5th and Final I.FAST Annual Meeting

Luca Garolfi (CERN)

WP4, Task Leader 4.1 & 4.2

The I.FAST Innovation Fund

1 M€ funding to an internal competitive call for innovative projects, starting early 2023, for a duration of 2 years

1. Funding between 100 and 200 k€ per project
2. Consortium: at least one I.FAST beneficiary and one industry;
3. Initial TRL 3 or higher (from proof-of-concept to laboratory/environment validation);
4. Project contributes to improving sustainability of particle accelerator technologies;
5. Project must have potential for industrialisation or commercialisation
6. Project must have potential to attract more resources than what deployed by IFAST alone.

- **Task 4.1 - Innovation Management and Committee:**
  - Eight IIF projects selection by the Evaluation Board (EB)
  - Eight IIF projects approbation by the Governing Board (GB)

18 projects submitted, 8 selected by a 10-member Evaluation Committee **2023**

The selected projects

2023 - 2025

- **Task 4.2 -** **support activities that introduce Innovation in Accelerator science and technologies**

High-efficiency RF sources

Development** of **Highly Efficient** Megawatt Class **Cross Field Vacuum Tube Amplifier for Particle Accelerators** Driven by a Solid-State Power Amplifier at 750 MHz **(CFA).

Permanent Magnet for High Efficiency Klystrons (PM4HEK).

Additive manufacturing

Demonstration of Additive Manufacturing for** Large and Complex Shaped **Vacuum Chambers** by **Plasma Metal Deposition (PMD®) (Hvac).

Superconducting materials

***Millisecond flash lamp treatment for SRF** accelerating **cavities** (FLA).*

High-Temperature High-Gradient Superconductors (HIGHEST).

Laser-plasma acceleration

KAIO Accelerator

Particle sources

***AM applications** of refractory metals **for ION Source** cavities (AMIS).*

*A **Field Emission Cathode** for a **TW RF gun** for High Brightness Beams in Industrial and Small Research Facility Settings **(FEC).***

Projects results

- To examine the results achieved, it's convenient to classify the projects by **type of development pursued:**

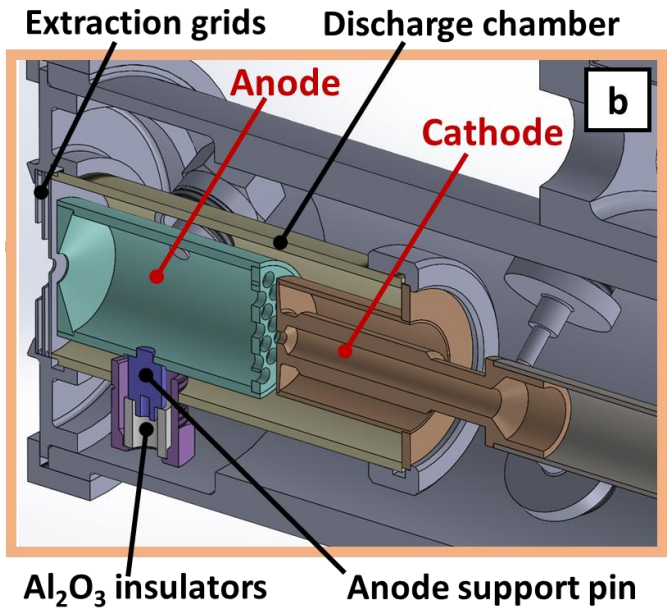
- **improved components** obtained with new (application of) manufacturing technologies to accelerator components:
  - AMIS,
  - FLA,
  - HIGHEST
  - Hvac

- **improved equipment's**, already available from vendors/OEM through the development of a new component:
  - KAIO,
  - PM4HEK

- **new components** for accelerators:
  - CFA
  - FEC

Improved components

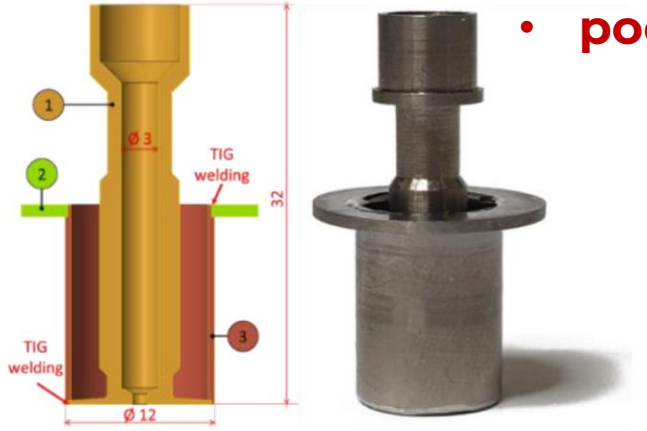
AMIS for SPES - increasing the reliability of the FEBIAD ion source

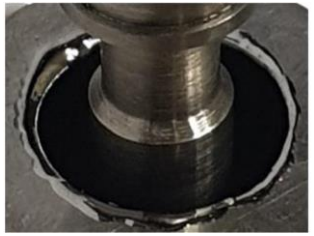


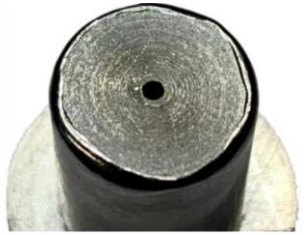
CASE STUDY: The FEBIAD ion source cathode

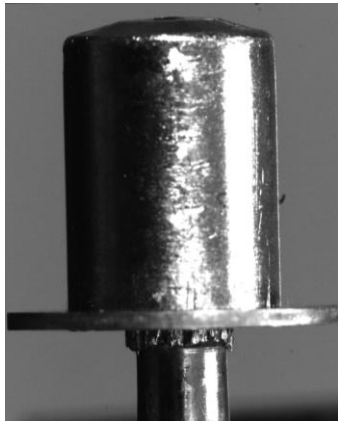
The standard FEBIAD cathode is composed by **3 welded Ta components**

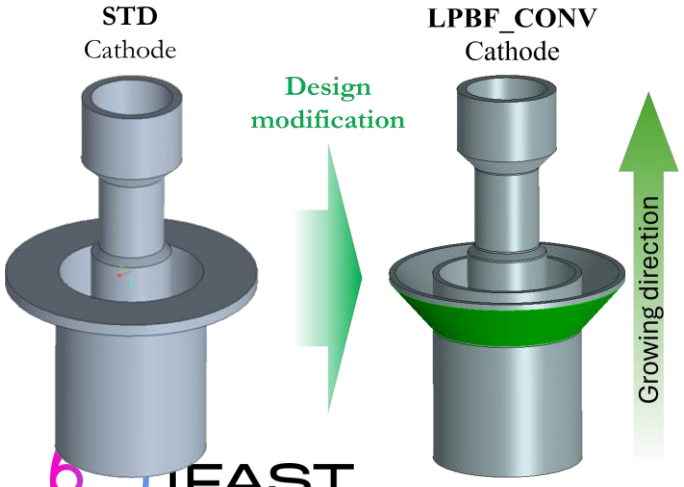
- poor geometrical accuracy
- **poor repeatability/reliability!!**











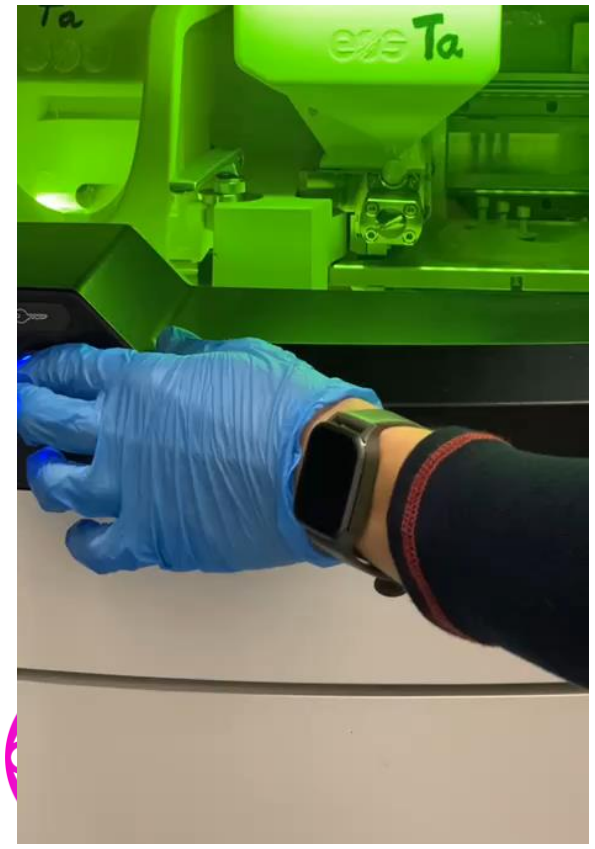
Better geometrical accuracy is achieved!

Dimensional/geometric feature	Avg value	Δ
Diameter cylinder Ø3	2.936 mm	0.064 mm
Diameter cylinder Ø12	12.018 mm	-0.018 mm
Cylindricity Ø12	0.025 mm	-
Flatness Flange	0.035 mm	-
Distance 16mm	16.056 mm	-0.056 mm
Flatness Front surface	0.003 mm	-
Cone angle 80°	79.549°	0.452°

AMIS contribution to improve sustainability and to reduce the environmental impact

1. ADDITIVE MANUFACTURING PROCESS

- *Build the final part in only one step*
  - *→ Production time reduction*
  - *→ Reduce the amount of wasted material*
  - *→ Post-processing phase time & cost reduction*
- *Recycling of the un-melted powder*



2. LOWER COSTS

→ *cathode example*

Standard cathode
(Cost ~ 1500 €)

First AM cathode
(Cost ~ 300 ÷ 500€)

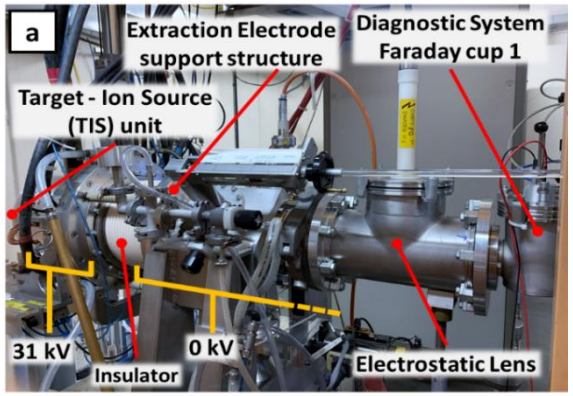
3. Potential application environmental impact

- *ISOL technologies for production of medical radionuclides can become a green alternative to nuclear fission reactors.*

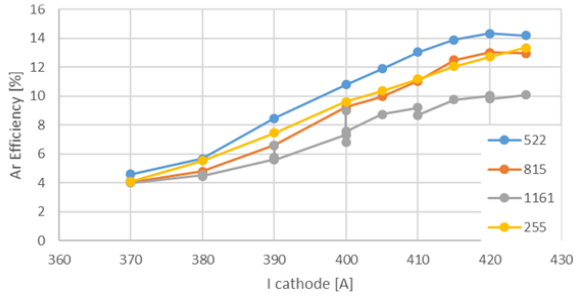
AMIS - TRL status

2022 (end)

→ ***TRL 3***



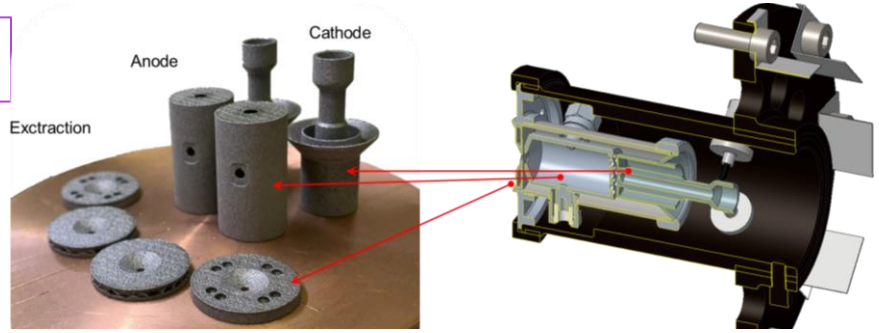
Ionization efficiency using AM Mo Anode comparable to STD Ta Anode

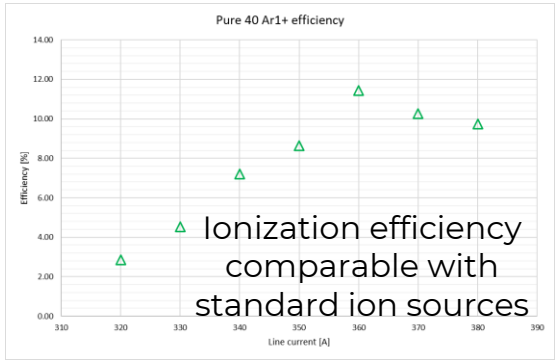


- **Proof of Concept Test of the AM ION Source and Prototype production**
- **Off-line Test of the AM Mo Anode with the traditional geometry**

2024-2025

→ ***Transition <u>TRL 3 to 5</u>***





- **Development of a fully refractory metals Ion Source with traditional design using AM parts for off-line tests.**

→ **Validation of the production process using the traditional design of the ion source.**

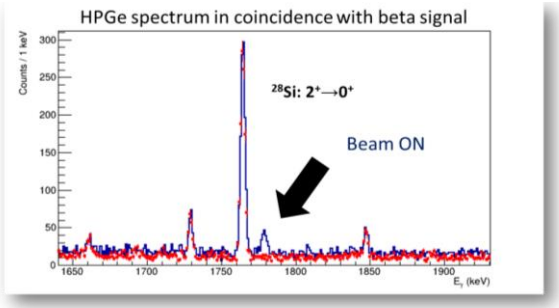
"Technology demonstrated in relevant environment"

→ ***Estimated time for TRL 6 & 7***

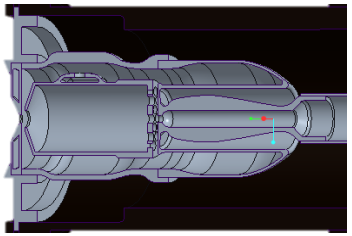
2026 … but

"System prototype demonstration in operational environment"

- **on-line test with FEBIAD Ion Source containing AM components (cathode) at SPES**



→ **NEXT Step**



- **on-line test with FEBIAD Ion Source full AM design**

Millisecond flash lamp treatment for SRF accelerating cavities

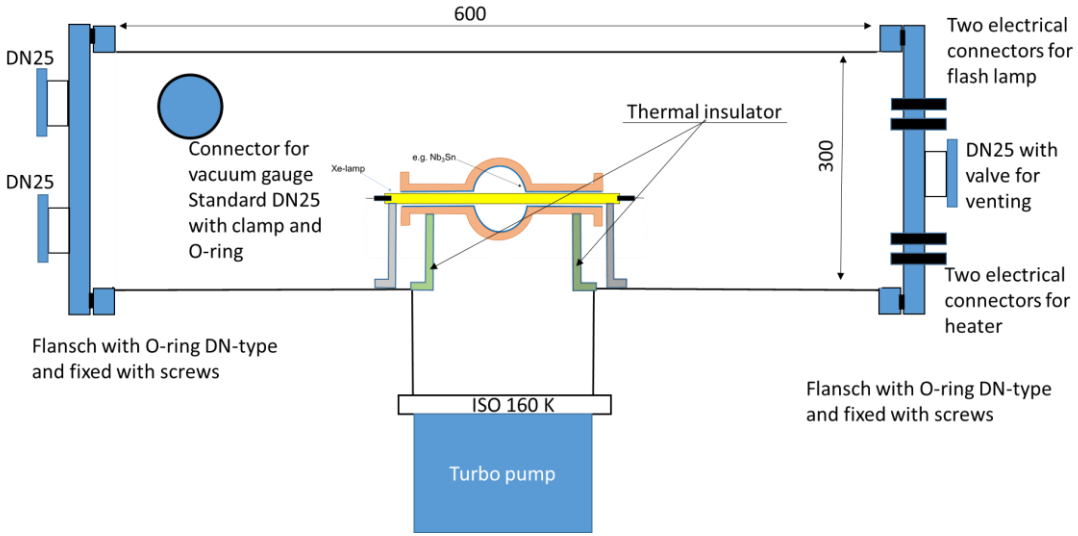
Cristian Pira, INFN
Slawomir Prucnal, HZDR

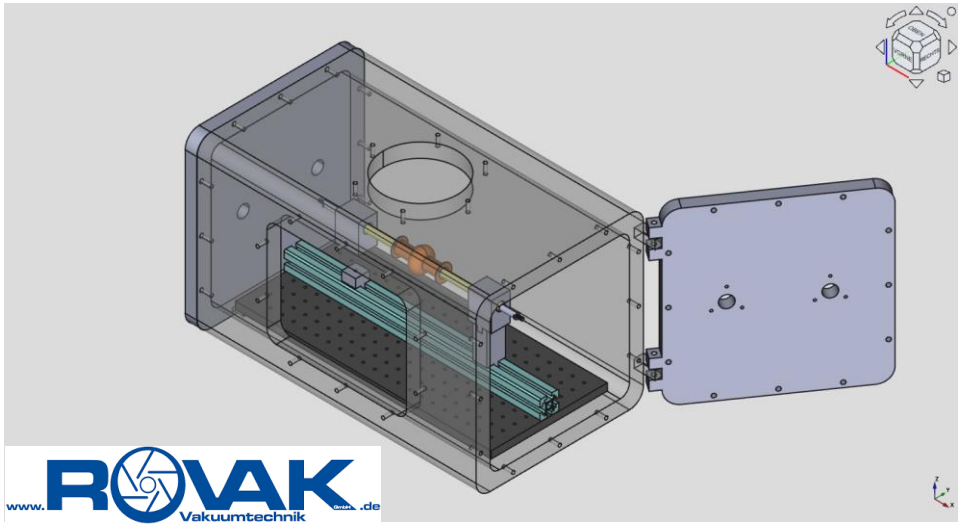
Main highlights

- **I.FAST WP9** demonstrate that for an optimum Nb_3Sn coating is mandatory:
  - Process Temperature > 600 °C

- **The goal** of Msec Flash annealing project is to develop a **novel thermal process** to **improve coating crystallinity** without affecting basic properties of copper substrate *(reducing Cu substrate heating to T<600°C)*

Vacuum chamber for the annealing of 6 and 1.3 GHz superconducting cavities has been designed and tested together with Rovak GmbH





FLA to flash 6 GHz cavity: last improvements

designed to operate in two modes: heating elements of any shape from above utilising light reflection from the chamber walls. Xe-lamps system placed under blue element visible in (a) or ms-annealing of cylindrical elements like SF-cavity presented in (b and c).

In the new version the heating band (instead of heating plate) is added to increase the initial temperature of Cu-cavity and reduce the thermal gradient during flash annealing.

Achieved Technology Readiness Level & Future

The proof of concept is achieved.

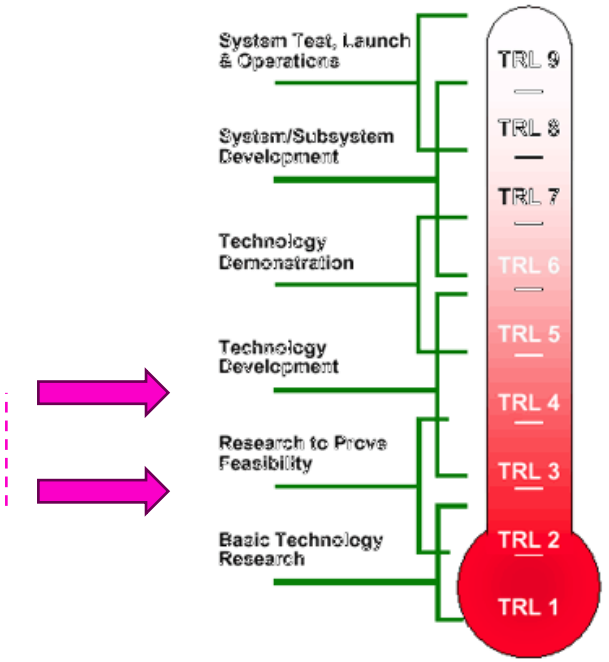
Future

- **conduct more experiments on annealing of Nb3Sn coated cavities using the FLA method) but waiting for new power supplies**

- **The chamber is designed, constructed and tested. The FLA of 6 GHz cavity is performed. The temperature distribution in cavity during FLA process is performed (more tests will be done for different number of pulses and pulse duration). The influence of the FLA on the microstructure of Cu was verfied by XRD. Thes strain relaxation in Nb3Sn after FLA is observed. According to PIXE there is no diffusion of Cu into SC film.**

- **Within next 3 weeks we will have COMSOL simulation about temperature distribution through the coating films and Cu including the interface engineering e.g. by adding AlN layer.**

- **The FLA is going to be back in operation these days. The first experiment will be to flash the 6GHz cavity with Nb3Sn layer made by Cristian. The cavity is in vacuum and after FLA the change of the coating properties will be tested.**



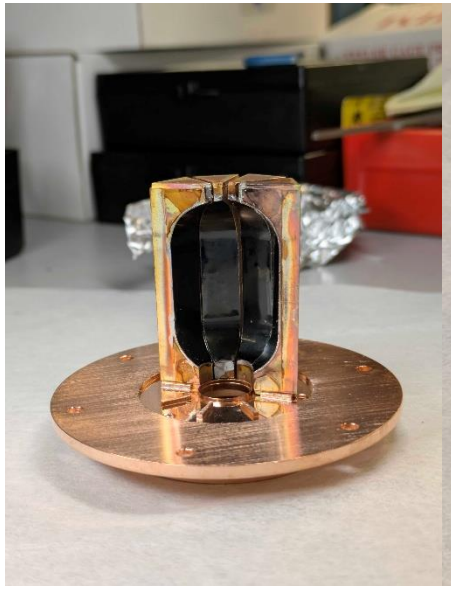
High-Temperature High-Gradient Superconductors *(“HIGHEST”)*

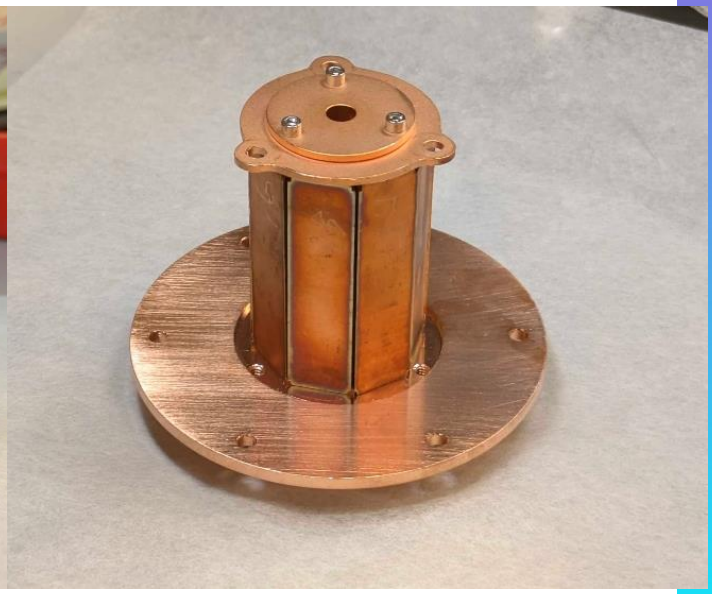
Sergio Calatroni, CERN
CSIC-ICMAB (public research center, ES)
KIT Campus Transfer GmbH (KCT) (private company, DE)
SLAC as supporting partner

Main achievements

- D1 - RF low power characterization of segmented cavities (small tapes)
- Extra – Segmented cavity from SLAC already produced (was foreseen after HIGHEST), coated with small tapes and tested at low power

CERN
RADES cavity
2nd generation





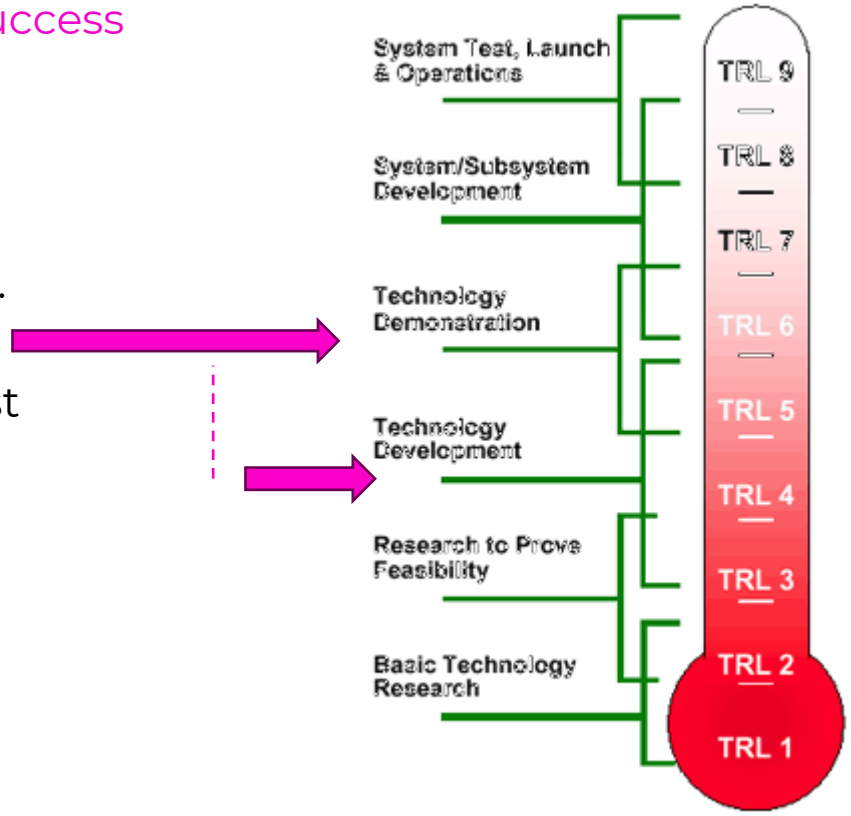
SLAC
Pulse compressor

Achieved Technology Readiness Level & Future

- The HIGHEST project concluded all expected deliverables with success and with very promising results for future RF applications.
- At the end of this study, we consider that TRL4 is consolidated.

- Prototype pulse compressor with SLAC will demonstrate TRL 5-6.
  - Initially foreseen to be started after completion of HIGHEST
  - Hardware completed and integrated, waiting for final RF test
  - Activity independent from HIGHEST, but based on our developments and results

- **TRL5 (Large tapes), TRL6 (Narrow tapes)**



The project HIGHEST2 has been submitted as an Emerging Technologies proposal in I.FAST2/EPITA, and was ranked 4th out of 45 proposals, and got practically fully funded (470 kEUR out of the 500 kEUR requested)

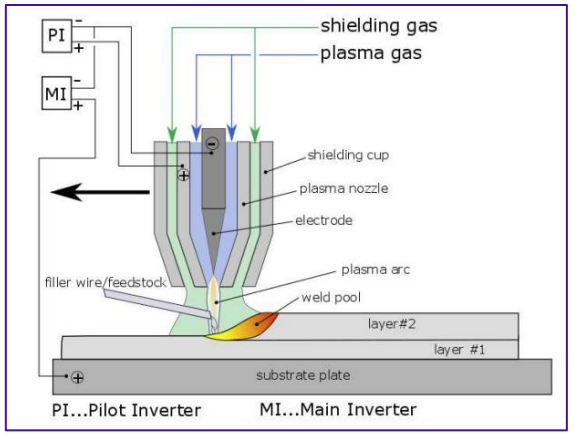
Hvac - Demonstration of ***Additive Manufacturing for Large and Complex Shaped Vacuum Chambers by Plasma Metal Deposition (PMD®)***

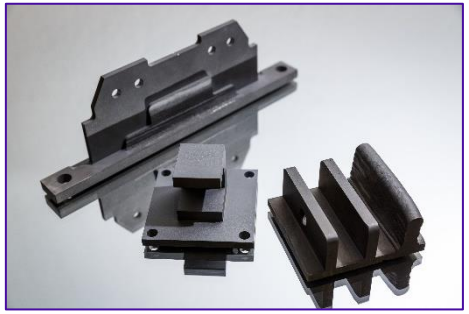
Dr. Carlos Belei, Project Engineer – RHP Technology GmbH

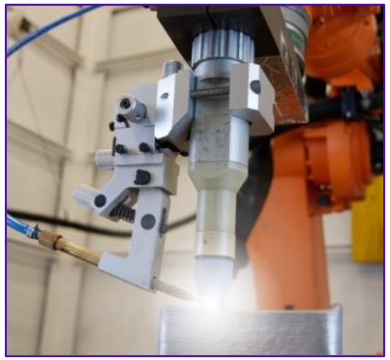
Dr. Erich Neubauer, Managing Director – RHP Technology GmbH

Main highlights

- **Plasma Metal Deposition** (PMD®) is an AM process suitable for the production of large near-net shape components;
- Accelerator science and technology requires several **vacuum chambers** of various sizes and shapes;
  - PMD has the potential to be used in the manufacturing of vacuum chambers, with **reduced raw material usage** and complex design.

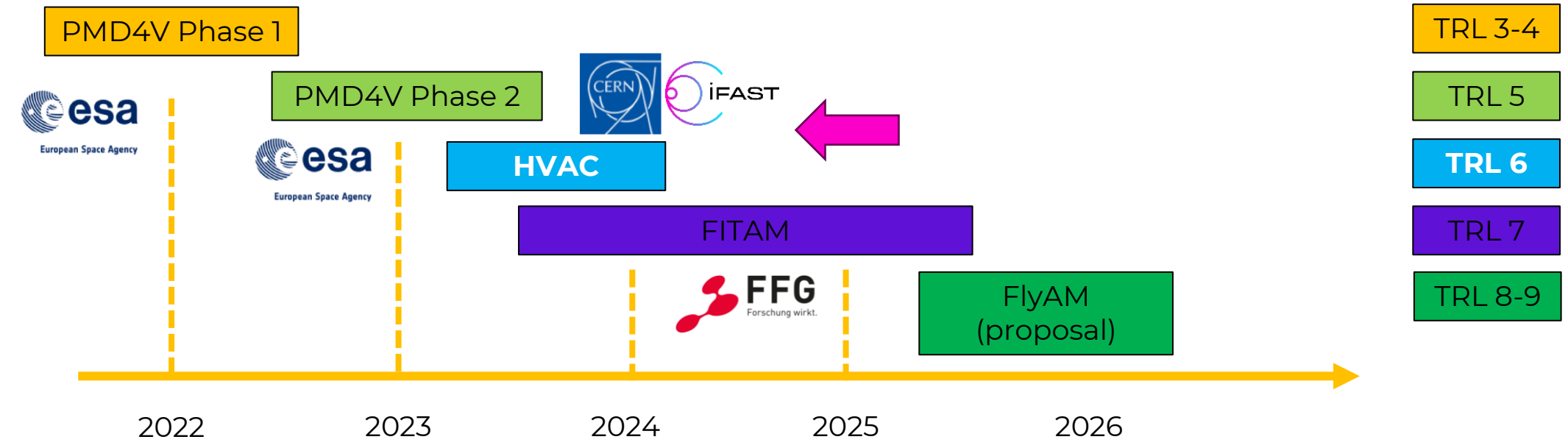






PMD PLASMA METAL DEPOSITION

Technology assessment – TRL progress



New materials

Improved equipment's

KAIO « Kit-All-In-One » commercial Laser-Plasma Accelerator (LPA) value chain

Industrial fs lasers

Ti:Sapphire laser:
ASTRELLA from Coherent
7 mJ, 40 fs, 1 kHz, 800 nm

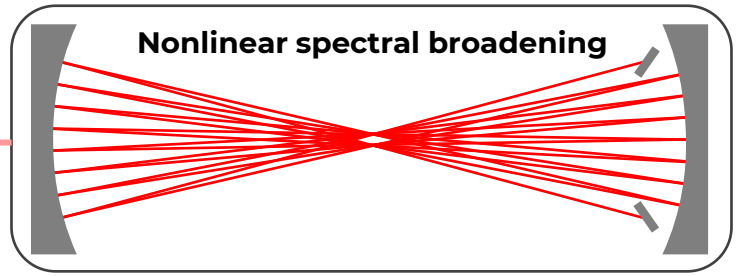
Ytterbium (Yb) laser:
MAGMA from Amplitude Laser Group
20 mJ, 400 fs, 1 kHz, 1030 nm

Yb laser technology:
- ❑ ***High average power***
- ❑ ***High wall-plug efficiency***
- ❑ ***Industrial & sustainable***

Scope of KAIO ACCELERATOR

Efficient post-compression in Multi-Pass Cell (MPC)

Hanna et al, Laser Photon. Rev. 2021



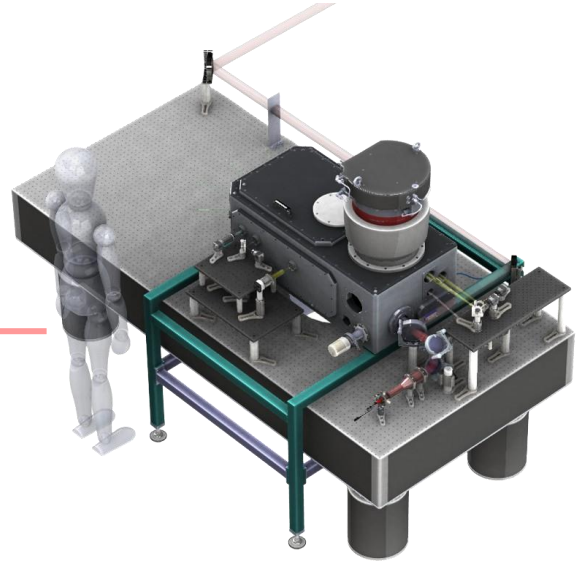
Pulse shaping for LPA operation:
- ❑ few-cycle duration
- ❑ TW peak power

MPC prototyping:

loa

SourceLAB

Commercial LPA module (e-KAIO by SourceLAB)



Few-MeV electron beam @ kHz

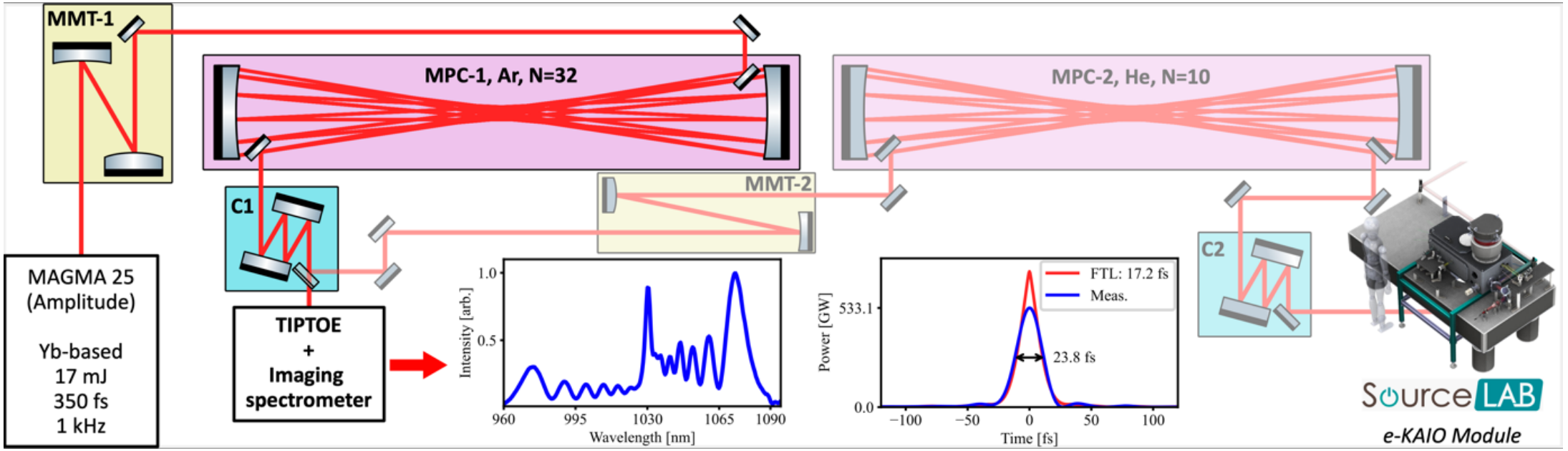
Radio-biology benchmarking:

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

LPA market study:

DF Photonics Consulting

MPC compression of MAGMA laser (Yb) for LPA: cascaded MPC architecture



Yb laser

Stage 1:

- Output: 17 mJ, ~ 20 fs (pulse compression factor ~ 17)
- Peak power ~1 TW @ 1 kHz
- Compression efficiency ~98 %

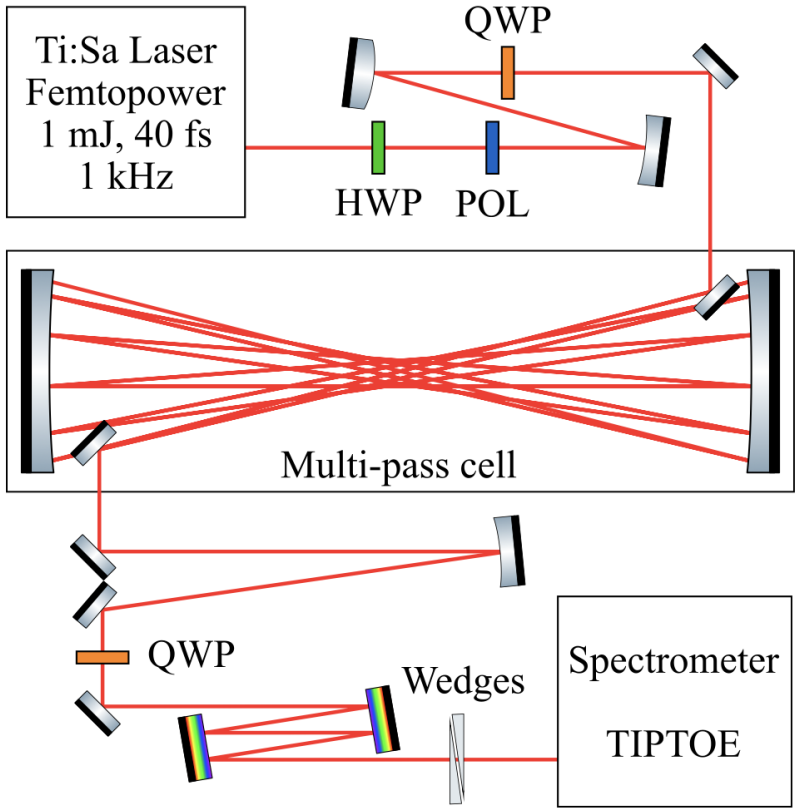
Stage 2:

- Projected: 10 mJ, < 4 fs (compression factor ~ 100)
- Peak power > 2 TW @ 1 kHz
- Design tests in progress
- Expected completion: end of 2025

Design tests for second MPC stage

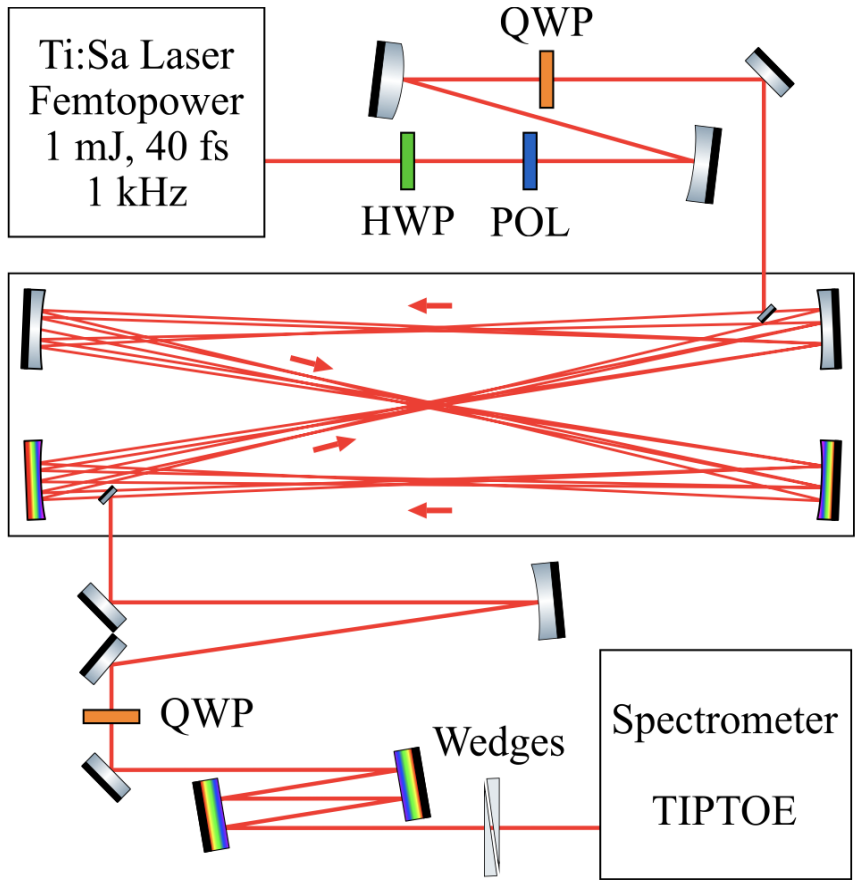
Ti:Sa laser driver + dispersion controlled mirrors

Ti:Sa laser



- MPC parameters: 4-m long, Argon-filled, dispersion-controlled mirrors
- Output pulse duration ~ 4.6 fs (best result since Daniault et al. Optics Letters 20, 5264 (2021)
- Input energy limited to ~175 mJ

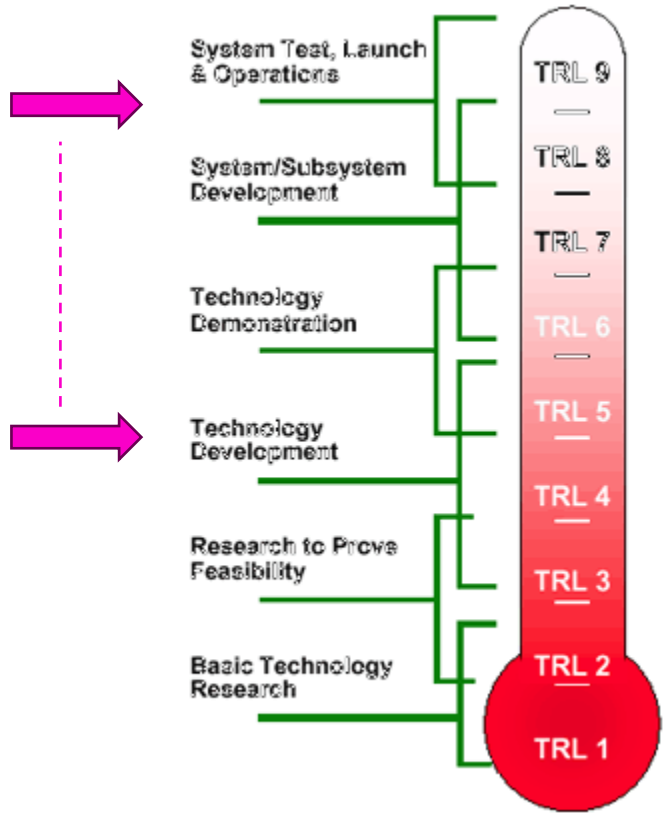
Ti:Sa laser driver + X-MPC



- X-shaped MPC geometry
- Input energy increased to ~ 450 mJ
- Post-compressed duration decreased to 4 fs
- Scalable design for high-energy Yb laser driver

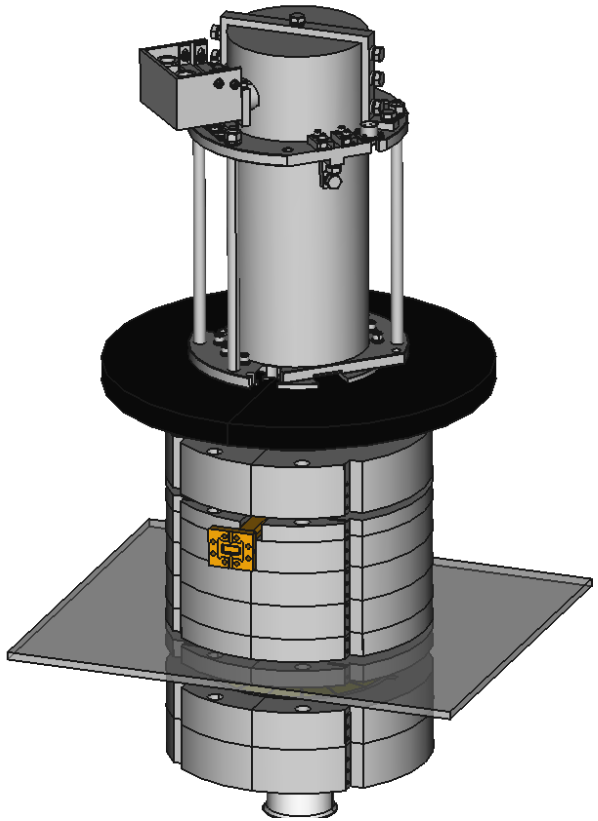
Achieved Technology Readiness Level & Future

- **Next steps:**
  - **Qualify the scaled design for the second MPC post-compressor for the high-power Yb laser driver**
  - **Design and assemble beam transport line to deliver the post-compressed pulses to LPA located in a radio-shielded environment**
  - **Demonstrate laser-electron acceleration with the post-compressed Yb laser (expected Q2 2026)**
  - **Benchmark LPA beam performance against conventional accelerator beam (expected Q4 2026)**



Permanent Magnet for High Efficiency Klystrons *(PM4HEK)*

Nuria Catalan Lasheras, CERN,
Elytt Spain



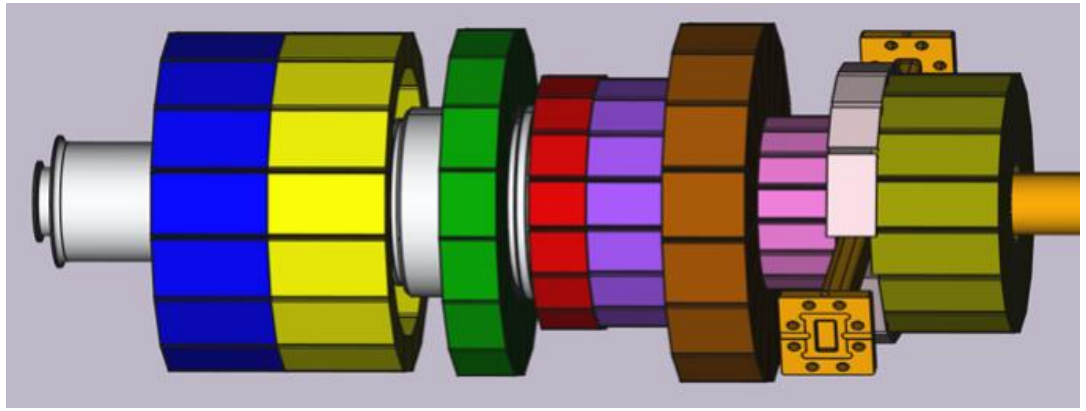
Design and fabricate a magnetic electron beam confinement system composed of permanent magnets (PM), to be installed in the 8 MW, 12 GHz high-efficiency klystron

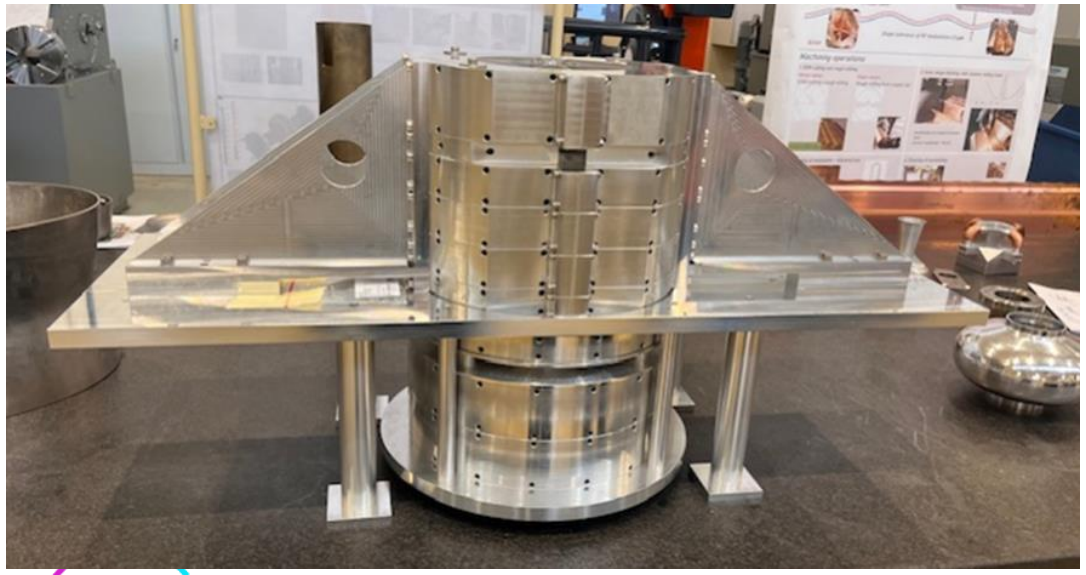
Main achievements

- **Design** an array of **PM** that **imitates the axial magnetic field of a solenoid** in the region of interest with high accuracy.
- **Simulate the klystron electron beam with the applied magnetic field** to verify the correct focusing and transmission along the entire length of the drift tube of the klystron, from the cathode to the collector.
- **Design a sorting system** for the **PM to minimize errors** in the applied magnetic field.
- **Manufacture a demonstrator** of the PM system to measure the obtained magnetic field distribution.
- **Simulate the absorption of the beam at the collector** walls and adjust the magnetic field to avoid reflected electrons for actual implementation at the klystron.

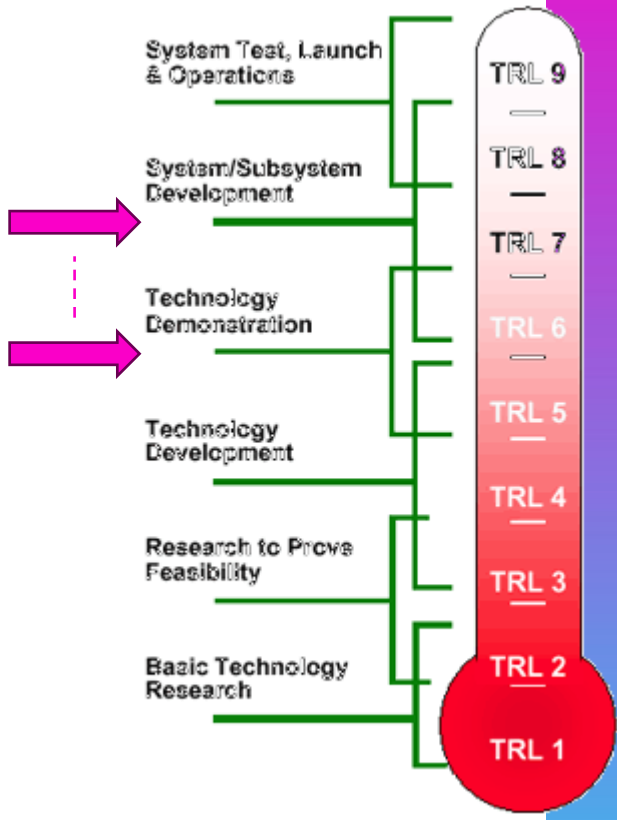
Achieved Technology Readiness Level & Future

A 3D model of the complete system





- Full manufacturing drawings were done as final stage of the design phase including:
  - magnets,
  - mechanical support & assembly,
  - magnetic measurement tooling.
- A physical has been manufactured:
  - mechanical structure holding the magnets in place is made mainly of Aluminium 6061
  - It is composed of individual holders that are filled with the magnets using the tooling



Future

- Measurement will be performed after the end
- Improvements to integrate it with the klystron
- Optimize the radius and geometry of the collector to absorb some of the beam power before the end of it

New components

Development of Highly Efficient Megawatt Class ***Cross Field Vacuum Tube Amplifier for Particle Accelerators*** *Driven by a Solid-State Power Amplifier at 750 MHz*

Anshu Sharan Singh and Dragos Dancila
(Uppsala University - FREIA)
Industrial partners: Scandinova AB and Exir Broadcasting AB

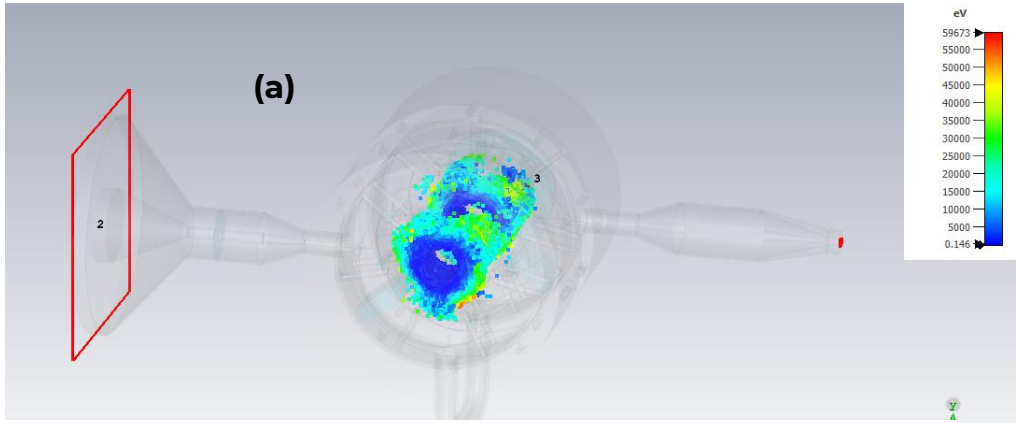
Main highlights

The aim of this application is to synergize the power generation technologies and develop the megawatt class CFA as the **main amplifier of the SSPA driver**, to achieve the **highest degree** of **efficiency**, **cost-effectiveness**, **compactness** and **lifetime** of an. **RF power source for particle accelerator and medical applications**

Challenge: Single CFA → 600 kW at 713 MHz, 27 dB gain, 20% efficiency. Increasing the number of slow-wave sections raised the gain but triggered instabilities and oscillations.

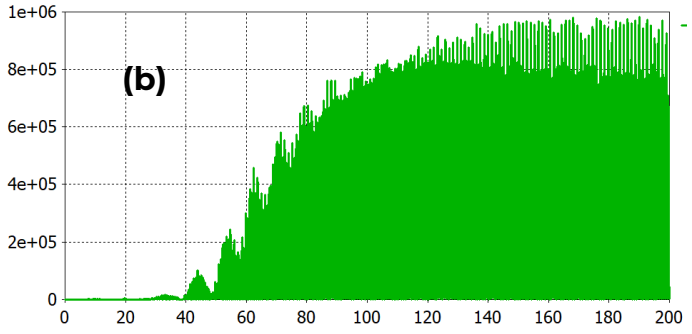
New approach (post-April): Stacked CFA design with two cathodes and two slow-wave structures on a common HV supply. Optimised slow-wave geometry to suppress instabilities.

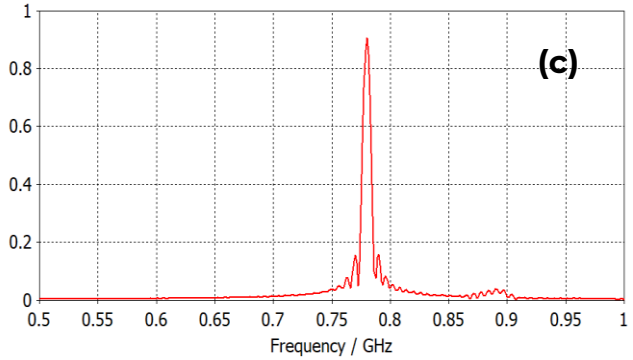
Result: Predicted ~1 MW RF output power near 750 MHz (stable operation).



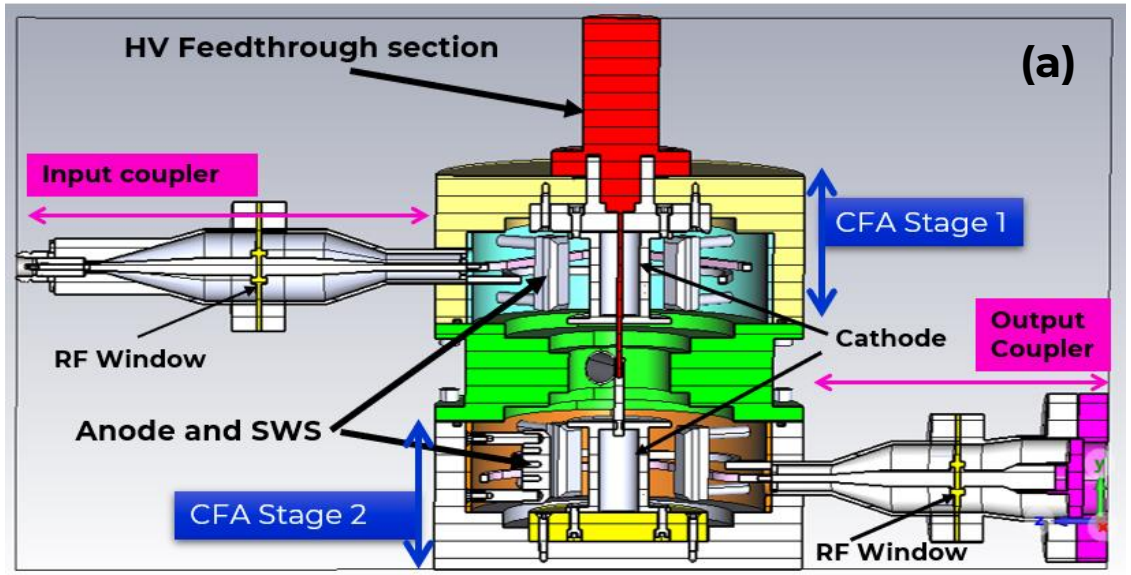
a) shows the **3D beam–wave interaction** within the stacked CFA

(b) and 1(c) show the temporal and frequency responses of the amplified RF power, confirming a stable output of ~0.9 MW near 780 MHz with ~29 dB gain, demonstrating efficient electron-to-RF energy conversion.





CFA Fabrication and HV and Microwave Setup Development



From the **megawatt-class CFA**, a **CAD model** was prepared, and fabrication has begun at the Ångström workshop (**Fig. 2a**). The process will be completed within a week.

The **anode vanes** made of **stainless steel** are shown in **Fig. 2b**, and **Fig. 2c** shows the **SWS components** used to hold and align these vanes within the structure.

Meanwhile, a **high-voltage and high-power microwave setup** has been established, and the **ScandiNova M100 modulator** has been **commissioned** for **field-emitter cathode testing** (**Fig. 2d**).

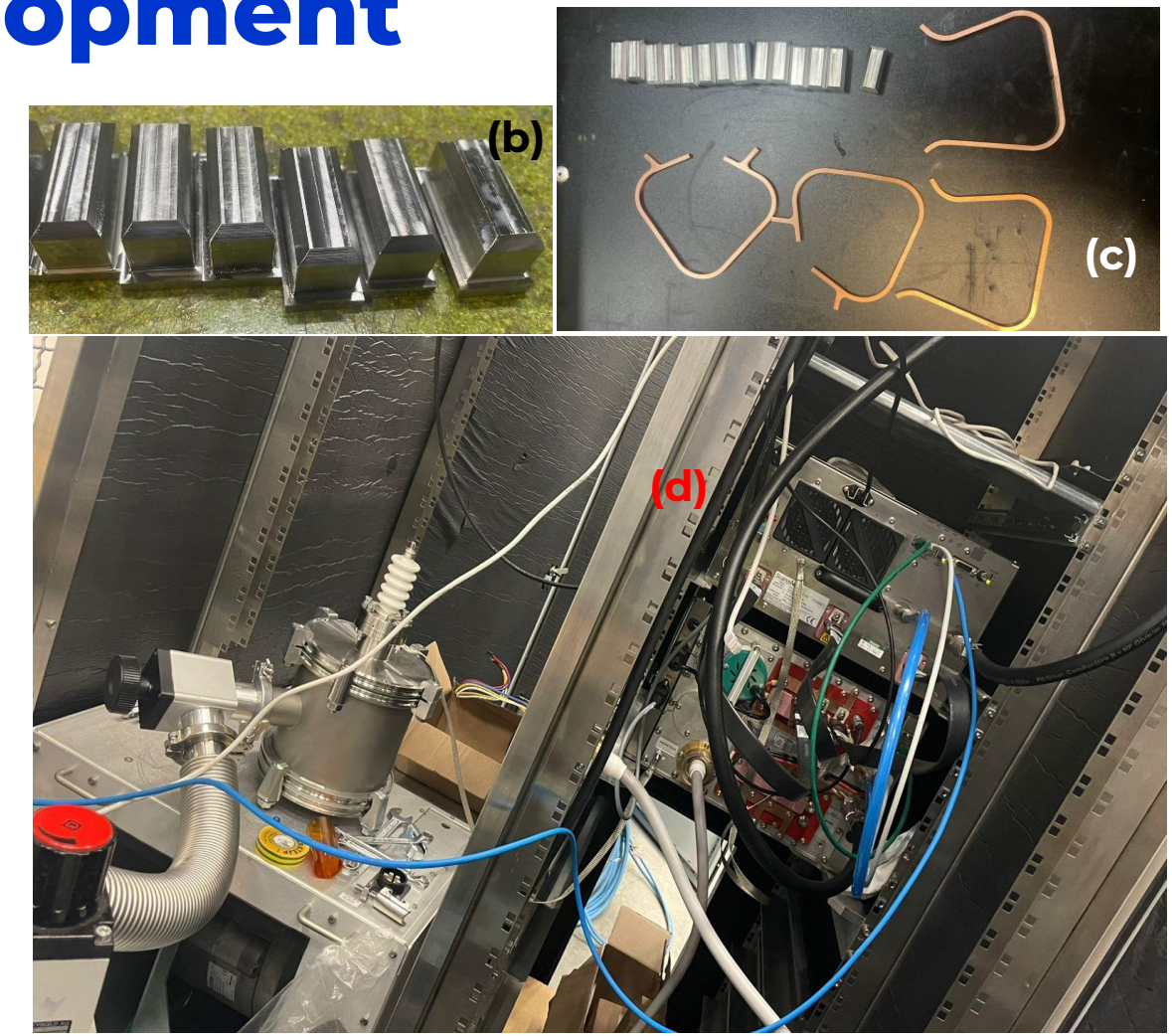


Fig.2 (a) CAD Model for Fabrication (b) Anode vanes (c) SWS parts (d) Scandinova M100 modulator at FREIA, UU

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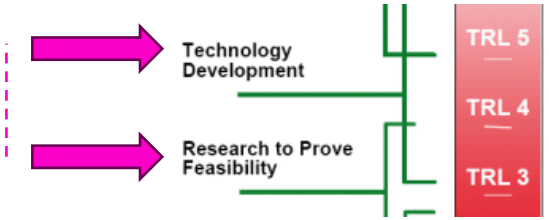
Impact



Component and/or breadboard validation in relevant environment

Component and/or breadboard validation in laboratory environment

Analytical and experimental critical function and/or characteristic proof-of-concept

Achieved TRL level: 4 *(expected TRL 5 after upcoming high-power RF validation)*

Results	Short- to Medium-Term Impact	Medium- to Long-Term Impact
1. HV & Microwave Station	ScandiNova-based high-power station at FREIA established for RF, beam–wave, and cathode testing.	Long-term platform for spark-gap, HV component, and cathode research supporting accelerator and industrial studies.
2. CFA Research	New experimental knowledge added to CFA technology, addressing stability and fabrication challenges.	Boosts global CFA research and offers an efficient alternative to magnetron phase-locking.
3. S-/X-Band LINAC Development	Infrastructure adapted for S- and X-band testing and accelerator applications.	Foundation for future LINAC and FLASH-therapy studies.
4. Research Infrastructure & Collaboration	Versatile test platform established for high-power microwave studies.	Continued work through VR grant and new collaborative infrastructure projects.

Impact in Period 2

Funding (as an attraction of additional resources)

Nov 2024, Additional small funding was obtained from Vinnova, Sweden's innovation authority, to work on the field emitters for high-power vacuum electron devices.

Conference Presentations:

- **MeVArc June 2025**, Uppsala, Sweden, " Development of Field Emitters for High Power Vacuum Electron Devices and Linear Accelerators" (A. S. Singh and D. Dancila) – Accepted contribution on CFE cathode integration in high-power systems.
- **January 7, 2025**, Anshu Singh delivered an invited lecture at the National Institute of Technology Patna, India, titled "Development of Micro Magnetron under the Marie S. Curie Fellowship Program."
- **Significant delay** (~3–4 months) due to extended design optimisation and PIC simulations until May 2025. Fabrication and integration are **now on track**; only testing and reporting remain **slightly delayed**.

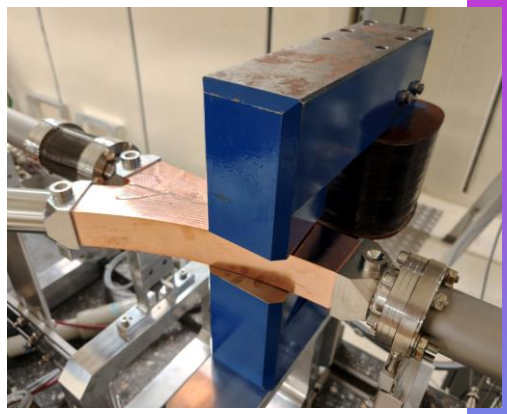
Sustainability: The CFA utilises cold field emitters, which reduce power consumption and extend device lifetime. Its modular, recyclable design lowers electronic waste and supports long-term, energy-efficient RF technology development.

*A **Field Emission Cathode** for a **Travelling-Wave RF gun** for High Brightness Beams in **Industrial** and **Small Research Facility** Settings (FE Cathode)*

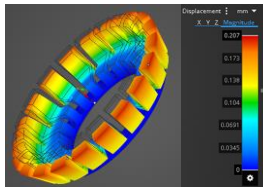
T. Lucas, Paolo Craievich, PSI (Switzerland) on behalf of Prof. Mike Seidel,
R. Jongen VDL ETG (Switzerland)

Main highlights

- **Conditioning with regular cathodes:**
  - achieved a gradient of 160 MV/m for 100 ns RF pulse at a breakdown rate of $6x10^{-6}$ bpp.
  - only paused due to a faulty vacuum pump.
  - we continue to push to investigate the upper limit of the cathode gradient.



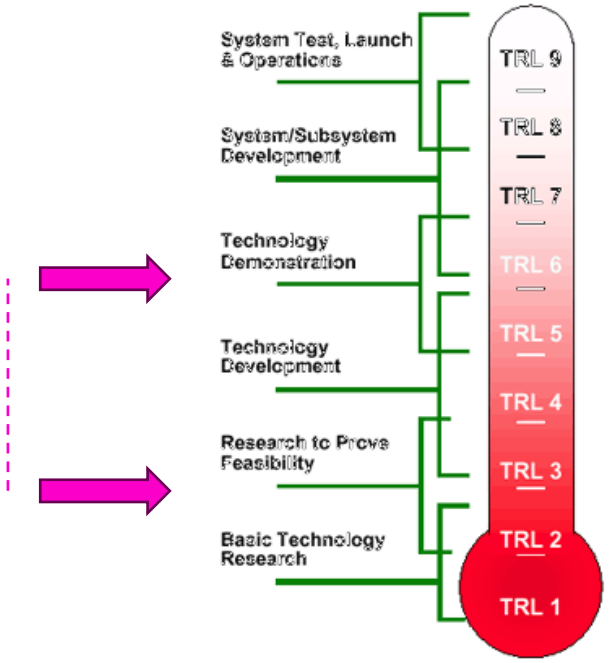
- **Realisation & Assembly of Components for Beamline:**
  - gun solenoid was realised thorough mixture of in-house design and industry.
  - Spectrometer was realised fully in-house using a magnet from SLS, a custom vacuum chamber and a SwissFEL screen.
  - Full diagnostic beamline has been built-up and is ready for operation.



Design, Realisation and Installation of new RF Fingers

Achieved Technology Readiness Level & Future

- Next Steps:
  - Condition to 200 MV/m with regular cathode and diagnose the dark current at this gradient.
  - Install Field Emission cathode and condition to achieve stable beam. Investigating possible limitations of the maximum curent achieveable.
  - Investigate phase ramping concepts for reduce energy spread from field emission cathode and measure on spectrometer.
  - Test new RF Finger geometries at high power.



Conclusions

- Innovation Internally Funded (IIF) projects in I.FAST were selected on the basis of specific requirements, like:
  - at least one I.FAST beneficiary and one industry
  - potential for industrialization, for commercialization and for attraction of additional resources

- The goal was to support activities that had a chance to introduce Innovation
  - Accelerator science and technologies
  - but also innovation of products and processes in industry with a concrete impact on the accelerator market

- **Impact to industrialisation:**
  - **Improved components:** In general the potential for applications is good but further investments are needed. more straightforward path where companies own a specific know-how
  - **Improved equipment:** since the developments aim at improving already existing commercial equipment, the path to industrialization and commercialization seems to be well defined, although not free from risks
  - **New components:** the fact that the TRL achieved by the project is still not so high make it less urgent to develop an industrialization plan

The IIF initiative was a first step in the right direction that has demonstrated to have a good potential to foster innovation development and uptake by industry

IIF projects R&D activities might vary significantly in terms of the type of activity, the type of industrial partnership, the commercialization approach, the IP situation, the motivation of the research groups, as well as the overall technological maturity and application readiness.

It would be important therefore to be able to characterize the R&D activities not only for the importance they have for Science but also for their likelihood of having a broader impact: it will be straightforward for some and impossible for others but up-front planning for success will be crucial

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Thank you for your attention

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