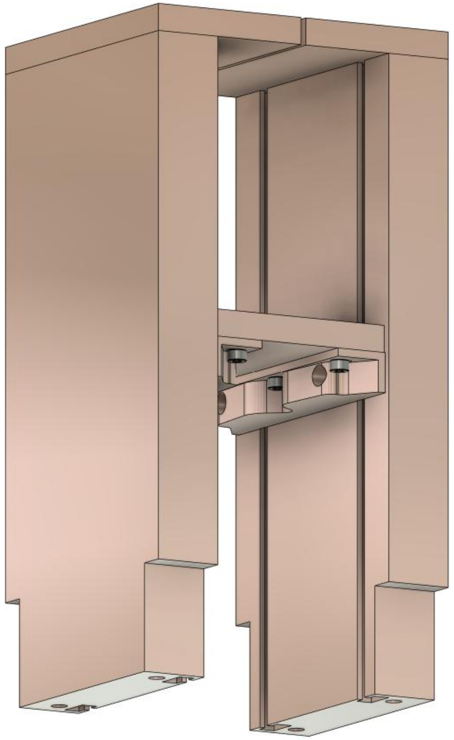


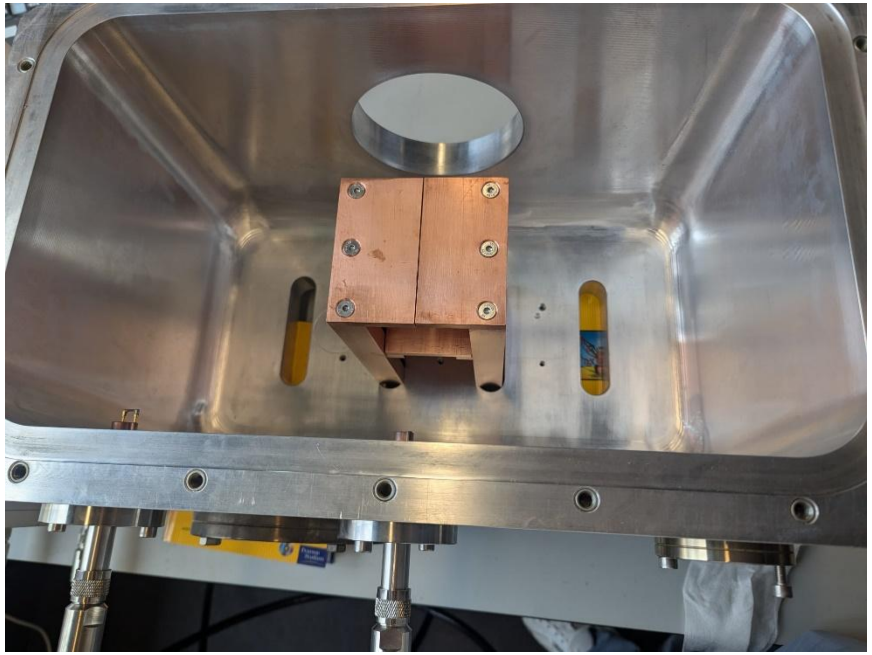
New Holder

- More than sufficient cooling in the contact areas
- Simpler and more cost-efficient design
- Q-factor improvements
- No tension in the assembly

T-Slots and Cooling are only possible,
due to additive process

Test setup for tuning plate mounting





Manufactured with conventional machining f_{res}=176MHz ± 50MHz; $Q_{0,Sim}$= 6800
Allows for clamped and screwed Tuningplates by rotating the stems
First results with rough machined surfaces: ; Q_0= 4300

- Limitations in the design of internal cooling channels
- Tension in the assembly due to clamped tuning plates
- Shunt impedance /Q-factor worse than simulations predict (~ 75-80 %)
  - Due to contact resistance of multiple connected parts
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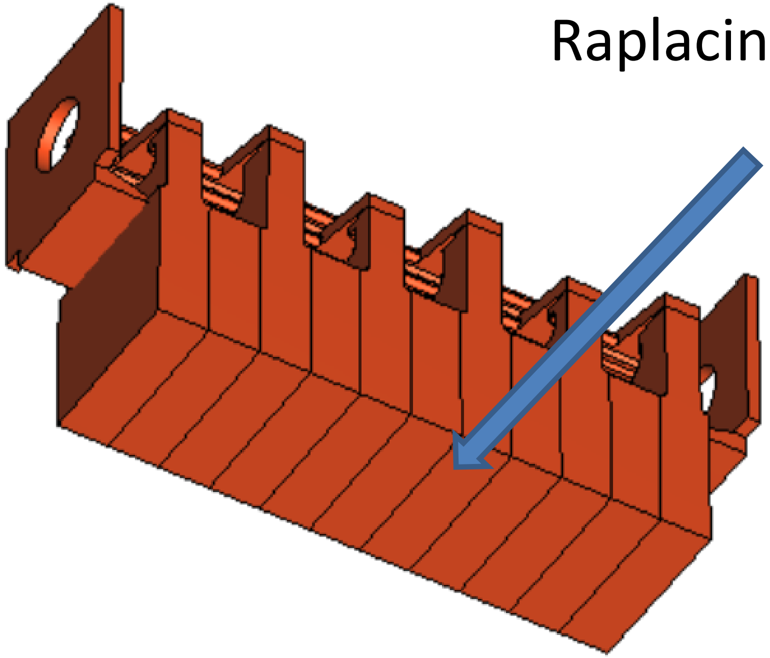
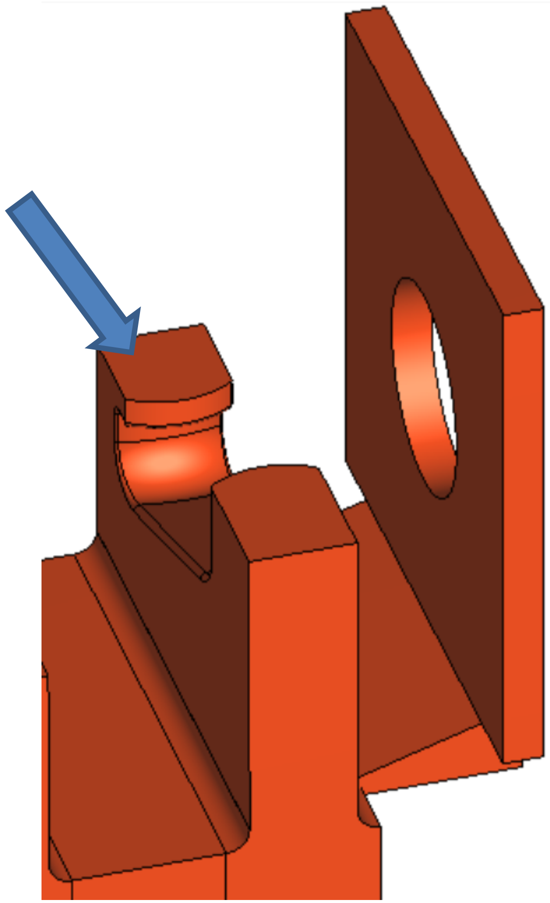
The LOEWE3 RFQ Project

Raplacing the o-rings with metal seals



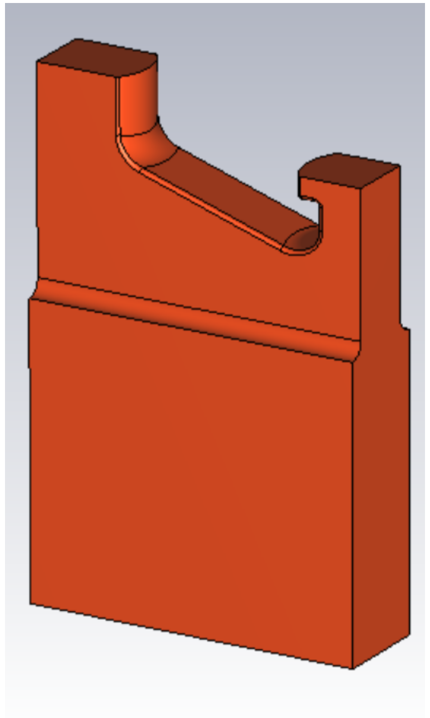


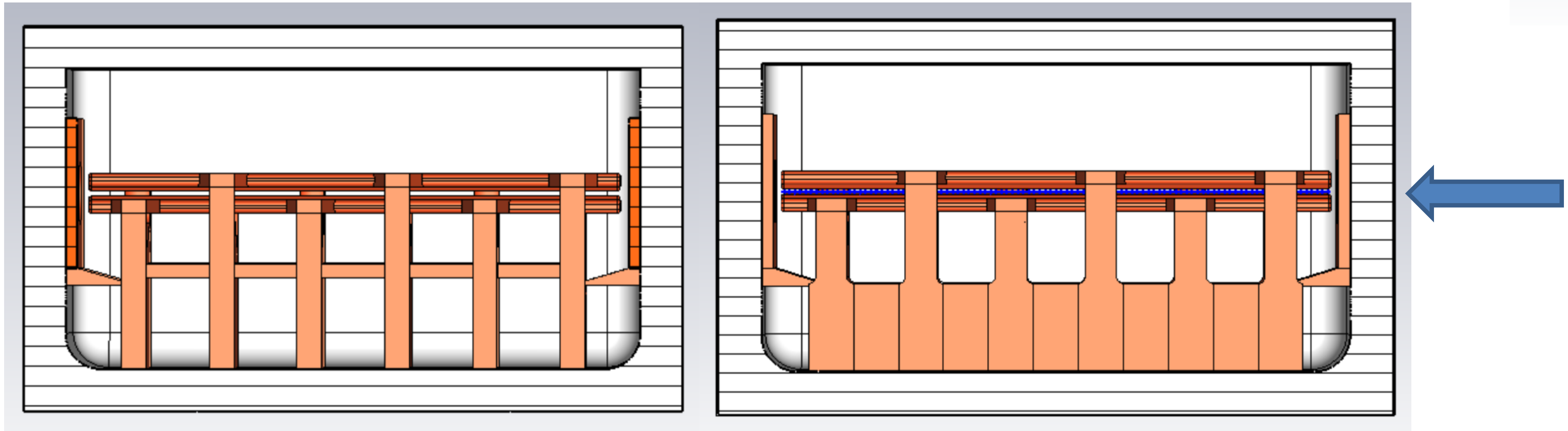
Radii of curvature and contact pressure are specified by the manufacturer

The LOEWE3 RFQ Project

- Stems and tuning blocks should have the same base area to use the same metal seals
- Transition at the support (rounding) should be at the same height as the tuning blocks to avoid the 90° angle

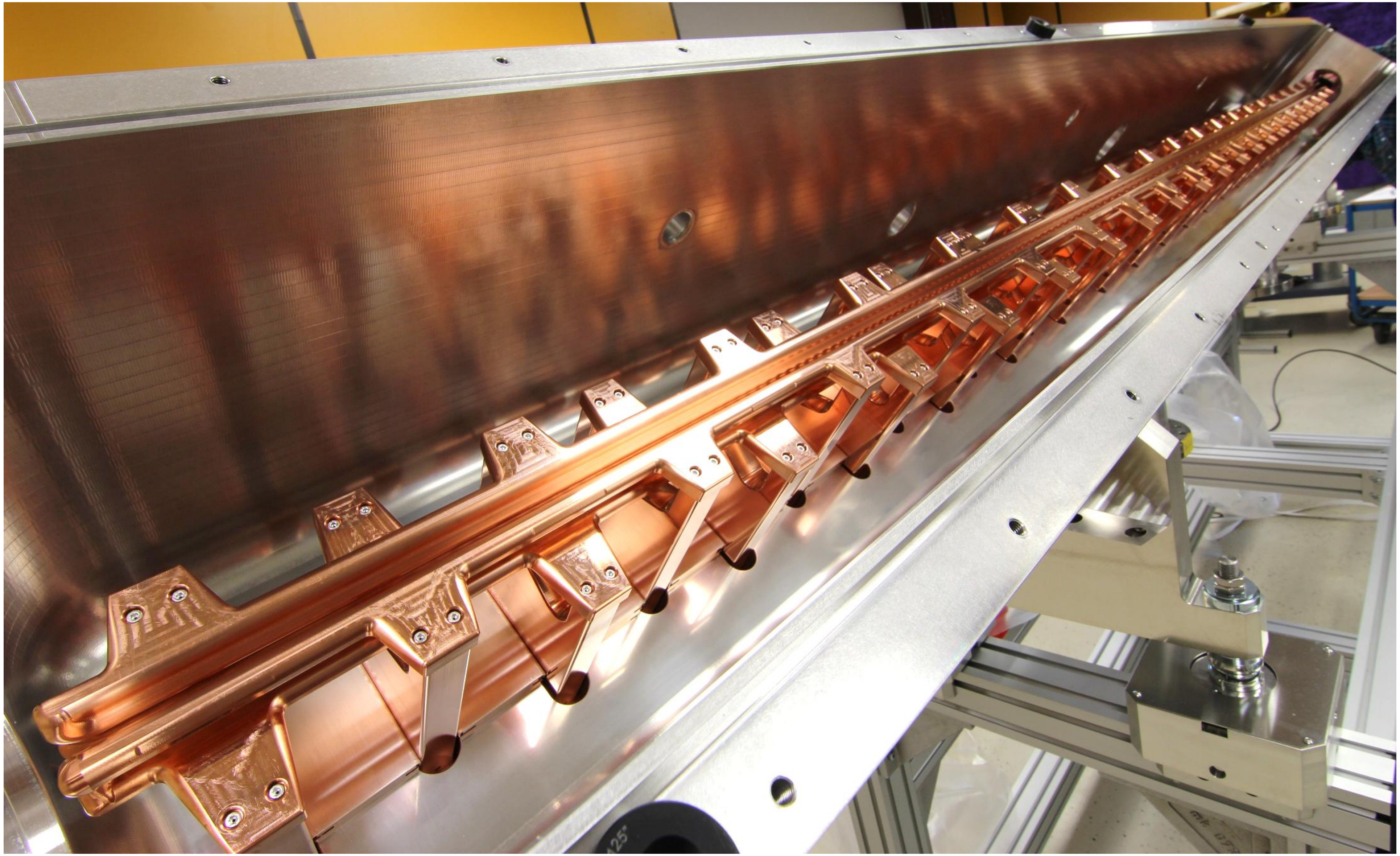
Model	conventional	LOEWE-3
Dipole	2.2 %	0.5 %
R_p	108 700	113 700
Q-factor	5860	6260



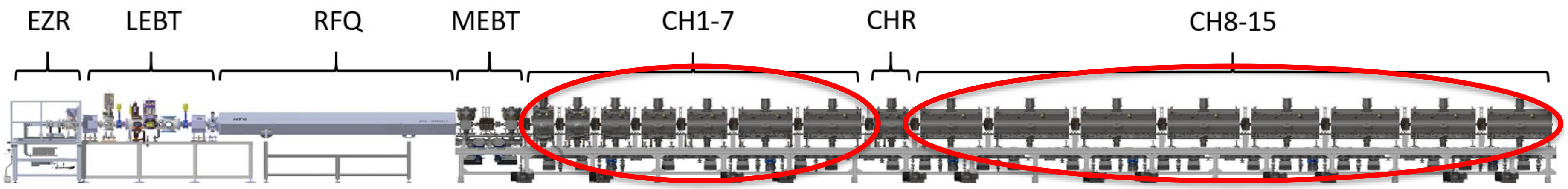


Demonstrator to be ordered in 2024 and measured in 2025

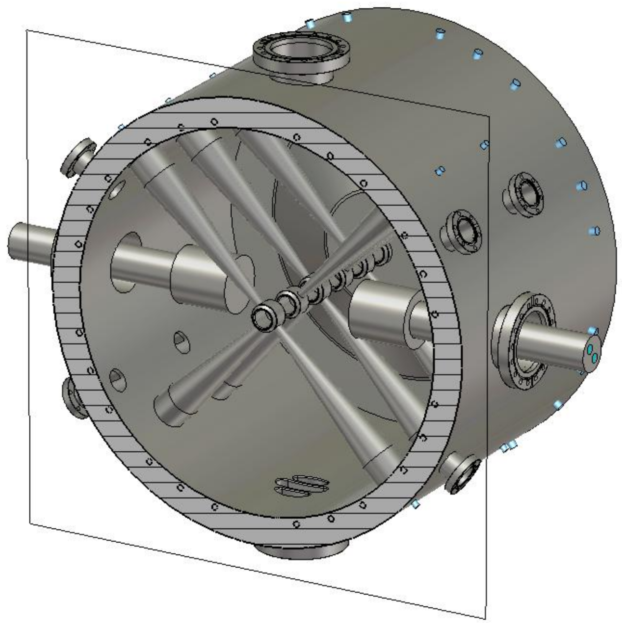
Back to the MYRRHA Injector…

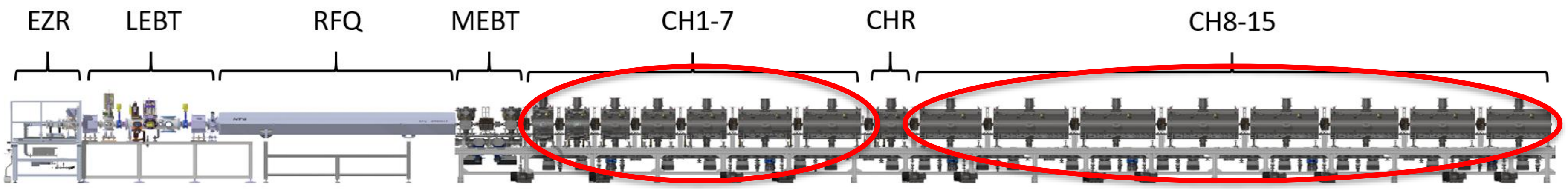


The MYRRHA Injector

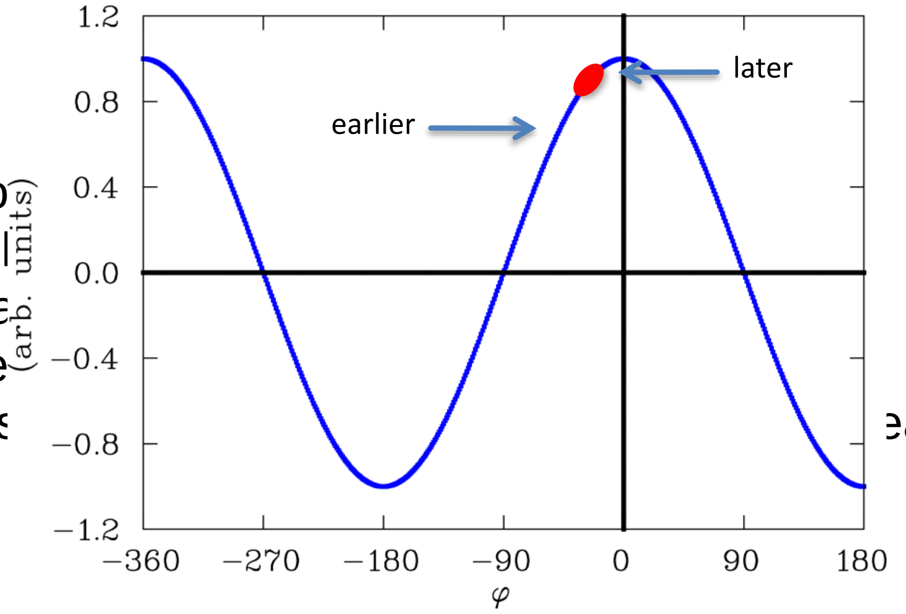


- Cavity resonator, operated in TE211 mode
- Constant phase beam dynamics
- 15 accelerating cavities
- 1-2 buncher
- Power consumption between 8 and 35kW (without bea loading)

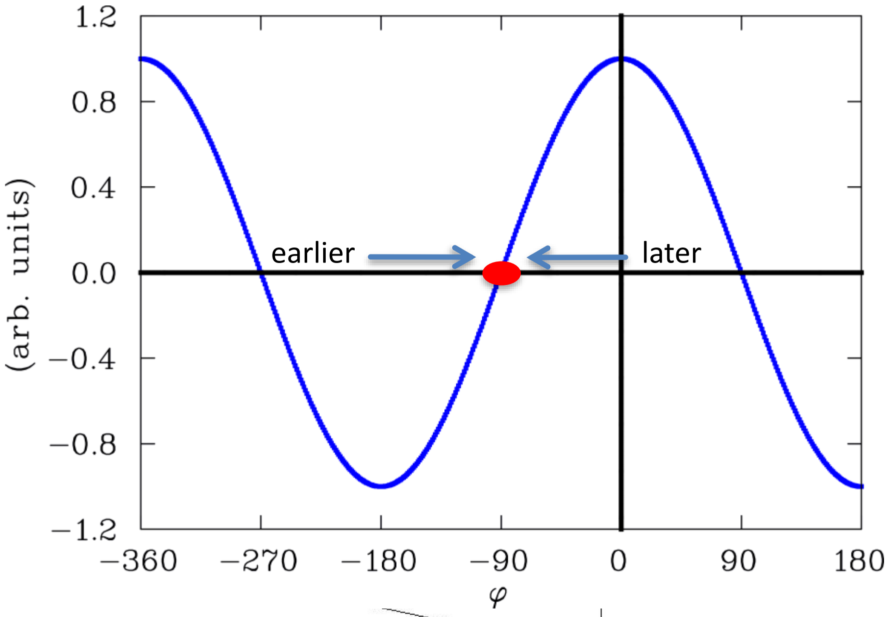




- Cavity reso
- Constant pl
- 15 accelera
- 1-2 bunche
- Power cons ea loading)

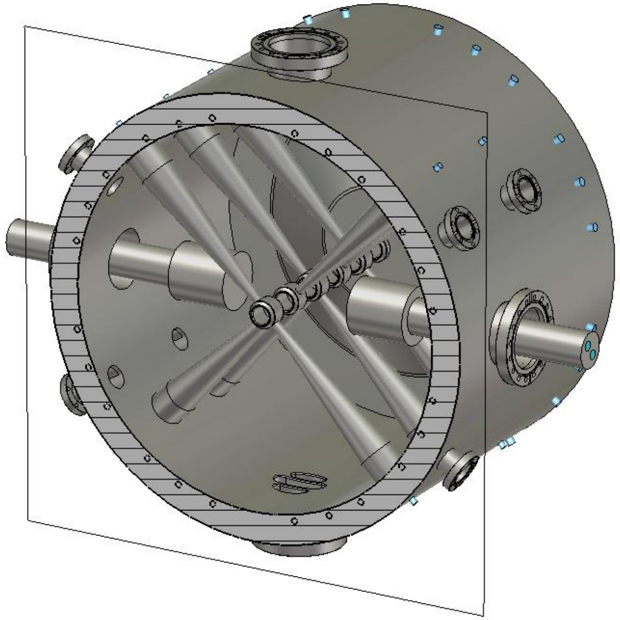


Acceleration with constant phase



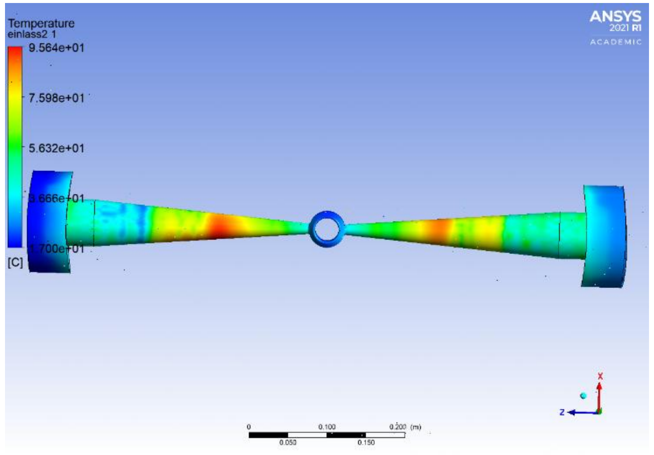
Bunching

Current Problems / Challenges of the CH-Structure



Design without Insert

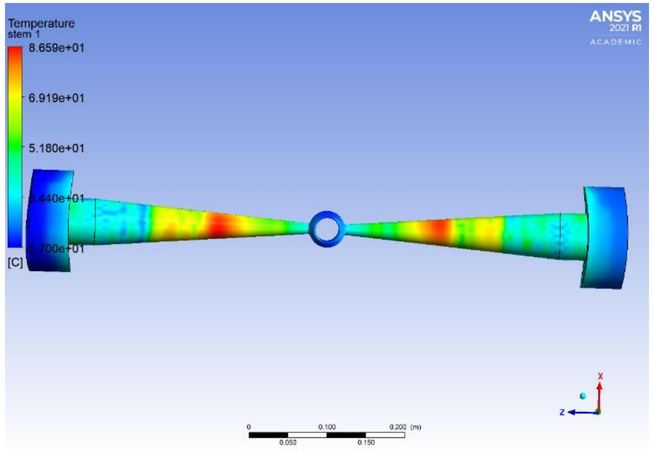
5 l/min



95,6 °C

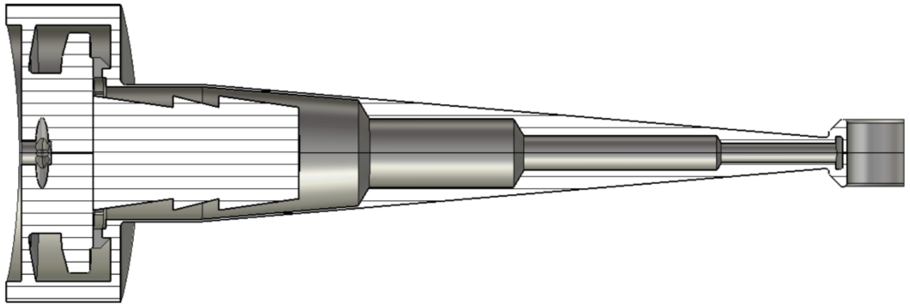
Design without Insert

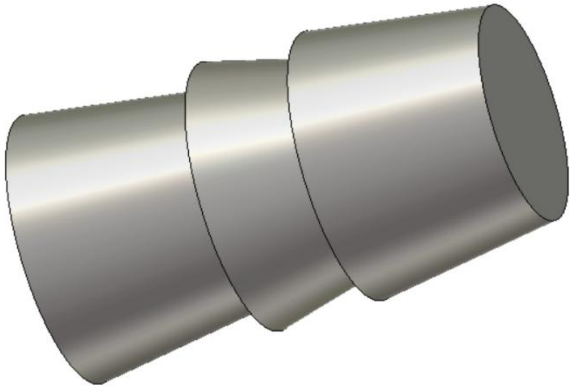
7.5 l/min



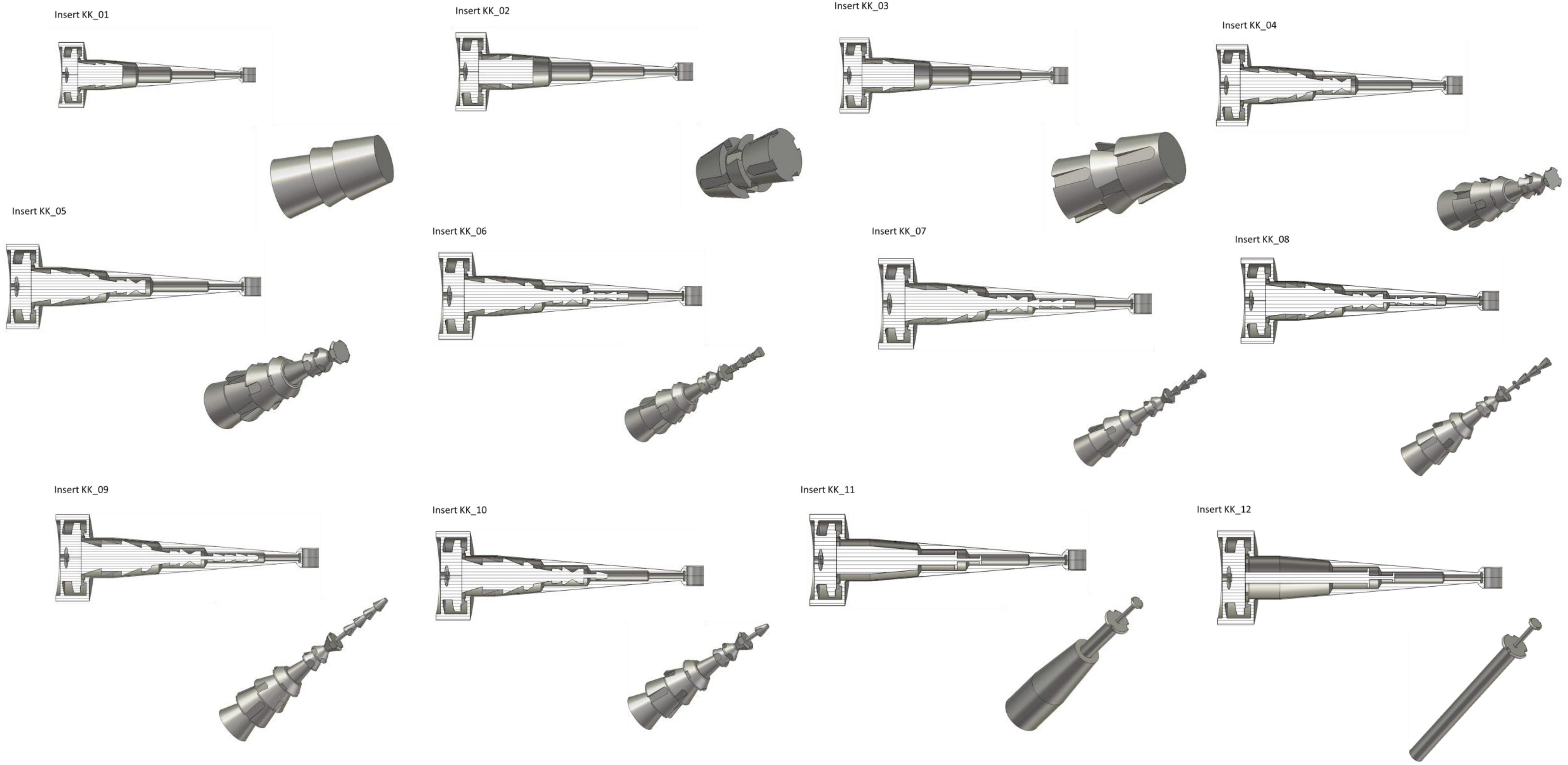
86,6 °C

Insert KK_01

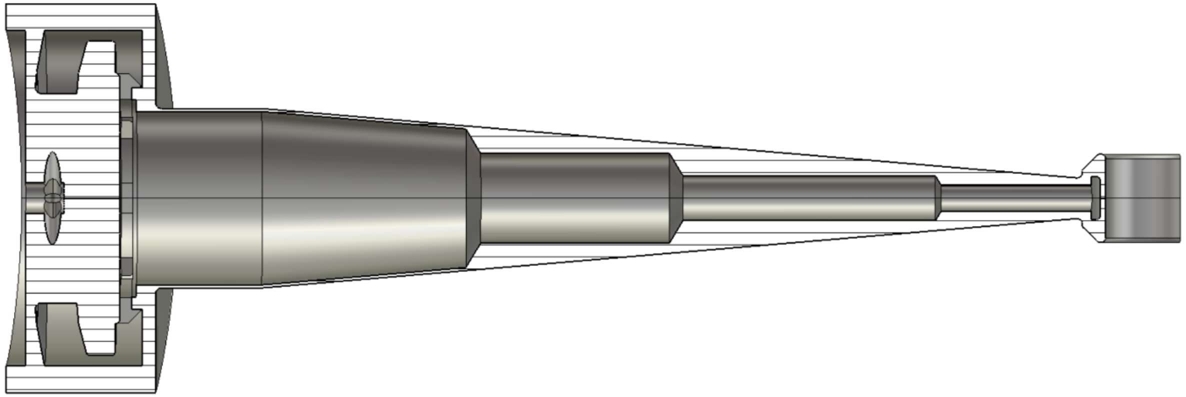




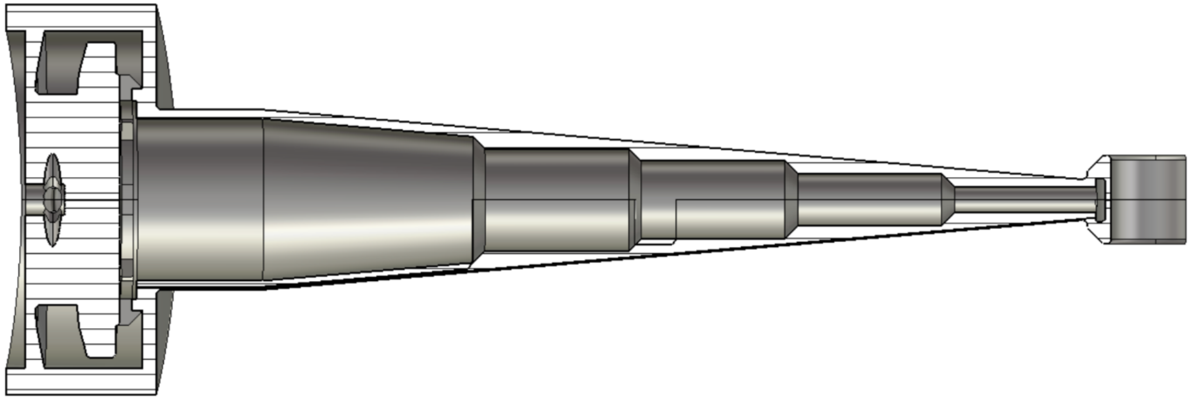
Current Problems / Challenges of the CH-Structure



First draft from the manufacturer



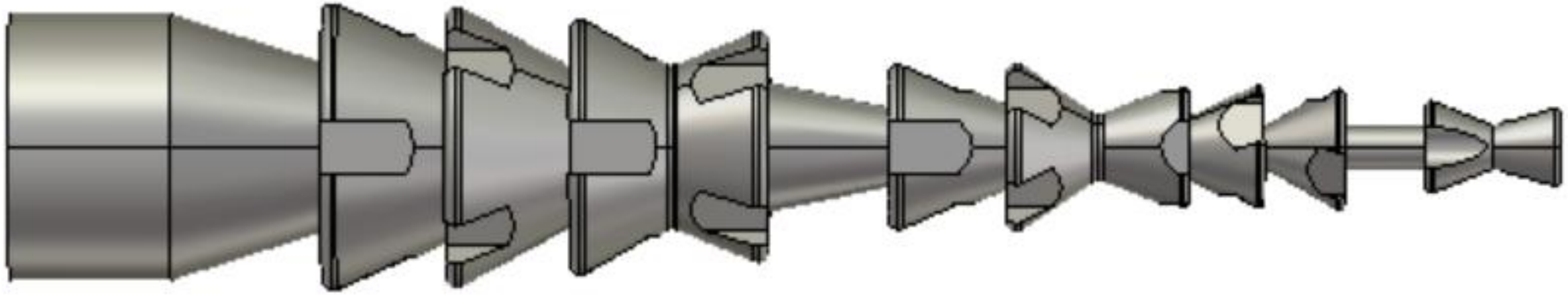
IAP Design KK_01

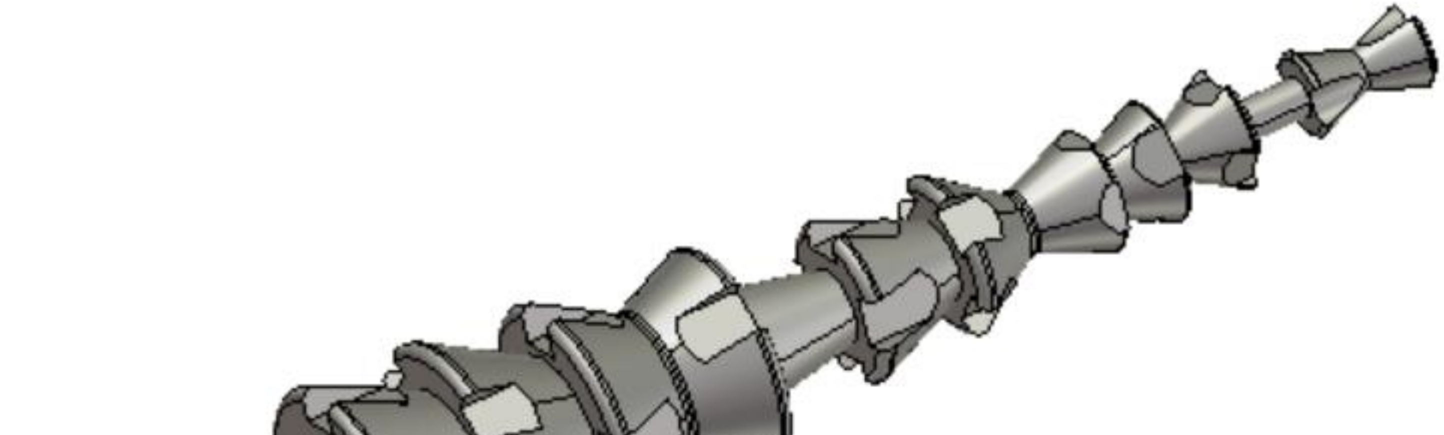


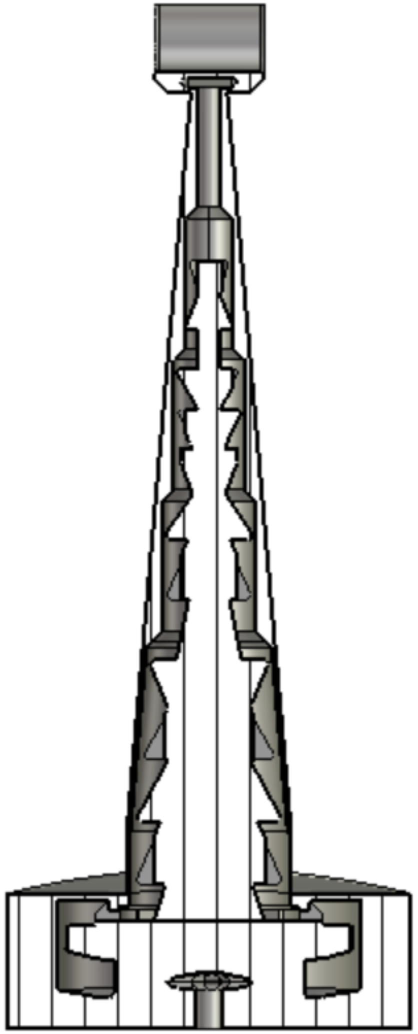
- thicker wall at the bottom
- wall thickness not less than 2mm
- one step more near the beam axis

Current Problems / Challenges of the CH-Structure

Insert KK_14



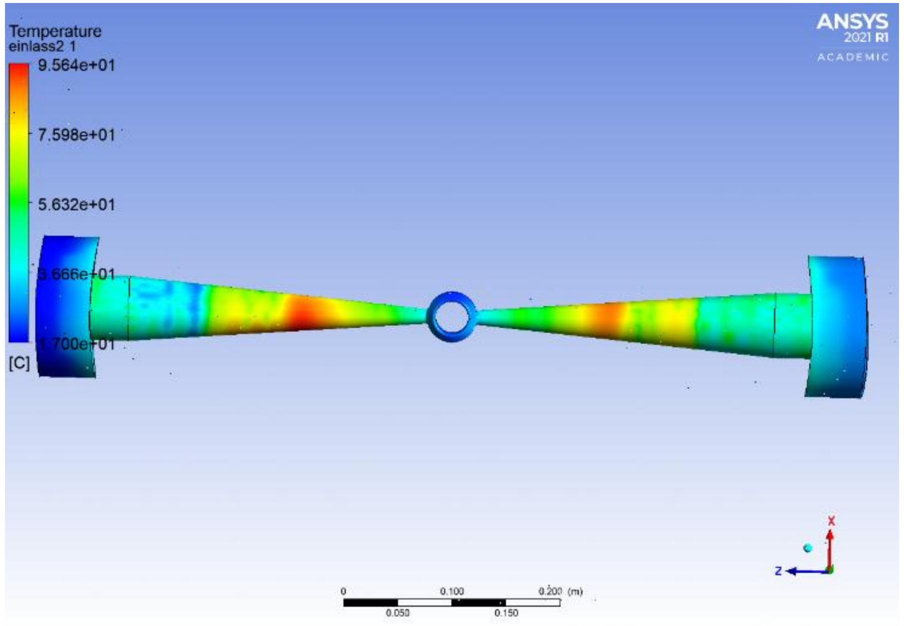


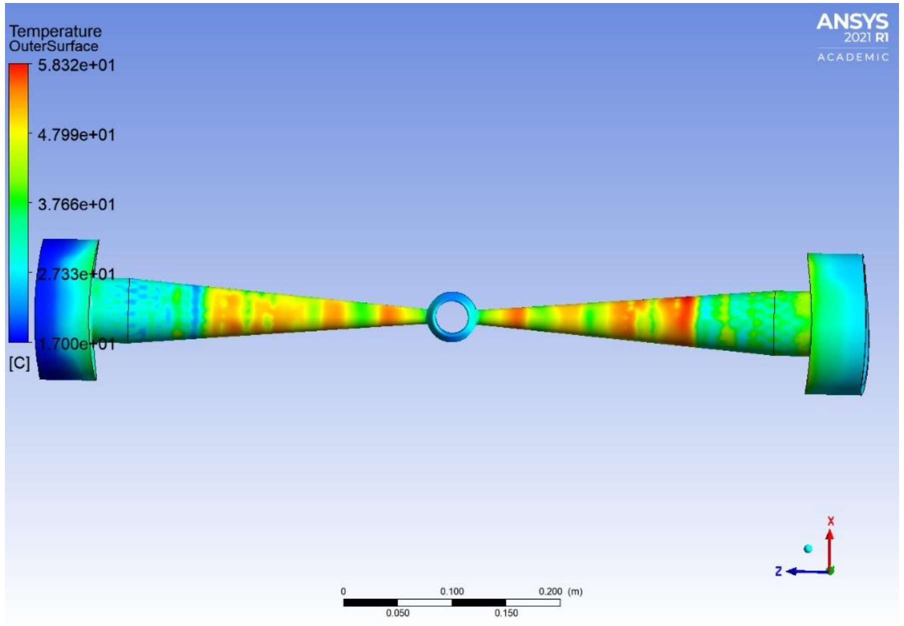


Original Design without Insert

5 l/min

New Stem design
with Insert KK_14





	Ri Design	IAP Design KK_09	IAP Design KK_14
5 l/min	95,6 °C	74,8 °C	58,3 °C
7,5 l/min	86,6 °C	70,7 °C	52,7 °C

What happens next?

CH5-15

CH3+4

CH1+2
RFQ

Design of the Cavity

- Beam Dynamics Simulations
- RF Simulations
- Multiphysics Simulations (Thermal, Mechanical.)

Construction of the Cavity

- Re-Simulations of the manufacturer drawings
- Factory Acceptance Tests (FATs)

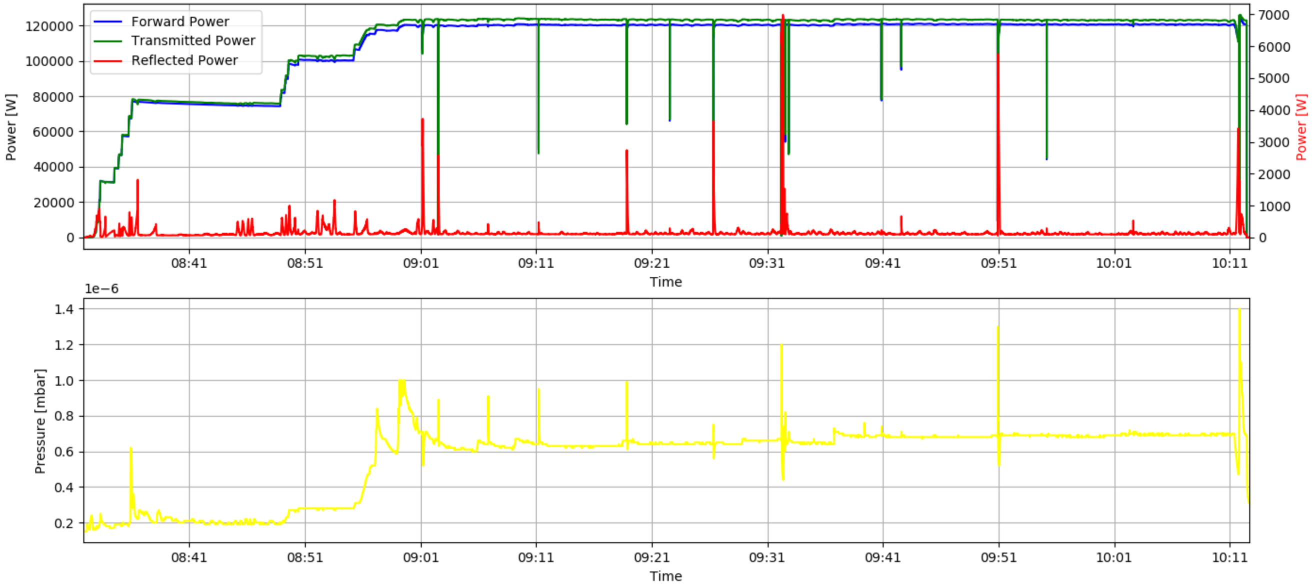
Low Level Measurements

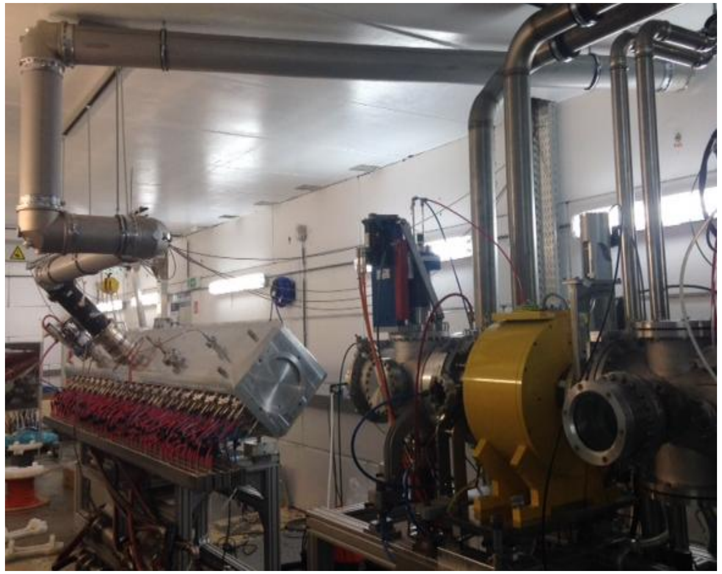
- Frequency
- Q-Value
- Tuning Range
- Voltage distributions
- …

High Power Tests / Conditioning

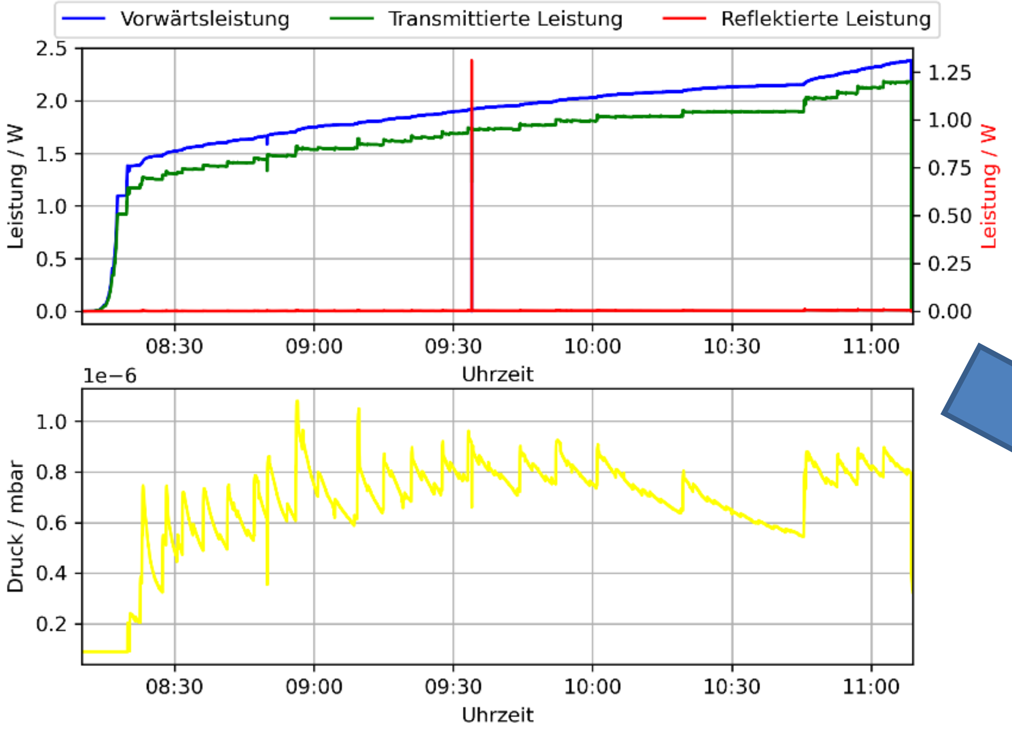
- Getting the cavity used to the required power

High Power Tests / Conditioning

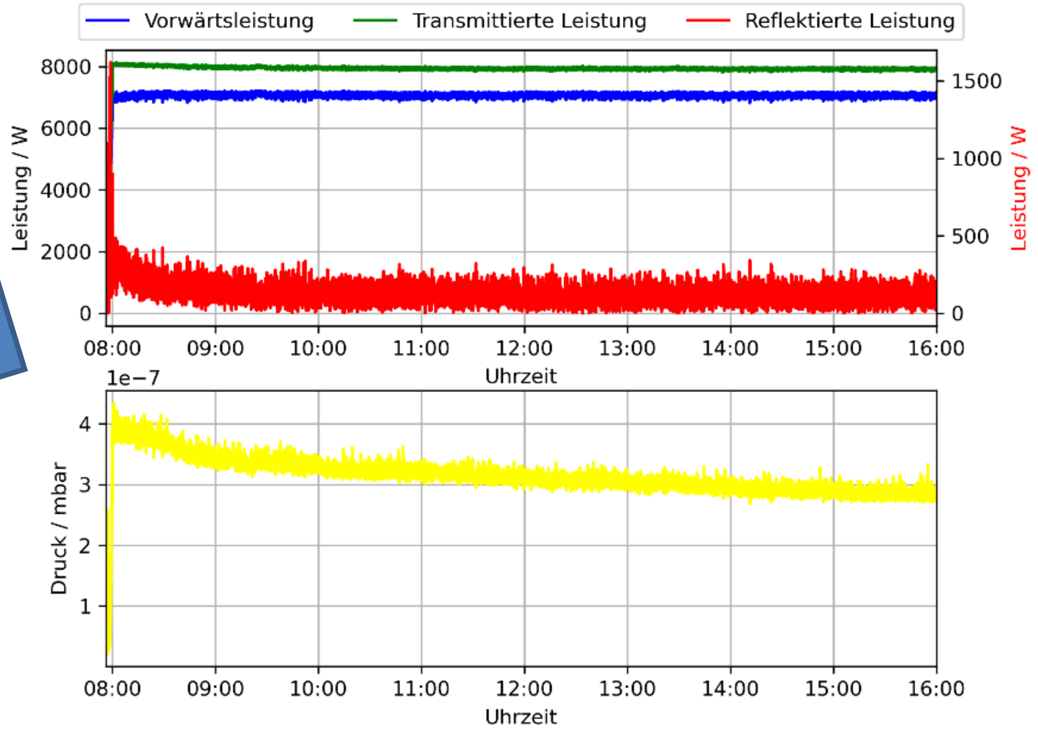




High Power Tests / Conditioning

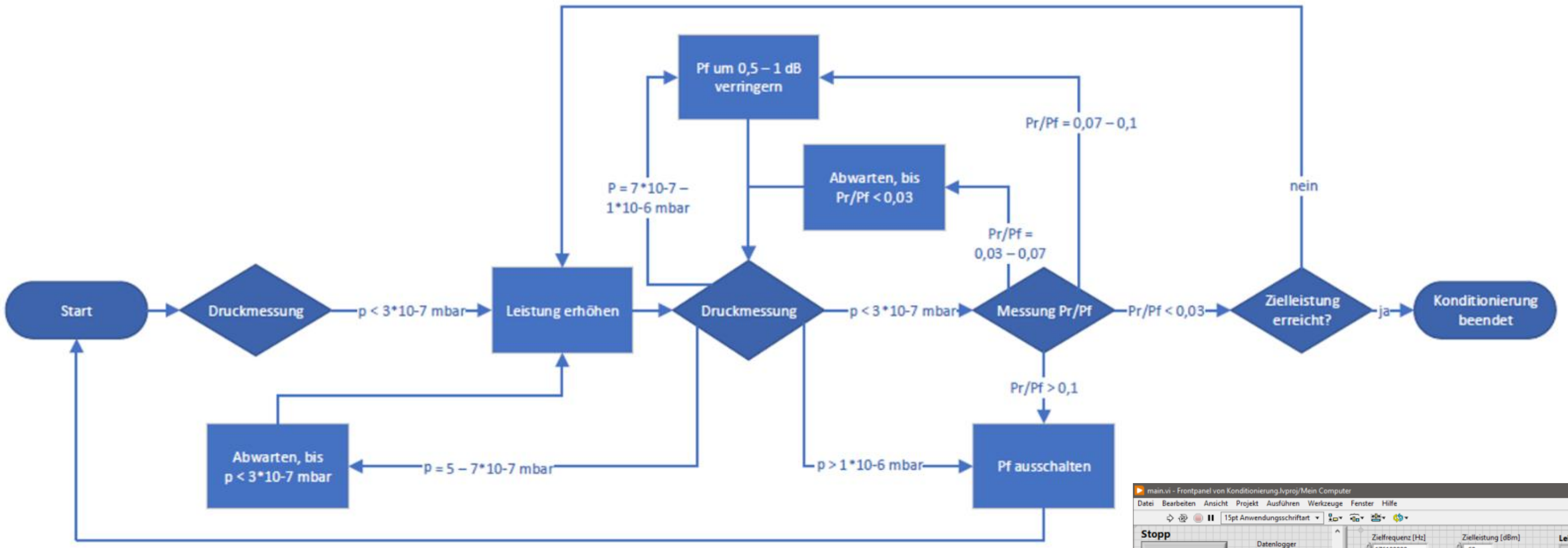


Both performed on CH1 „new lid“

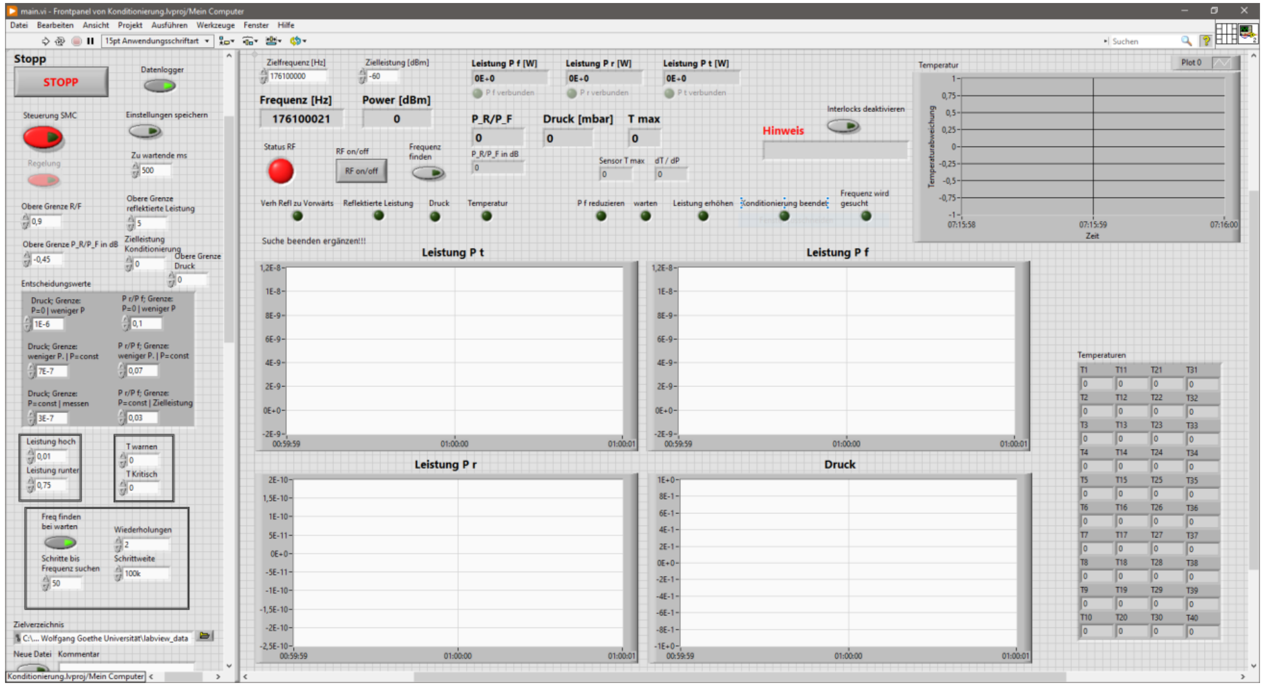


Dauertest bei CH1 „new lid“

High Power Tests / Conditioning

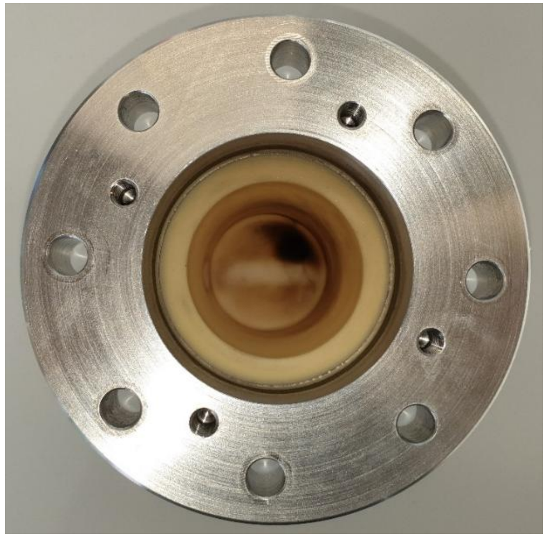


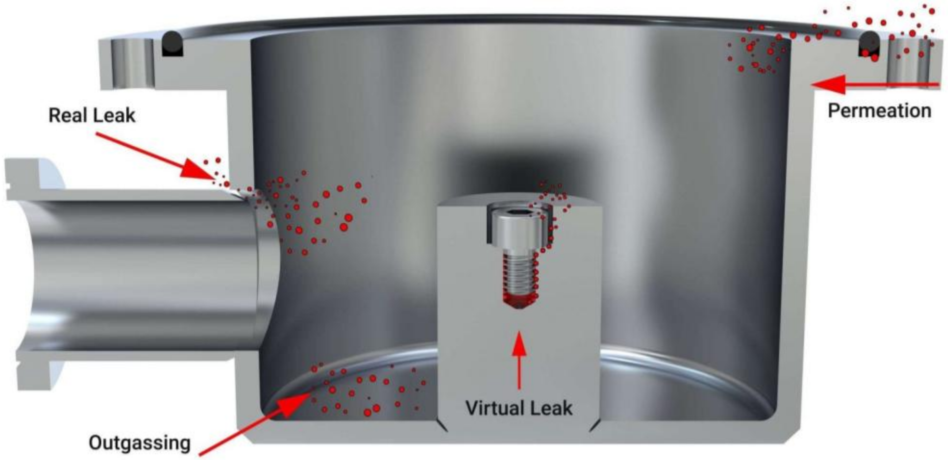
- Possible Events during Conditioning (list is not complete)
  - Multipacting
  - Outgassing
  - Discharge



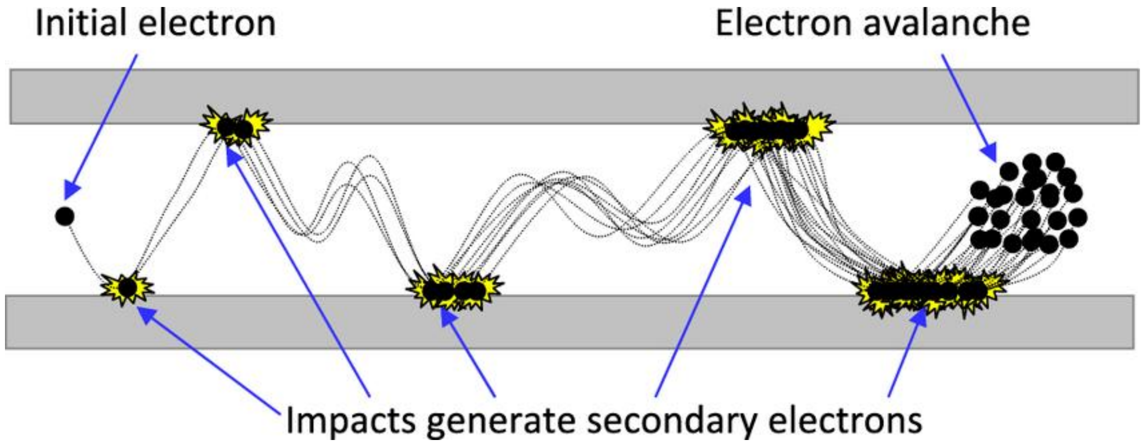
(from left to right: loop in original condition; strongly warmed loop; irreparable loop)

A ceramic cup and a loop have suffered irreparable damage.





https://voc-vacuum.com/virtuelle-lecks/

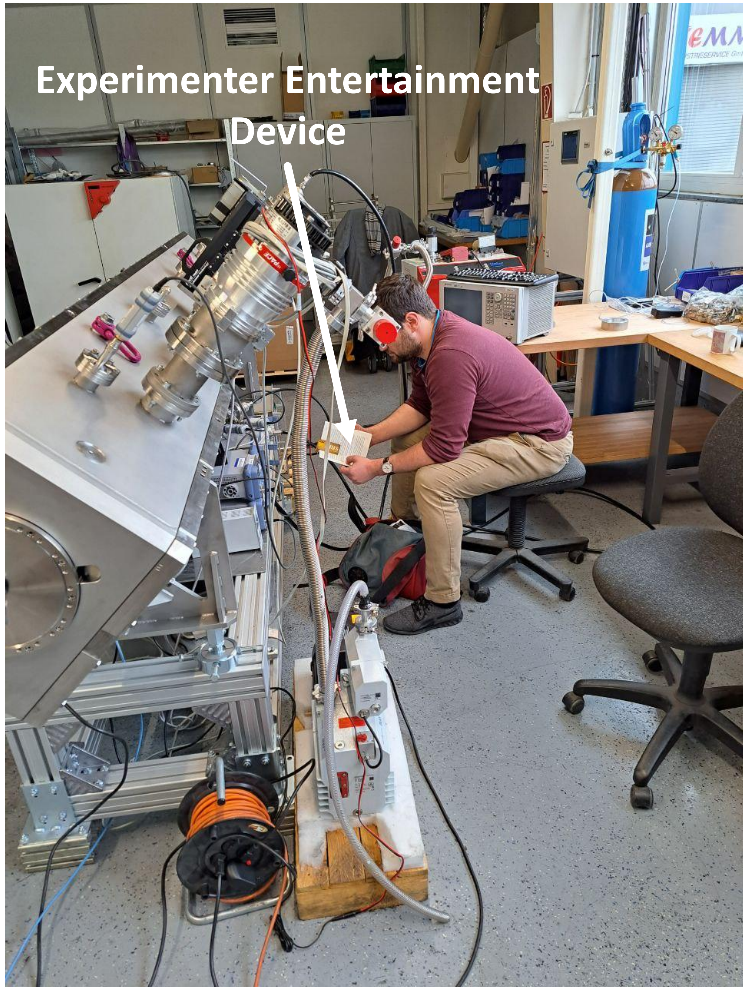


Navaridas, Javier & Pascual Saiz, Jose Antonio & Galarza, Julen & Romero, Txomin & Muñoz, Juan & Bustinduy, Ibon. (2024). On the parallelization of multipacting simulation codes for the design of particle accelerator components. The Journal of Supercomputing. 80. 1-22. 10.1007/s11227-024-05896-2.

- Conditioning is a time-consuming process
- Because of the high risk for cavity and used instruments, constant supervision is necessary
- No clear analytic description of effects happening
  → Conditioning needs a lot of experience and intuition
- Classic algorithms ineffective at conditioning
- But: Most of the time nothing happens

→ Costly and exhausting process
→ Automation desired

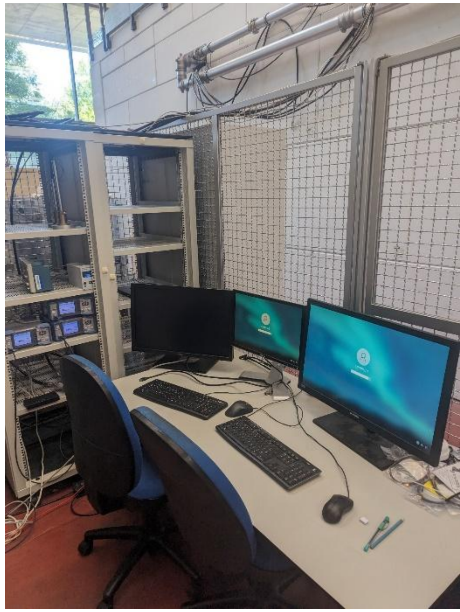
Machine Learning for Conditioning
(ongoing PhD Thesis)



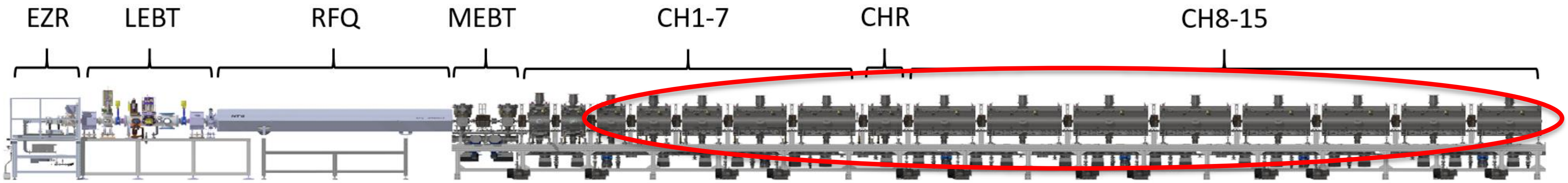
Final MYRRHA page

Current Setup for testing the MYRRHA-CH-Cavities:

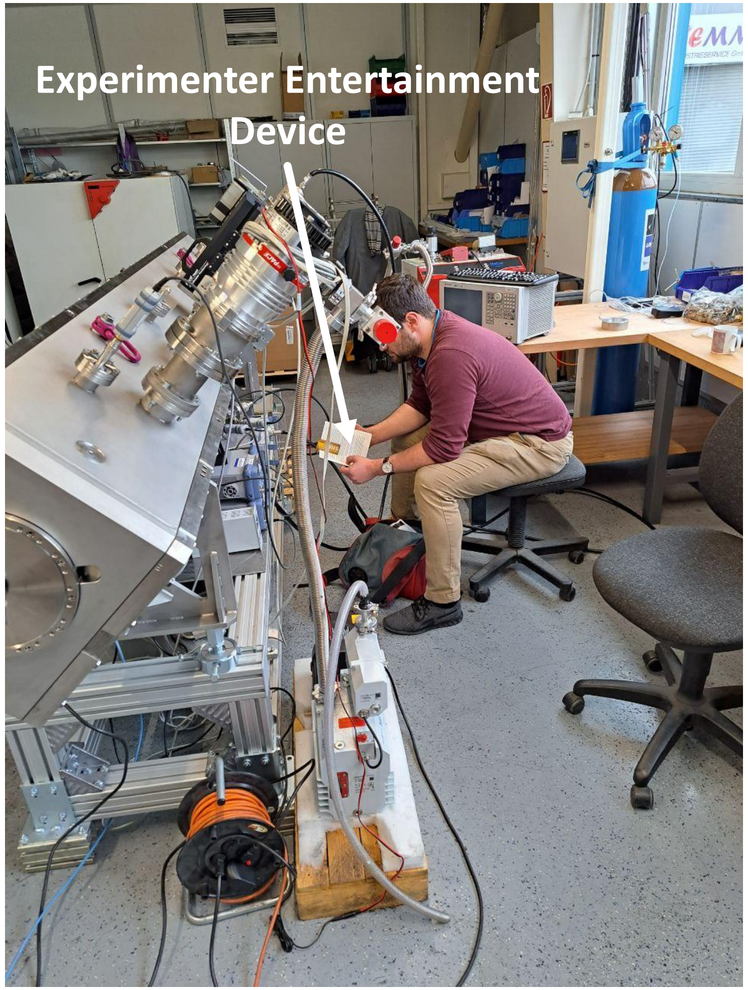
- Up to 15 CH-Cavities
- Low-Level-Measrements
- High Power Tests / Conditioning



- ➢ Cage outside the Bunker
- ➢ Cavity is tested inside the Bunker
- ➢ First test of the Setup is currently running with the FRANZ-RFQ-Prototype



Thank you!



https://www.uni-frankfurt.de/159823517/LINAC_AG?