A 3D printed IH-type linac structure

Proof-of-concept for additive manufacturing of linac rf cavities

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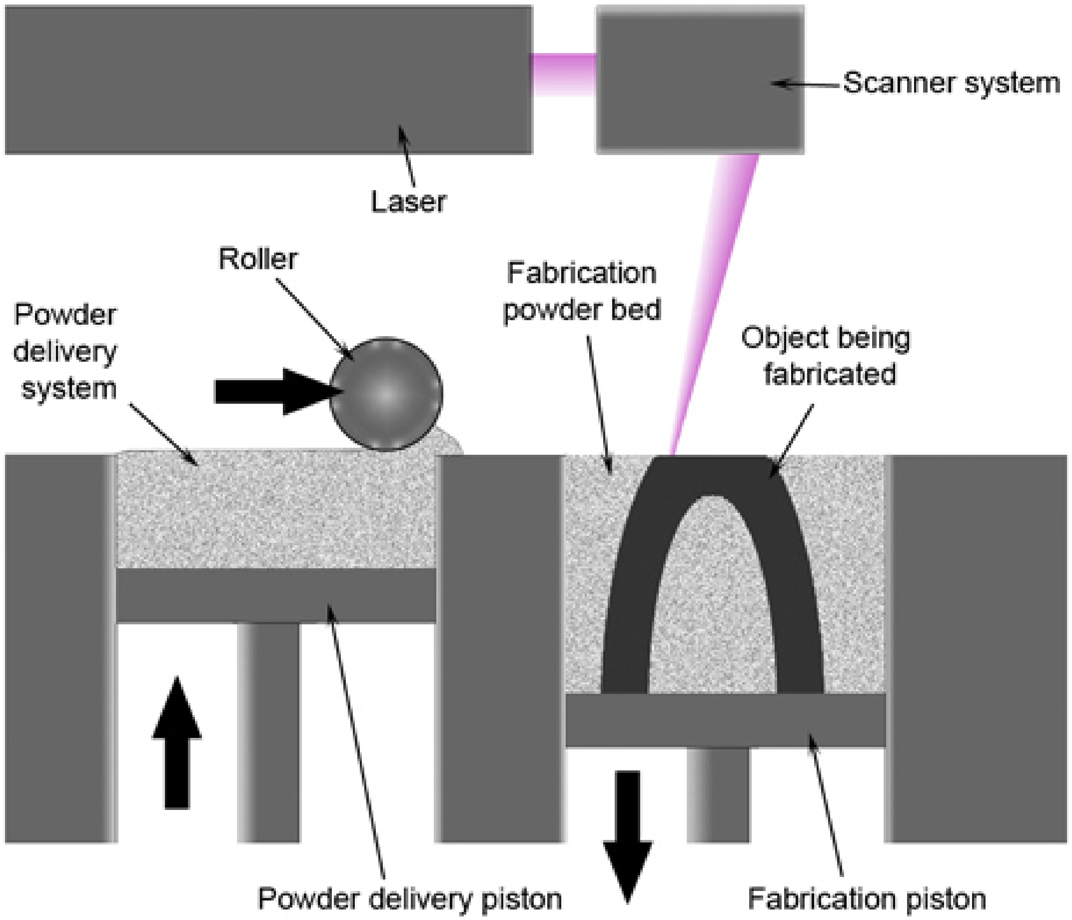
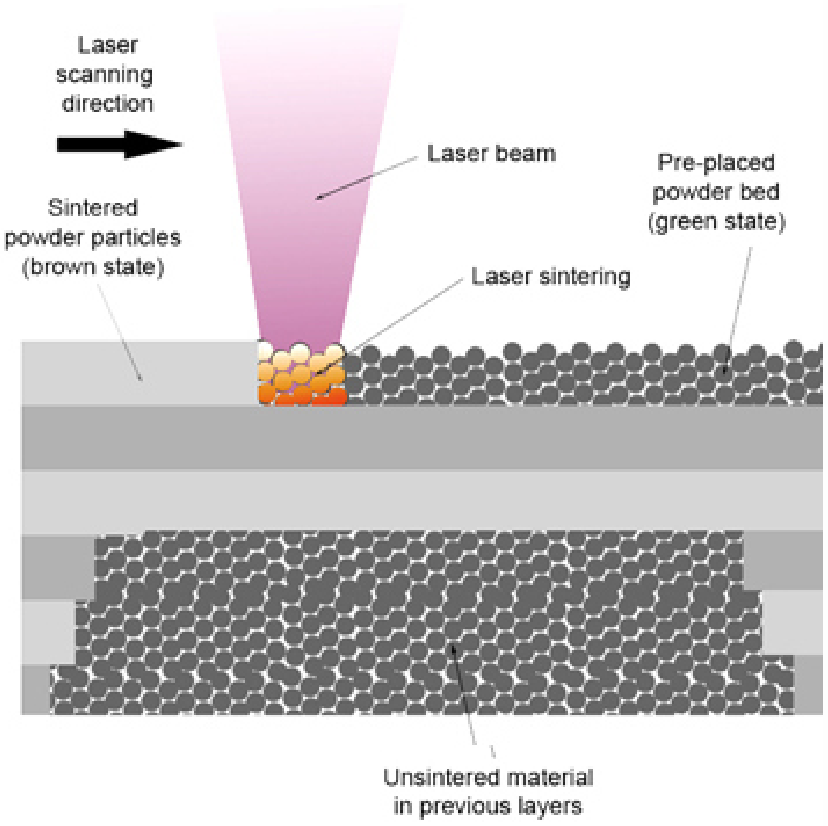
How does it work?





Source: https://de.wikipedia.org/wiki/Selektives_Lasersintern

Additive Manufacturing

3D printing of metal parts is state of the art for rapid prototyping and also parts production in some special cases.

Laser based systems are commonly used.

<u>3D metal printing has many names:</u>

- Direct Metal Laser Sintering (DMLS) eos
- Selective Laser Melting (SLM) SLM SOLUTIONS
- Laser Beam Melting (LBM) Fraunhofer IFAM
- Selective Laser Sintering (SLS)
- Laser Powder Bed Fusion (LPBF) Fraunhofer ILT
- …

But more important than the name is the question:

“Can we build accelerators this way?“
→ Printing Accelerators?

Preliminary Experiments

Checking feasibility of AM parts for UHV

Preliminary Vacuum Experiments

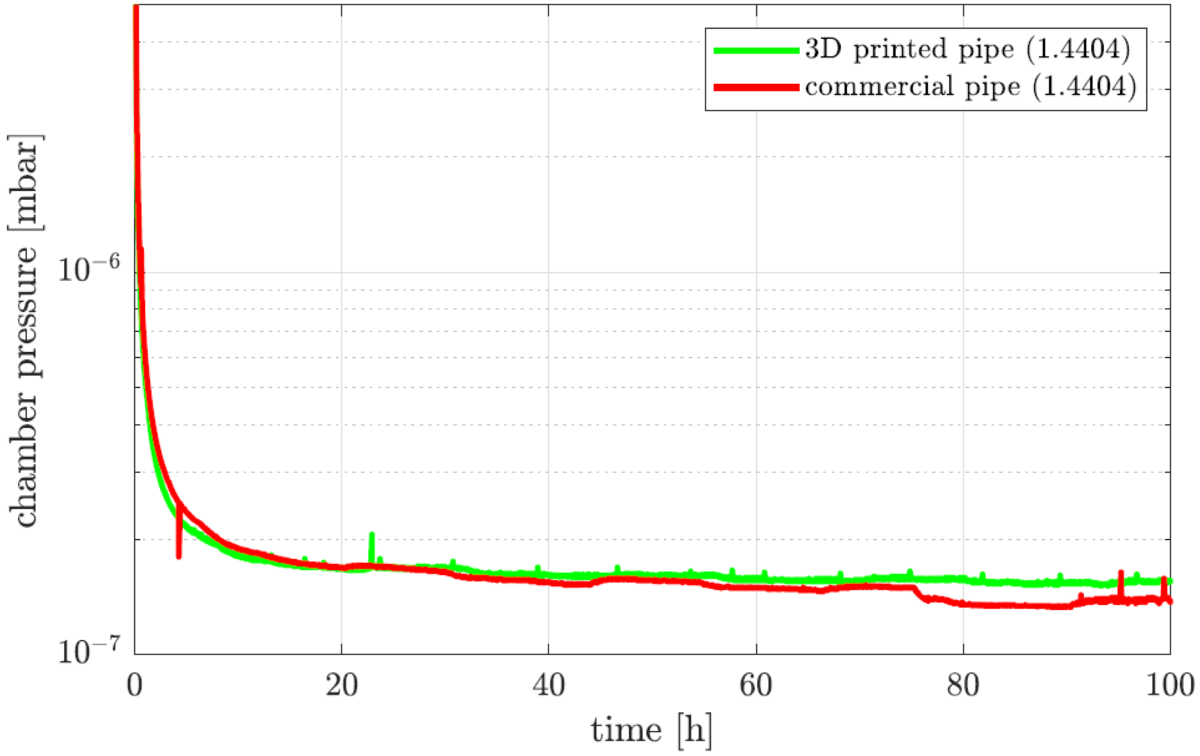
Printed KF40 beam pipe

- Sealing surfaces were milled
- Stainless Steel 1.4404

Vacuum Test vs. Pfeiffer Beam pipe

- Many cycles of pumping and N_2 purging
- Small Turbo Pump (18 l/s)
- In the end, performance is at least equal

→No Vacuum problems foreseen

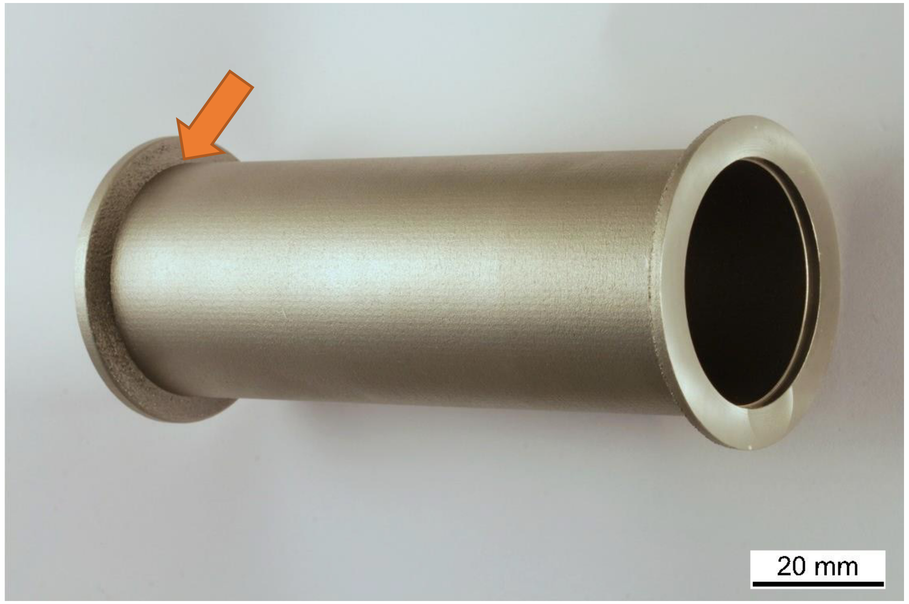


Reproduction of experiments of: S. Jenzer et al., Proc. IPAC'17, WEPVA043 |G. Sattonnay et al., Proc. IPAC'19, WEXXPLS3

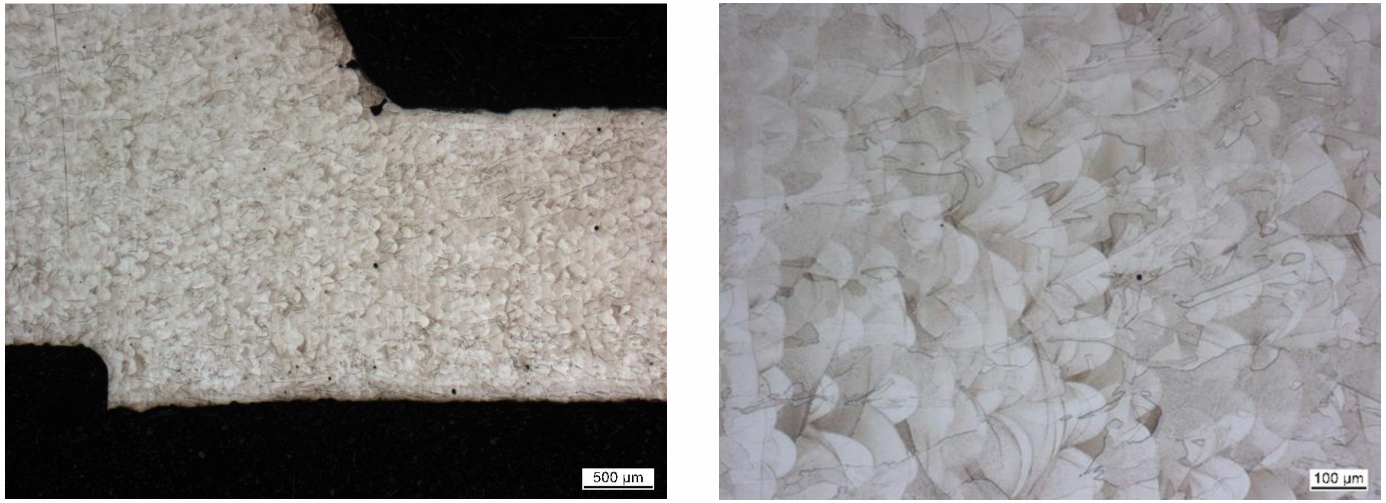
Material Properties

Printed pipes were analyzed at MPA Darmstadt

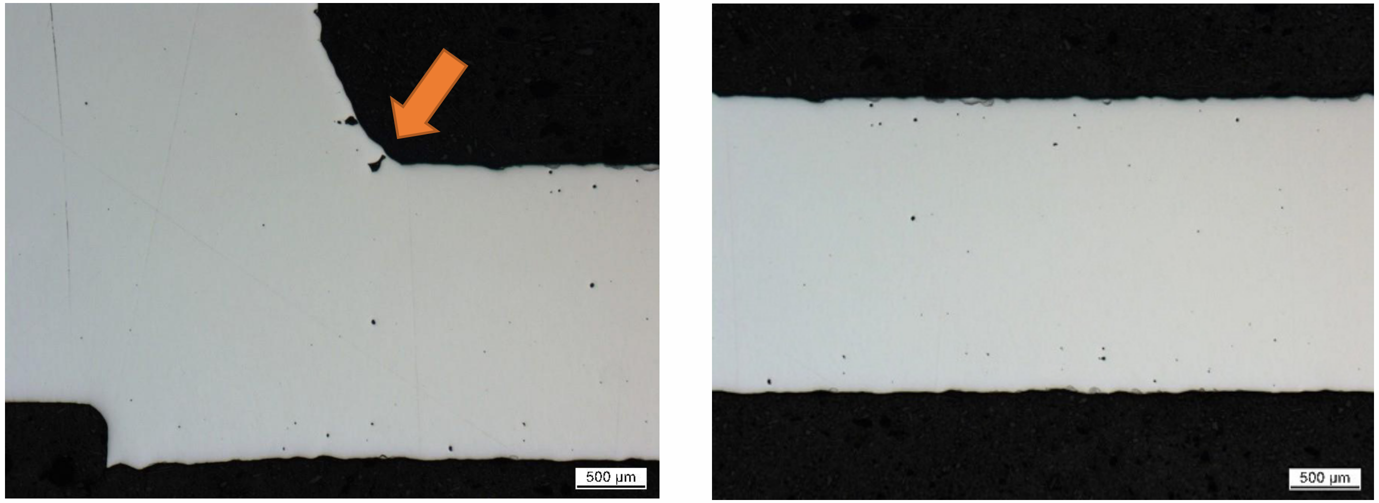
- 1.4404 composition confirmed
- Porosity 0.04 %
- Surface roughness $R_z = 17 - 30\ \mu m$
- Cross-sections of significant areas



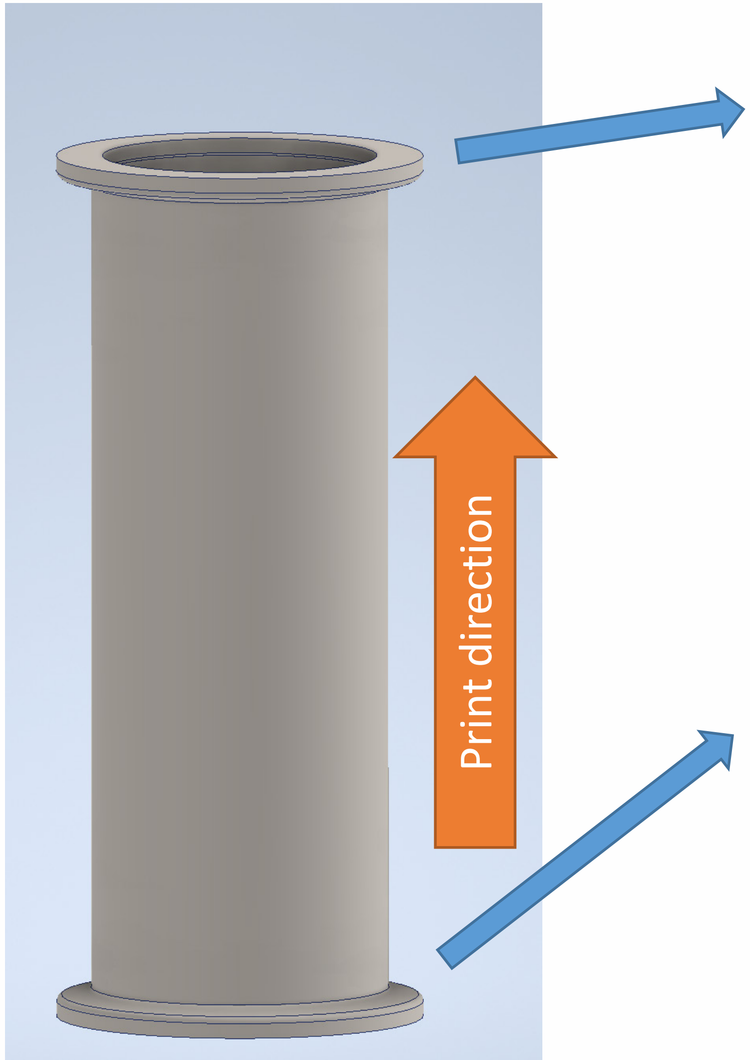
Etched cuts reveal melt pool structure



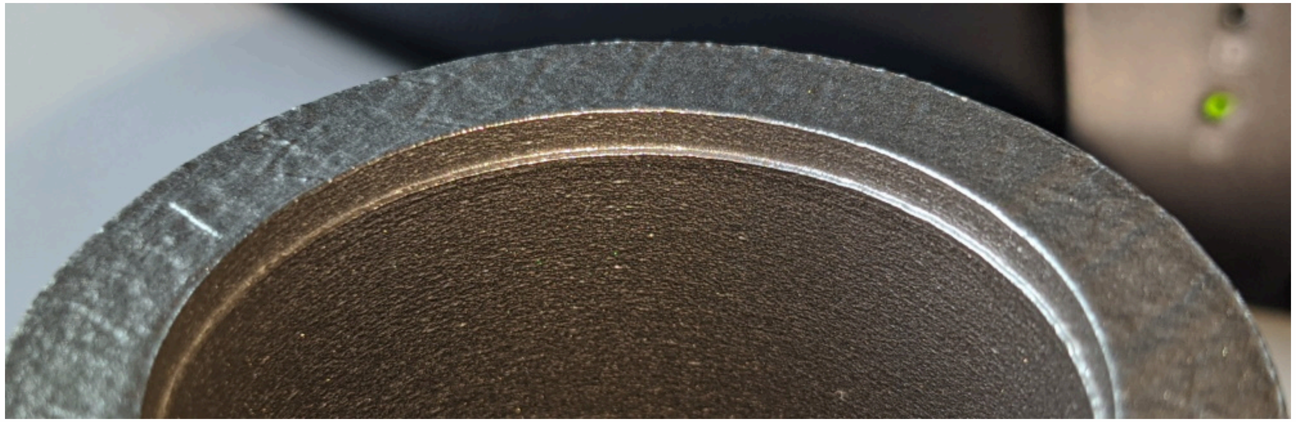
Optical porosity measurements



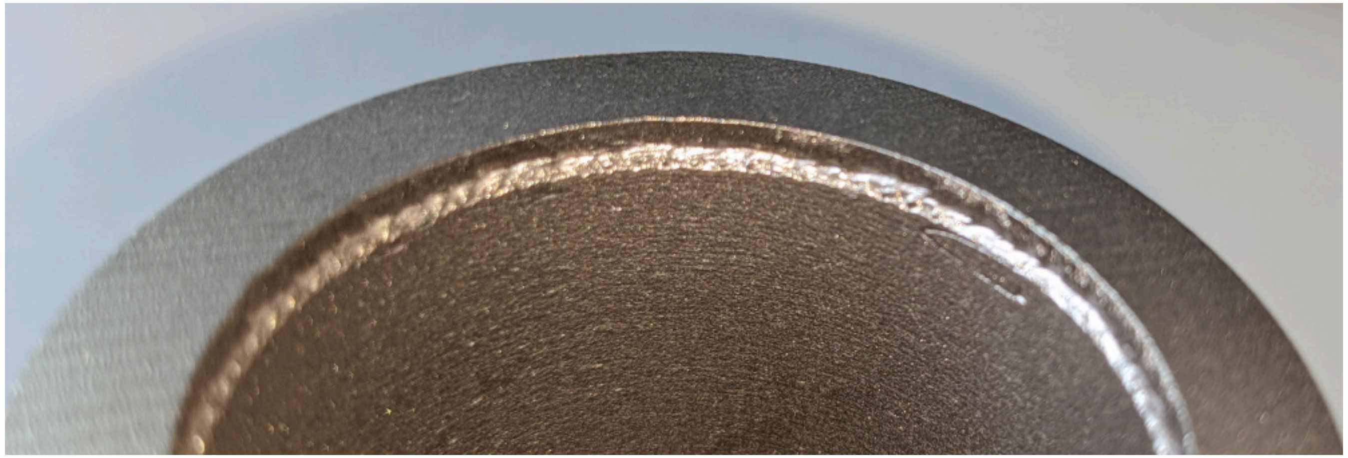
Material Properties



Top of printed part: good edge quality, top surface distorted



Bottom of printed part: bad edge quality, surface rough cut



- Print orientation & direction can have significant influence on part quality
- Intelligent design → mitigation of issues
- Postprocessing may be inevitable for some cases

The ADDLINAC Project

Graphics designer needed …

Project at IAP Frankfurt (BMBF as of 2021)

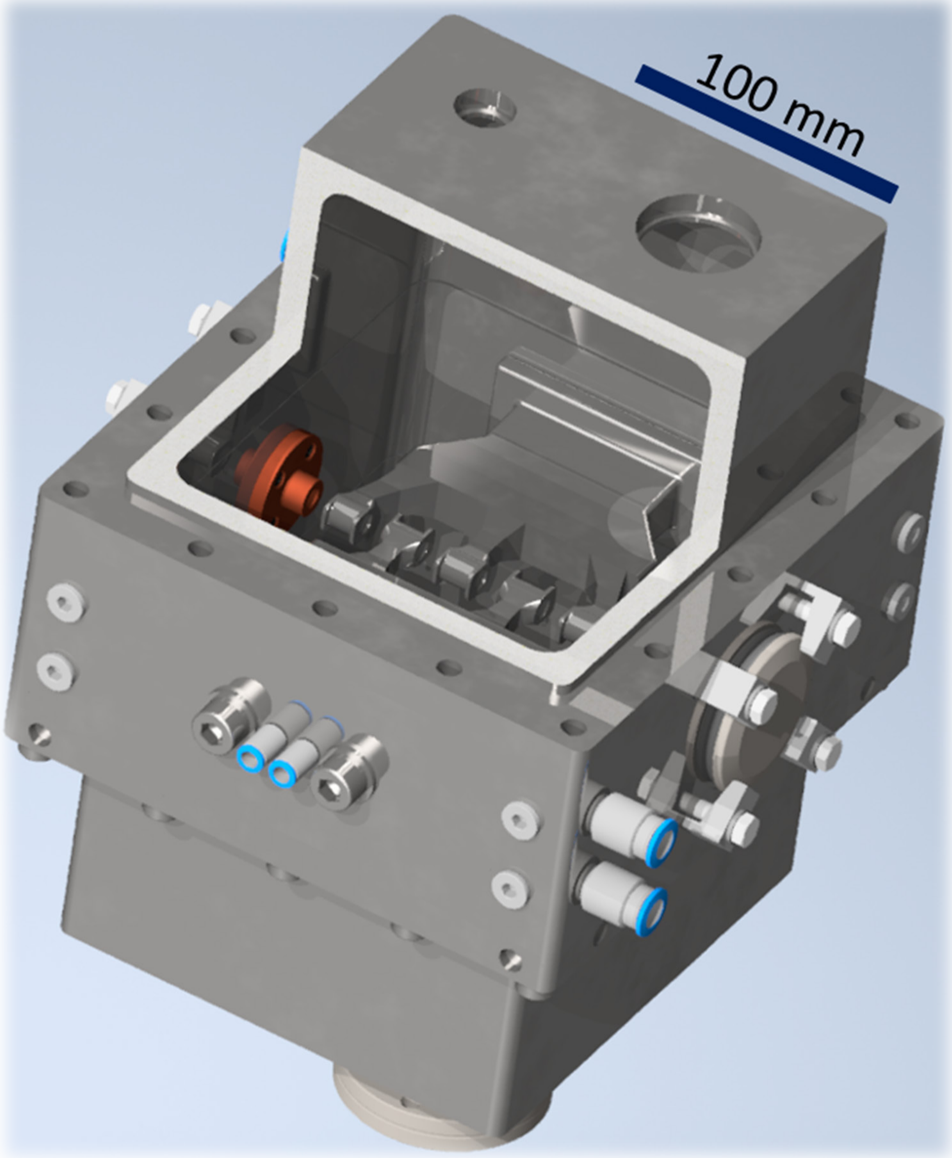
Investigation Goals

- What are the vacuum properties?
- How good is the manufacturing accuracy?
- Copper plating
- What are the possible benefits?
- Finally high power rf tests

ADDLINAC Project

First IH-DTL with printed drift-tube structures

Publications: IPAC2021, Instruments, HIAT2022

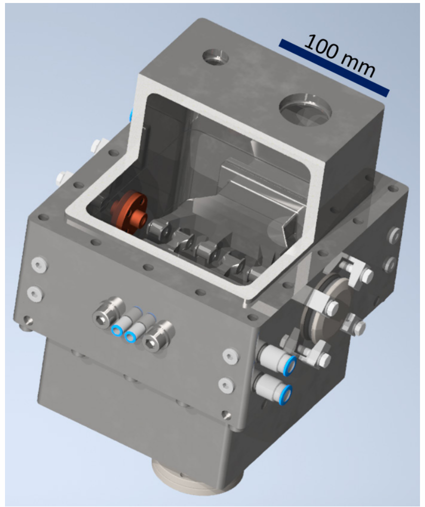


ADDLINAC Project summary

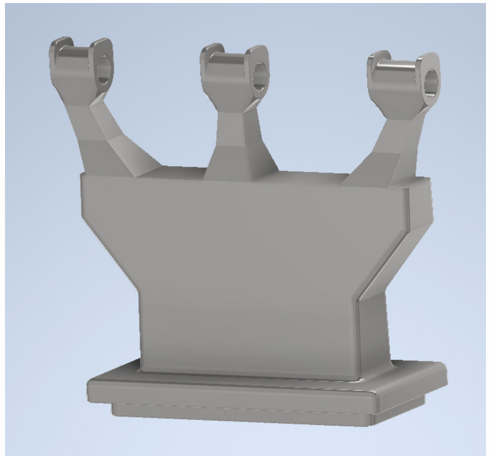
- $433.632\ MHz$ (UNILAC harmonic)
- $1.4\ MeV$ protons
- $1\ MV$ acceleration → $6.8\frac{MeV}{m}$ gradient
- Small beam aperture (7 mm)

- Center frame and lids are milled steel
  - Lids & small parts: IAP Workshop
  - Center Frame: PINK GmbH
- Drift tube structure is printed in 1.4404 stainless steel
  - Geometry optimized for printing
  - As little supports as possible

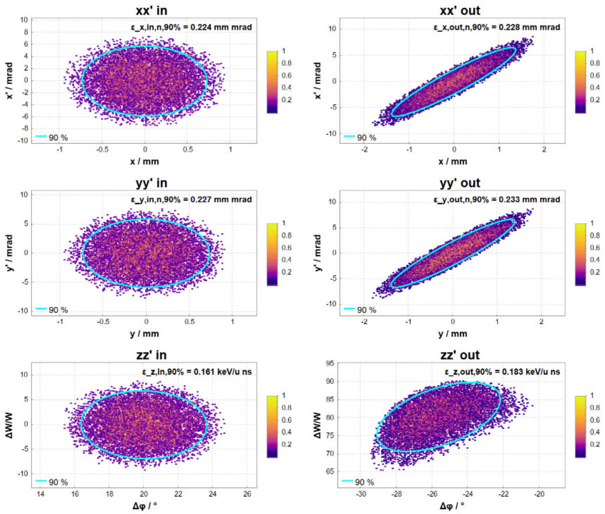
CAD Construction



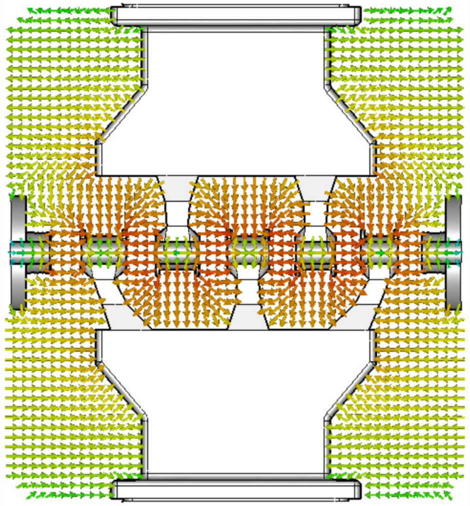
Print geometry



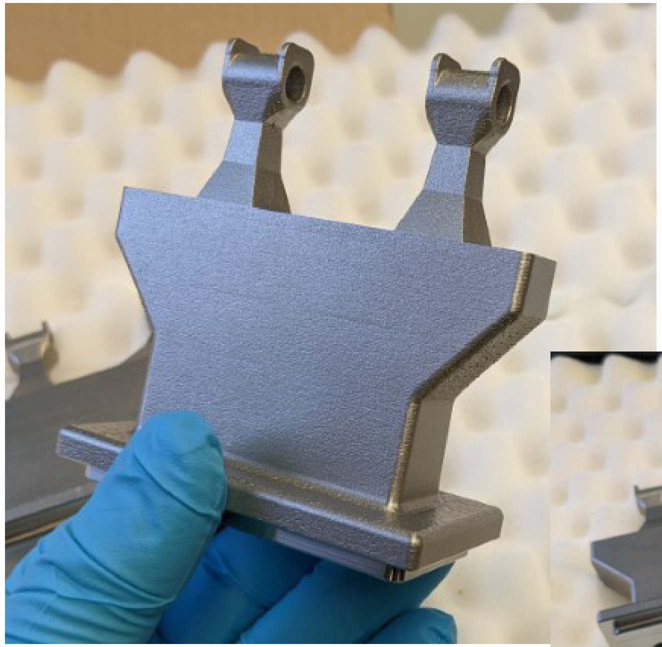
Beam dynamics

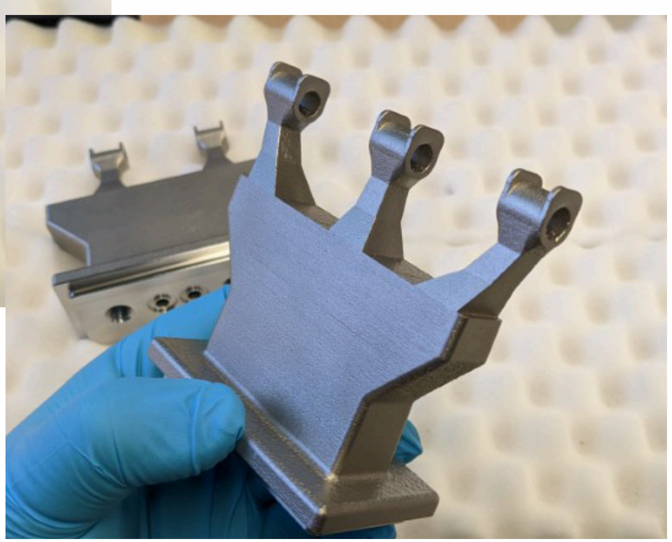


RF simulations



Printed IH-structures

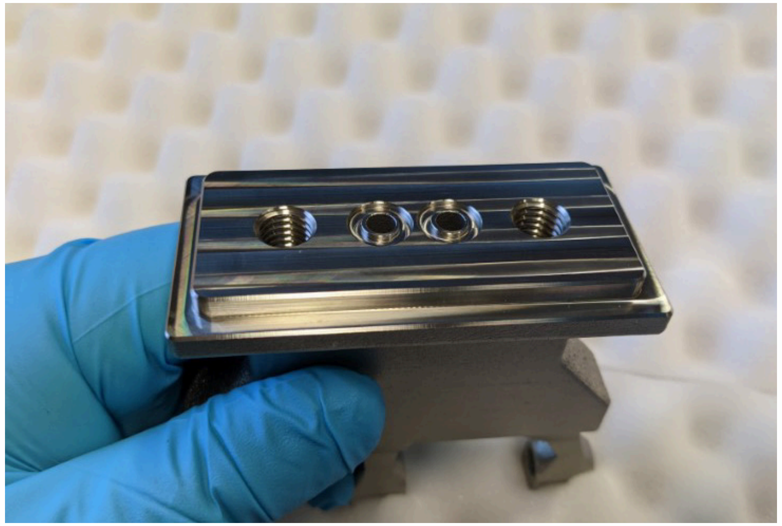




From the contractor:
- Sandblasted surface
- CNC machining on the bottom
- No further postprocessing

Print parameters:
- Print time 21 h
- Layer thickness: 50 µm
- Spot size: 80 µm

Bottom surface milled



Debris from the cooling channels

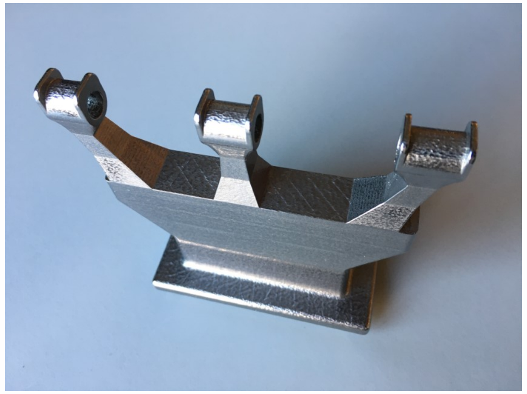
Copper Plating

A first set of structures was polished and copper plated.

- The results look promising.

- Vacuum & LLRF measurements will follow.

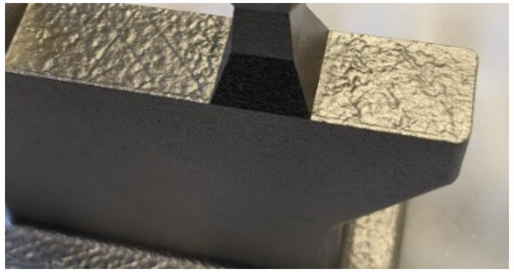
Polished structure



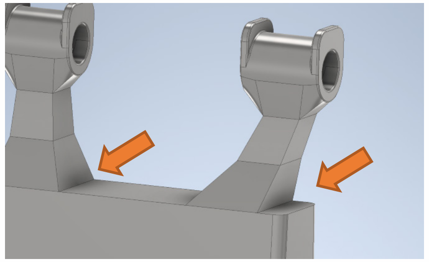
Design Improvements

The following issues showed in the first prototypes:

Flat surface quality not ideal



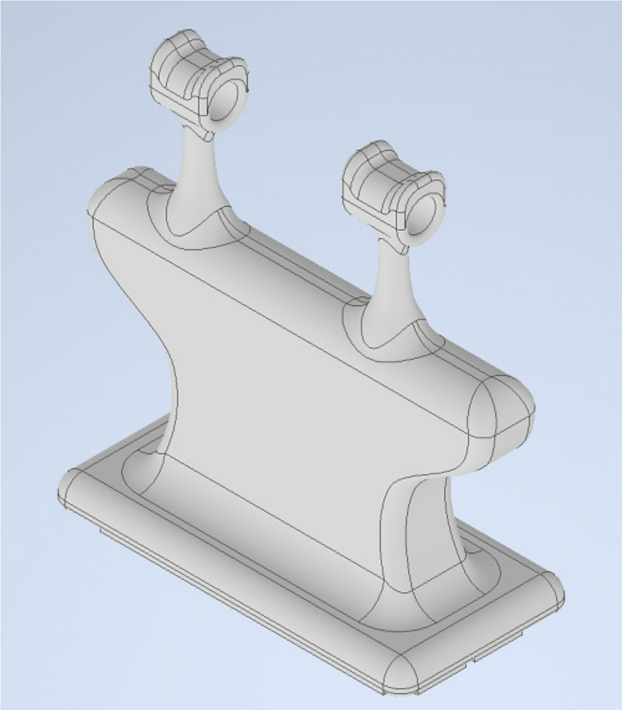
Polishing deficiencies at inset edges



Mitigations:

- Research of higher accuracy printing (THM Friedberg)
- Geometry optimization of the IH Structure
  - Larger radii help with polishing, copper plating and peak surface fields

Girder V3
geometry optimizations



Cooperation: THM Friedberg

BMBF Project Cooperation (Prof. K. Behler)

Project partner focusing on printing accuracy

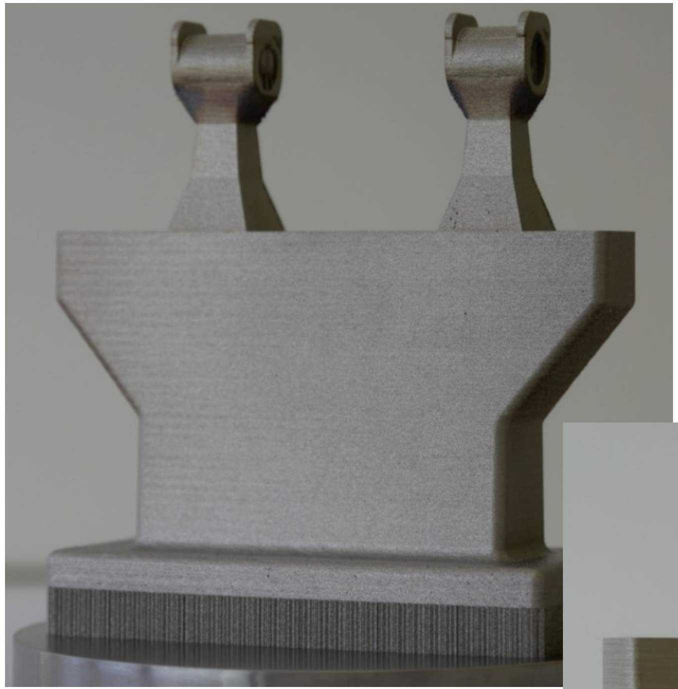
- Close cooperation with IAP
- Working to improve part accuracy

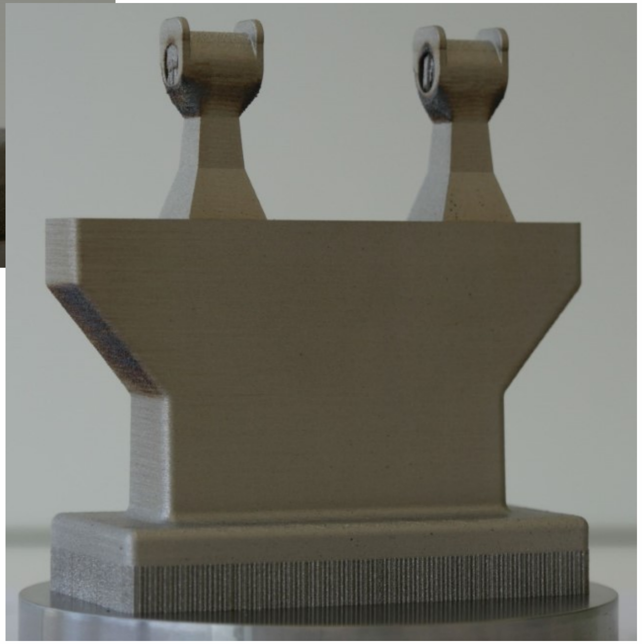
First promising results:

- Top surfaces more uniform than contractor printed part

TRUMPF TP1000 - fiber laser

- 98 mm diameter build base
- Layer thickness $10 - 50\ \mu m$

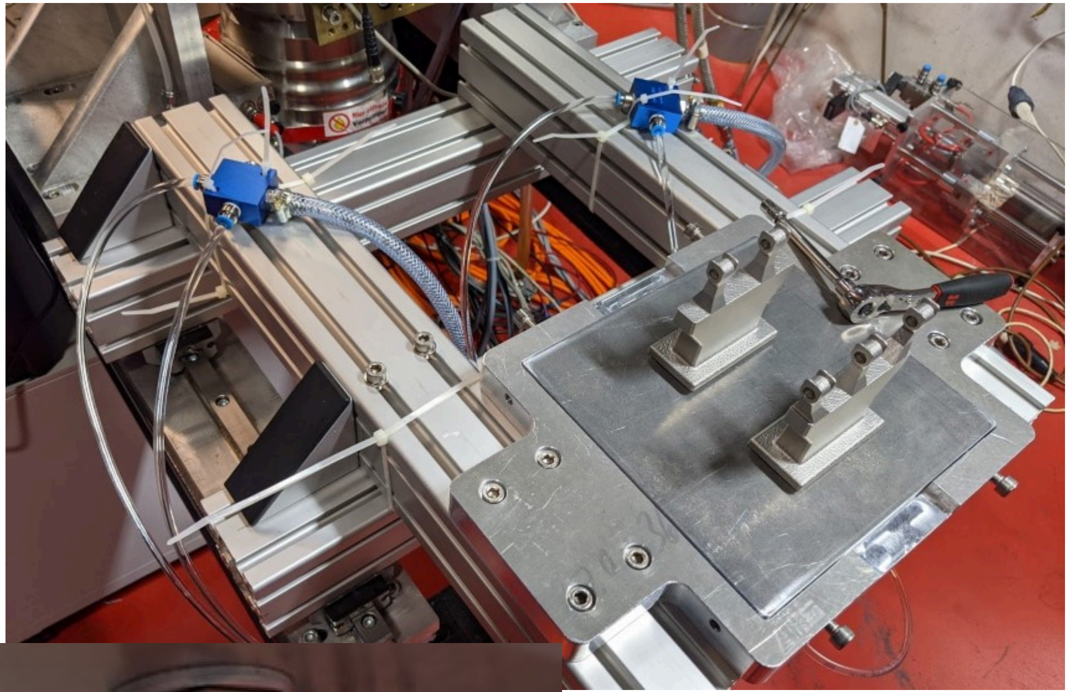




D. Thölken, THM Friedberg

The Experiments

Water flow tests



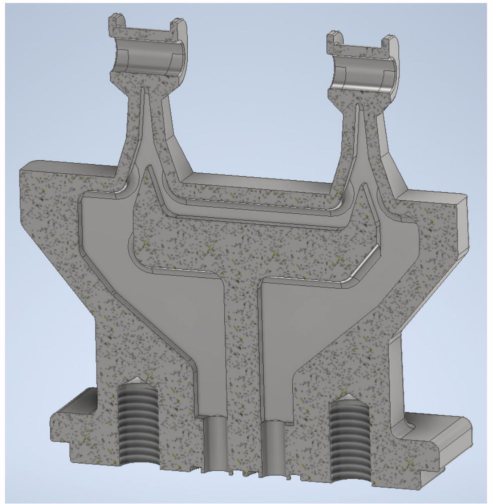
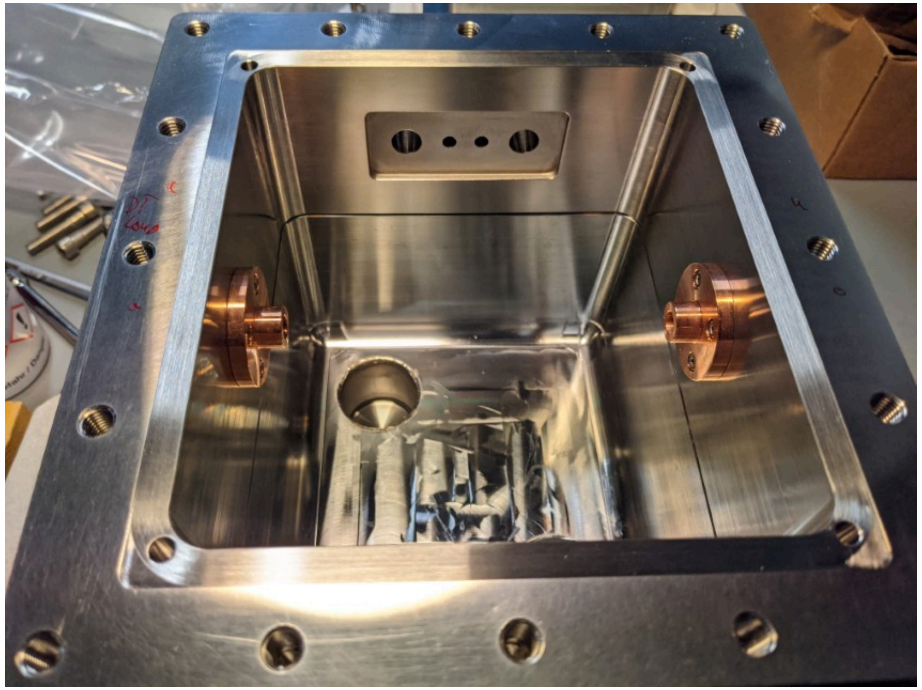


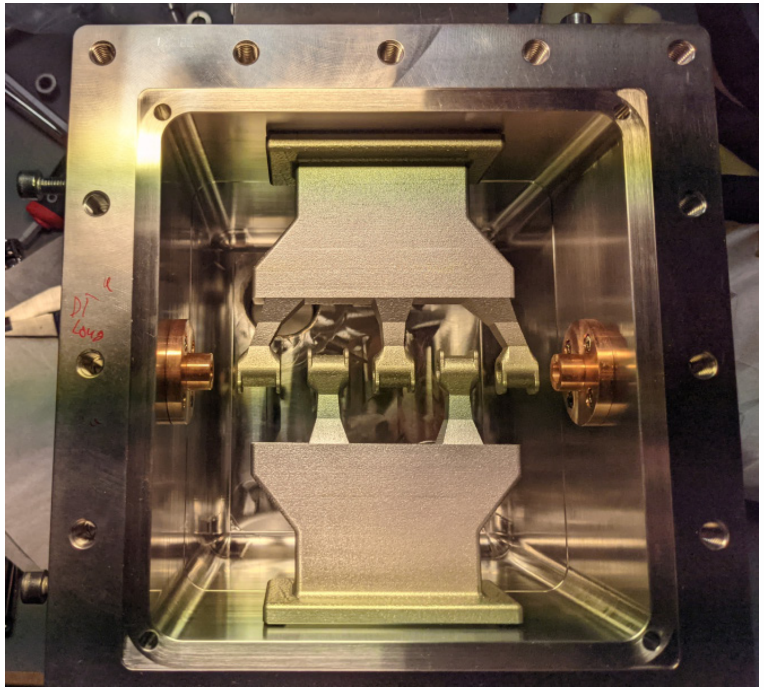
Table 1: Waterflow Measurement

Scenario	**Water Flow**
Source	10.8 l/min
6mm tubing	7.2 l/min
Girder 1	4.8 l/min
Girder 2	5 l/min
Girder 1&2 parallel	7.6 l/min

Cavity Assembly

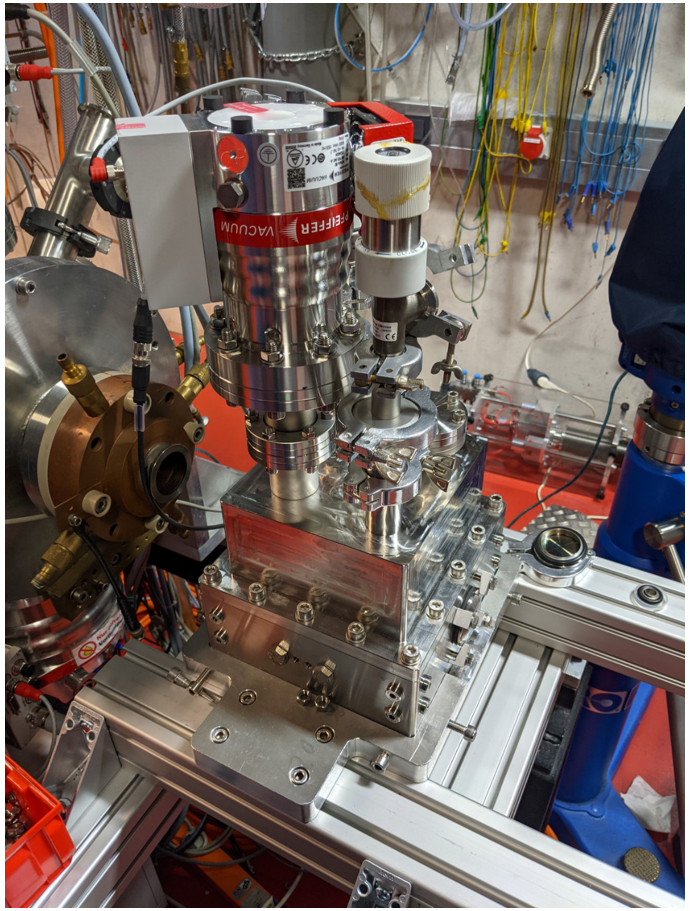
End-drift-tubes are mounted “in vacuum”





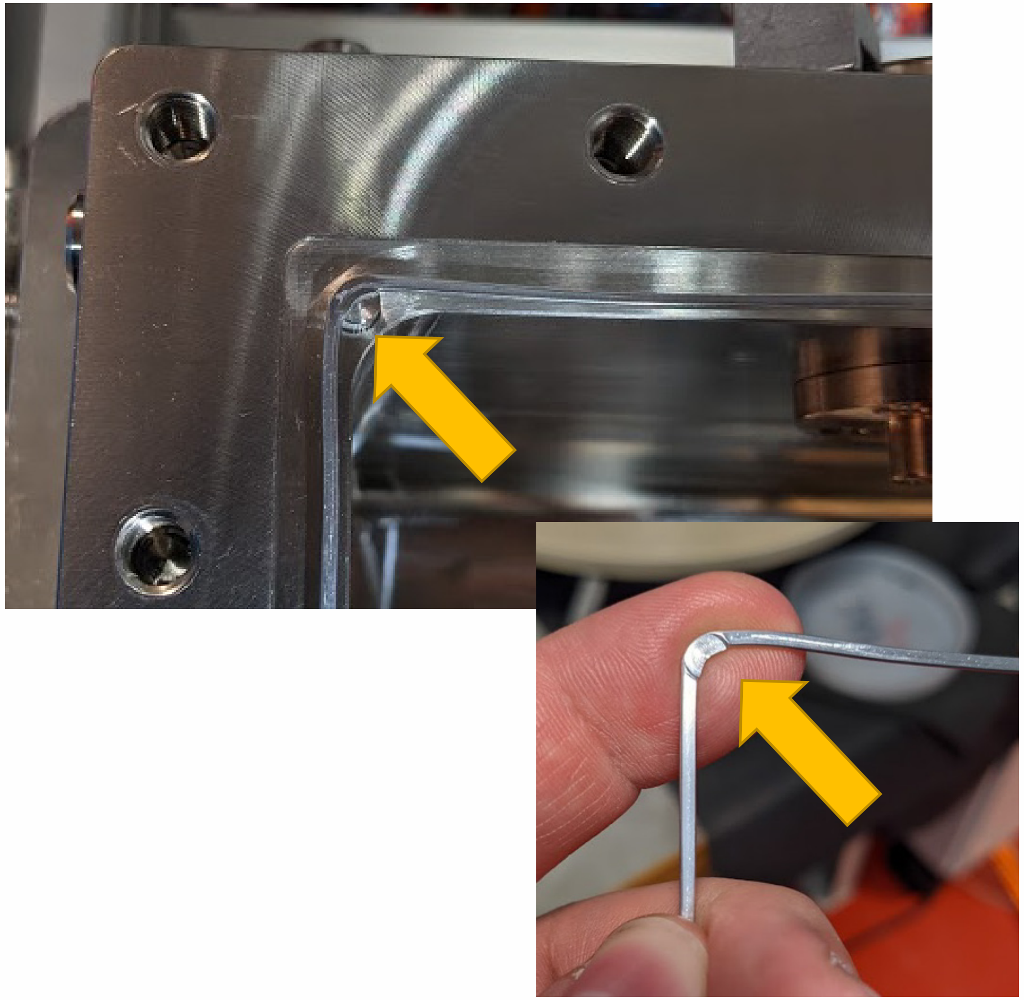
IH Structure is mounted to the precision ports.
An aluminum wire seal is used.

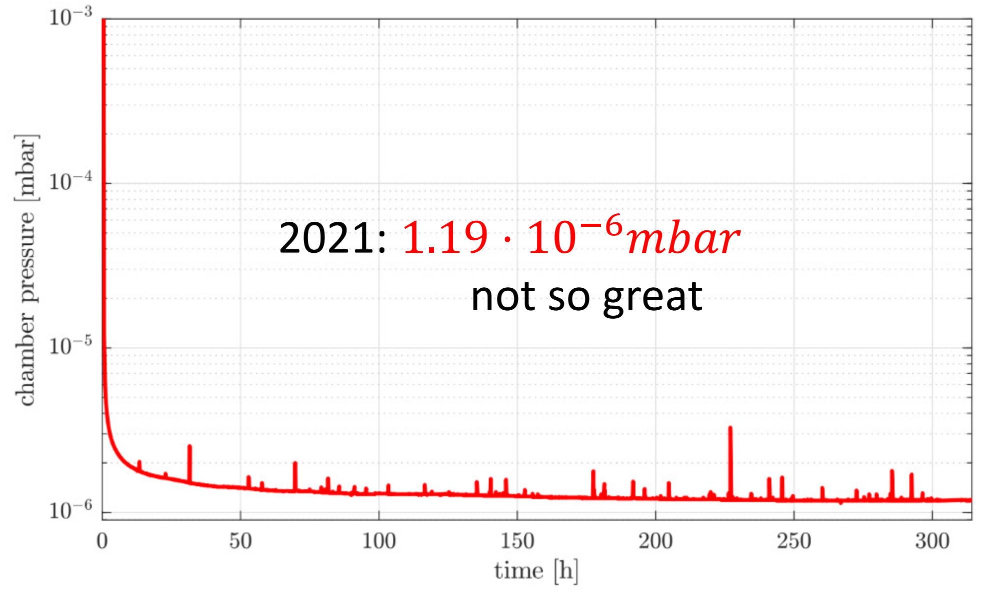
Final setup with Turbopump.



Cavity Vacuum Testing

After some initial hiccups (see left image), the first vacuum measurements in 2021 were not satisfactory.





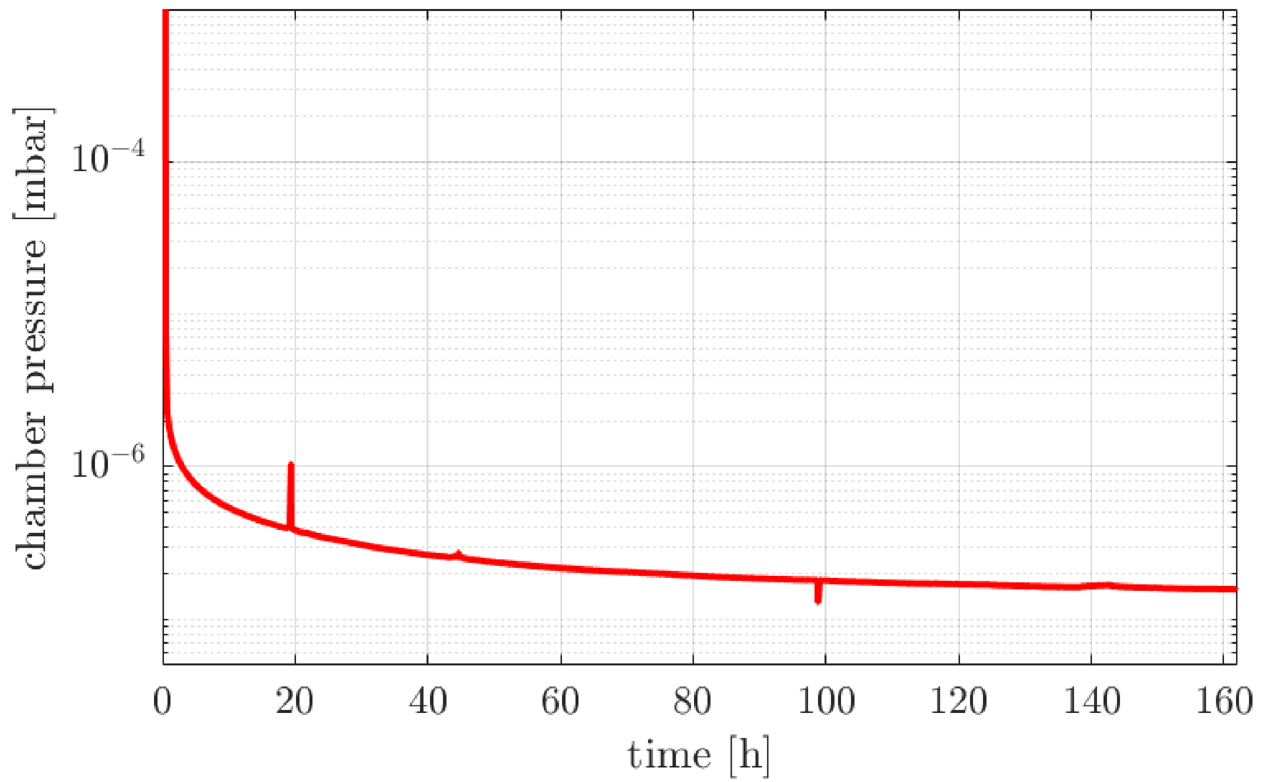
Ironically, the issue seemed to be with the conventionally manufactured components of the cavity.

Cavity Vacuum Testing

In 2021, only $1.2 \cdot 10^{-6}\ mbar$ were achieved.

Late 2021, sealing surfaces of the lids were revised.

Pump down curve May 2022



Latest measurements reach
$\mathbf{1.4 \cdot 10^{-7} mbar}$

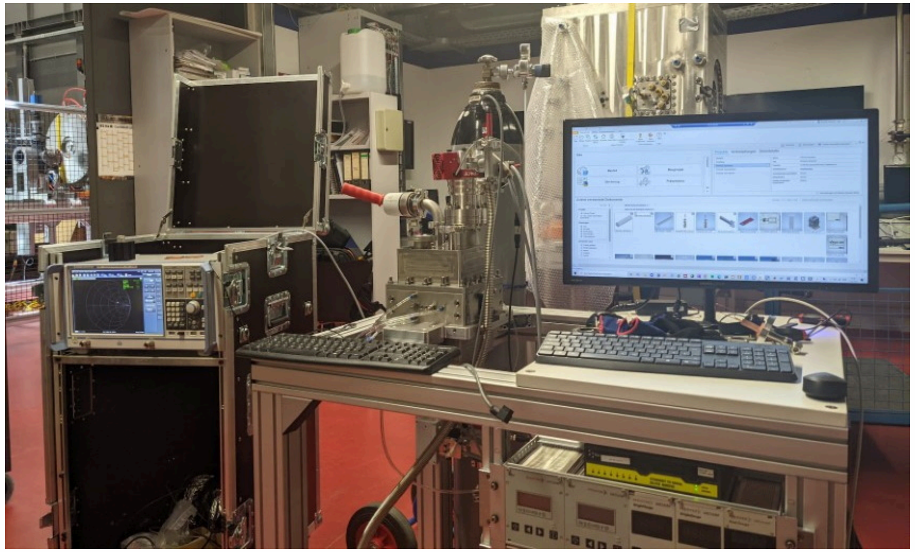
- Sufficient for high power rf tests.
- Printed parts sealing surfaces work
- No excessive outgassing from printed parts observed

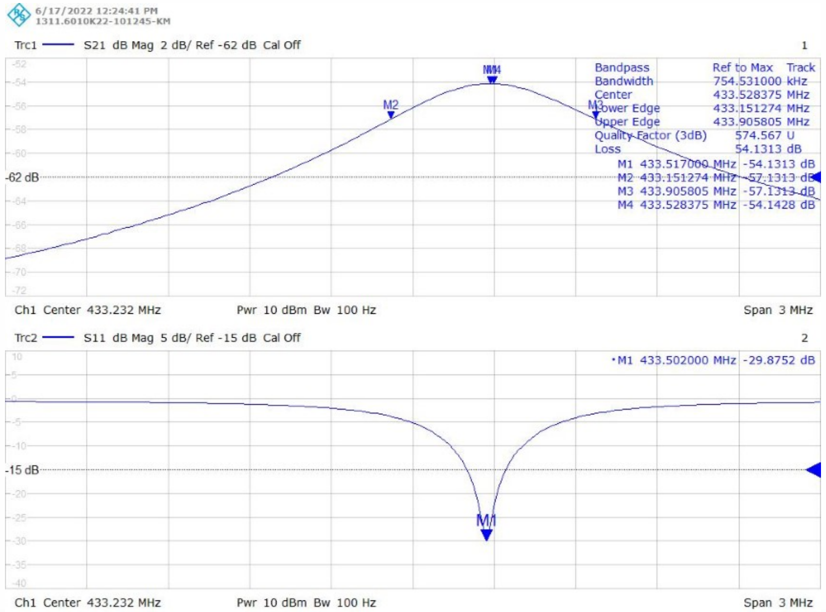
Further improvement expected from heating the cavity to speed up outgassing.

Cavity LLRF Measurements

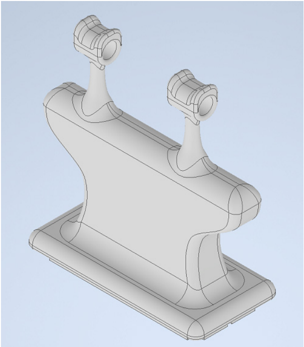
- First LLRF measurements without copper plating
- Measured resonance frequency and Q-factor agree well with simulation
- Simulations were performed with the idealized CST model, as well as actual CAD files used for manufacturing.

Parameter	Idealized Model (CST)	CAD Model (CST)	Measurement
f_{res}	$433.3\ MHz$	$433.445\ MHz$	$\mathbf{433.524\ MHz}$
$Q_0(steel)$	–	1321	**1132**
$Q_0(copper)$	8601	8715	–
$Z_{eff}(copper)$	$287.13 \frac{M\Omega}{m}$	$241.2 \frac{M\Omega}{m}$	–





Next Steps

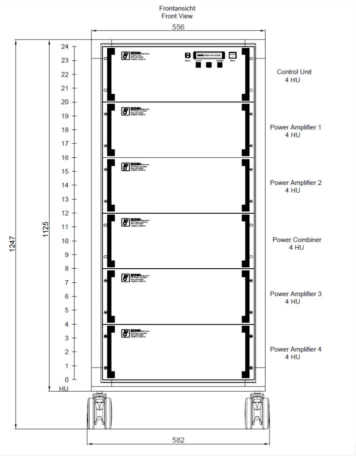


Short Term:

- Vacuum & LLRF Measurements with copper plated structures
- Bead pull measurements
- Manufacturing of improved IH-Geometry
- Copper plating of cavity

Long Term:

- Setting up the power test stand at IAP
- Conditioning of the cavity
- Full power tests with 30 kW pulsed solid-state amplifier



BONN Elektronik
YOUR ULTIMATE RF POWER SOURCE

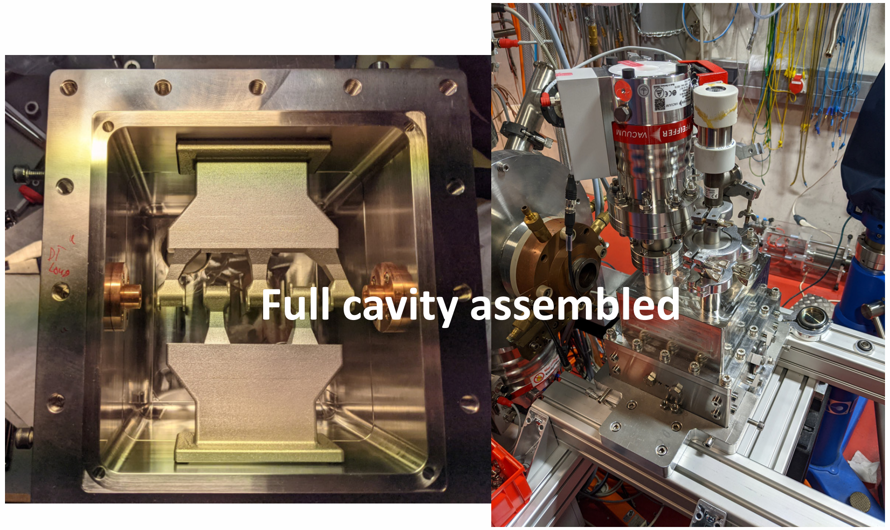
$433.6 \pm 1 MHz$
$30\ kW, 2\ ms, 10\ Hz$

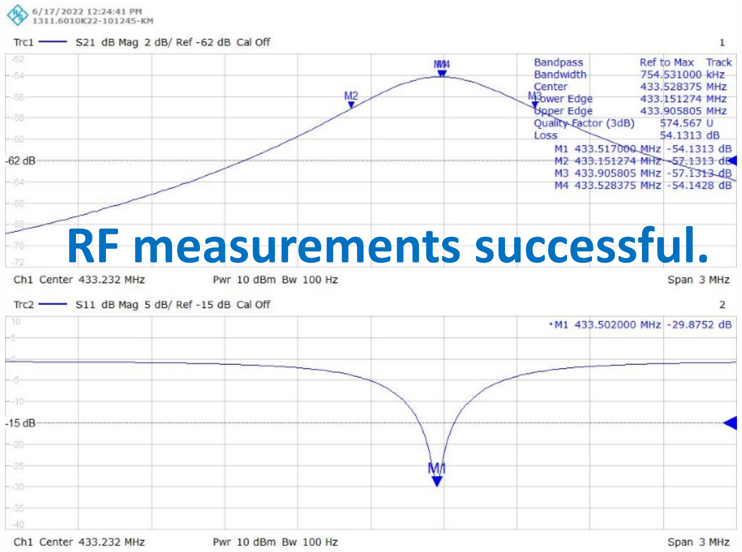
Delivery in 2022
(hopefully)

Summary and Conclusion

AM shows promise for linac manufacturing.

Vacuum & LLRF look good, how will it hold up to power tests?





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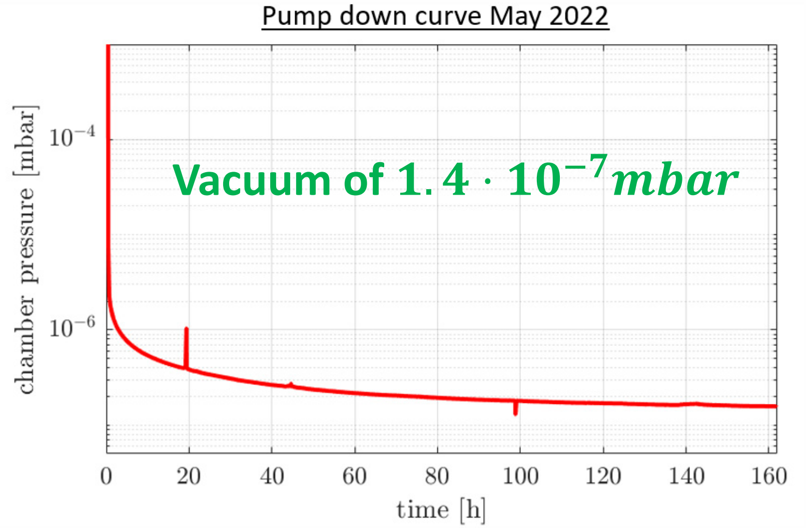

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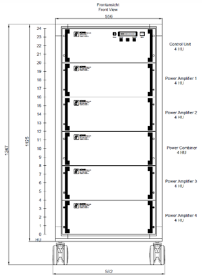

Amplifier coming soon! (hopefully)