IFAST IIF PITCH

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

Lead Organization and IFAST member: FREIA laboratory at Uppsala University

Industrial partners: Scandinova AB and Exir Broadcasting AB

UPPSALA UNIVERSITET

Submitted by:
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Background and aims

- With climate change, scarcity of resources and the recent shortage of energy in general, sustainable and efficient technologies are ever more important for industrial applications, and also for research infrastructures.

- The basis of this project is to develop and demonstrate **a megawatt class cross-field amplifier (CFA) based RF system for particle accelerator applications.**

- The CFA is similar in operation to the magnetron and is capable of providing relatively large amounts of power with high efficiency i.e. up to 80%. In contrast to the magnetron, the CFA has and excellent phase stability. Therefore, it has a similar low manufacturing cost.

- The aim of this application is to 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.**

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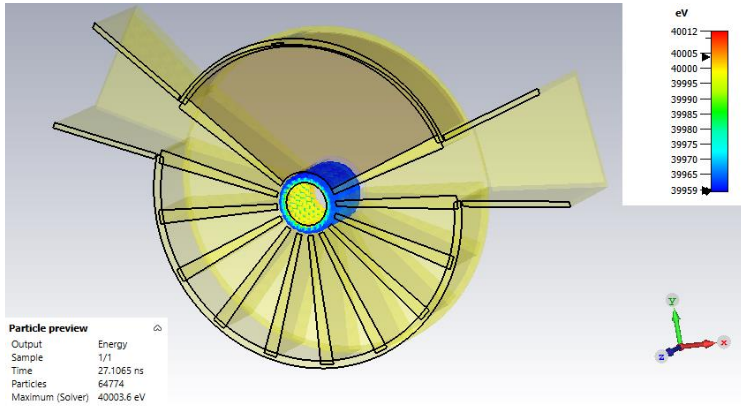
Improvement on efficiency, cost-effectiveness, compactness and lifetime of the proposed technology - quantitatively compared with existing alternatives

Parameter	Tetrode	Inductive output tube (IOT)	Klystron	SSPA	Magnetron	CFA **Proposed**
fficiency	70 %	70 %	55% * (70% in back off)	55-65 %	80-90 %	85%
ain in dB	13-16 dB	20-25 dB	45-55 dB	40-50 dB	NA	>30 dB
ower at requency	200kW at 450 MHz (pulsed)	250kW at 267 MHz 1.2 MW at 704 MHz (pulsed)	1.2 MW at 704 MHz (pulsed)		100kW at 915 MHz	1 MW (pulsed) at 750 MHz
ongevity	32000 hrs	50k hours	60k hours	50k-80k hours	8k Hours	>50k hours
ost	40 k$	313 k$	300 k$	200 x 200$	40 k$	40 k$
ost per watt	0.5 $/W	1 $/W 2-4 MB IOT	4 $/W	4 $/W	1-2 $/W	< 1 $/W
ompactness	0.5X0.3 m 10kg	1X1 m <50kg	1X10 200-300 kg		0.5X0.5 m; wt <10kg	0.5X0.5 m; wt <10kg
emark	Operation limited by frequency up to 400 MHz	operation limited by frequency up to 1.3GHz	Bulky costly and moderate efficiency MW class generation upto X band	Bulky costly and moderate efficiency	Economical but Poor Phase stability not suitable for accelerator application	Economical compact efficient excellent Phase stability suitable for accelerator application
tate of the art work	1.Thales has developed Diacrodes which are doubling the power but bulky 2. power increment research is going on	Multi beam IOT by L3 and CPI/Thales 1.2 MW 65% > 50,000 hrs	Four program for Efficiency enhancement program is going on		Phase locking research activities by CCR. Fermi LAb and CPI	

CFA Desired Goals

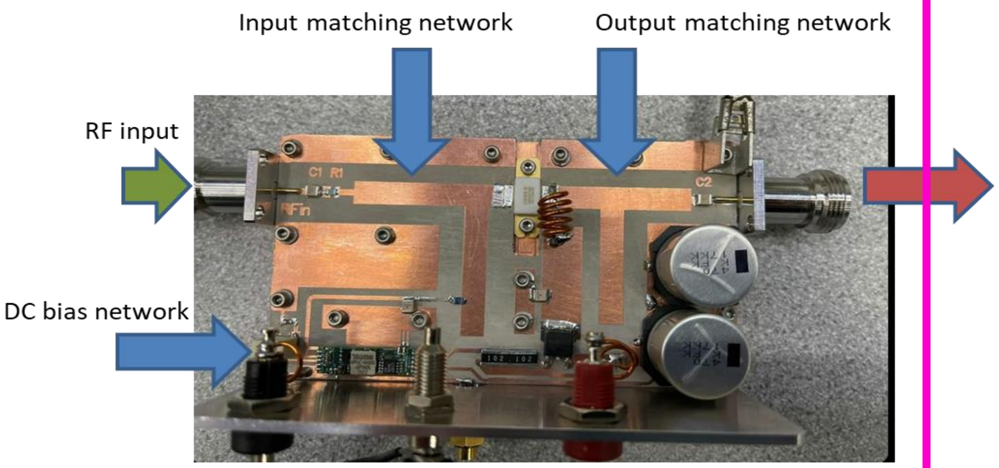
Peak RF power 1 MW at 750 MHz
Efficiency >80%, Gain ~30dB
Duty cycle 0.1 % and PRF 1 kHz

Preliminary results on CFA design:



Technical Summary

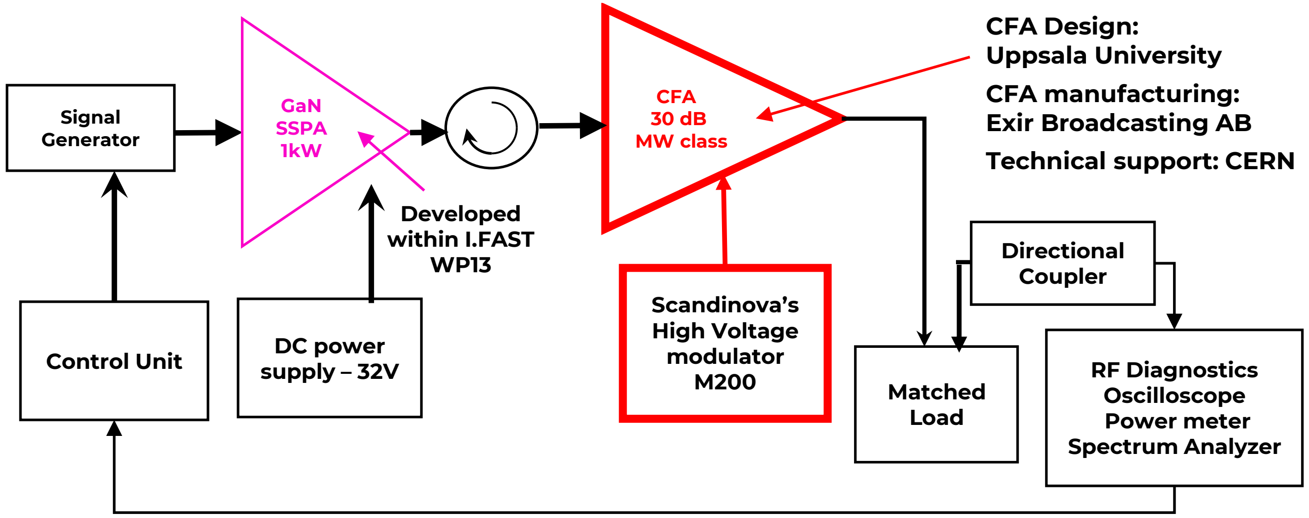
750 MHz GaN amplifier developed in I.FAST WP13



Measured output power of 205 W possible, with a signal gain of 17 dB and an efficiency of 84% in compression. This will be further combined till kilowatt level.

Pout = 53 dBm (60 dBm with combiner) / PAE = 84% @ 750 MHz

Block Diagram of new SSPA driven CFA – this project



- **The current status of the CFA technology is that most of the research was done before solid state power amplifier (SSPA) were available as driver.**

- **Actors such as Raytheon Inc, Litton Inc, CPI (Varian) Inc and L-3 Harris were using tube-like klystron, TWT or even CFA as drivers, which are really high cost solutions.**

- **Furthermore, a very few research is available in public domain.**

	Frequency / Lab	Author / Year	Output power / Gain / Efficiency	Application & Remarks
1.	3 GHz - S-band	Thomas Ruden	1.5 MW	For particle accelerator
			13 dB	Water cooling
	Raytheon Company	1965 [1]	>70 %	>10000 hours Life
2.	11.4 GHz X-band	**Eppley *et al.***	300 MW	In linear collider and particle accelerator, experimental Max power 30 MW is achieved as the arching occurred above 100kV. Also inaccurate prediction of cold frequency
			17 dB	
	SLAC	**1992** [2]	65 %	

Work Plan and risk analysis

<table>
<tr><th>Work package, period</th><th colspan="2">Responsibilities</th><th colspan="2">Team and Expertise</th></tr>
<tr><td rowspan="5">WP-1 , Month (Mo) 1-6</td><td colspan="2" rowspan="5">Design of SSPA driven CFA and its components</td><td colspan="2">Dr. D. Dancila, Lead applicant</td></tr>
<tr><td colspan="2">Dr. K. Pepitone, Field and Secondary emission Cathodes</td></tr>
<tr><td colspan="2">Dr. A. Mohadeskasaei, Researcher, SSPA</td></tr>
<tr><td colspan="2">Dr. Anshu Singh, Researcher, Vacuum Electron Devices</td></tr>
<tr><td colspan="2">Dr. X, New Post Doctor on megawatt class CFA - this project</td></tr>
<tr><td>Deliverables, Mo. 6</td><td colspan="4">Design reports, Particle in Cell codes</td></tr>
<tr><td rowspan="4">WP-2, Month 7-18</td><td colspan="2" rowspan="4">Development and manufacturing of the CFA
Material purchase
Collaborative development of passive RF components
Assembly of tube and processing
Acquisition of Power supply unit, vacuum pumps and gauges</td><td colspan="2">Dr. Dancila’s team at the FREIA Laboratory/workshop</td></tr>
<tr><td colspan="2">Exir Broadcasting AB for CFA manufacturing</td></tr>
<tr><td colspan="2">Scandinova System AB for M200 modulator unit loan</td></tr>
<tr><td colspan="2">Dr. Eric Montesinos, CERN</td></tr>
<tr><td>Deliverable, Mo. 18</td><td colspan="4">SSPA unit, CFA tube , Power supply unit , Test report of SSPA alone and SSPA-CFA</td></tr>
<tr><td>Risk</td><td colspan="4">Administrative delay in material purchase and equipment acquisition</td></tr>
<tr><td>Countermeasures</td><td colspan="4">Proactive measure and borrow resources from CERN</td></tr>
<tr><td>WP-3, Mo. 19-24</td><td colspan="2">Testing and device diagnostics</td><td colspan="2">Same team as in WP-1</td></tr>
<tr><td>Deliverable, Mo. 24</td><td colspan="4">Reports preparation and disseminating the results among the different target groups and research community.</td></tr>
<tr><td>Risks</td><td>Arcing & pulse shortening</td><td>Frequency shifts</td><td>Lower RF power</td><td>Oscillations</td></tr>
<tr><td>Countermeasures</td><td>Inspection and blending of field enhancing corner
Best vacuum practices</td><td>Voltage tuning
SWS changing</td><td>Reflection minimization
Current density enhancement</td><td>VSWR * gain < 1
VSWR reduction using Op and Ip Coupler</td></tr>
</table>

Application and impact

- The outcome of the technological development will fill the gap of the non-availability of the CFA research in the public domain and could serve future participation to EU grants.
- CFA have immediate impact on energy consumption and thus on the overall efficiency of the system they integrate. With identical RF output power, an increase of operational efficiency from 50% to 80% will reduce the energy consumption by 48%. Consequently, the DC supply and the cooling system could be become smaller.
- Other industrial sectors that could benefit of the project outcomes, as follows:

Applications	Industrial sector	Basis for Validation
Airborne and Spaceborne RADAR transmitter	Aerospace , Metrological R&D	High efficiency, High power/kg or Vol The GaN SSPA driven CFA have potential to become new product range as Microwave power modules.
Communication Wireless backbone link in 5G and Space	Telecom and Space	
Industrial Heating	Related to Material processing	Uniform and precision heating can be given with broadband CFA. Example: CFA QKS1262 (Raytheon Inc)
Wireless Power Transfer	Energy and Space	Raytheon Inc. demonstrated wireless power transfer in 60s

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The market in the following sectors is expected to reach in the following 5 years: microwave devices 11 B$, Industrial microwave heating 1.8 B$, Wireless power transfer 15 B$, 5G technologies 60B$, etc.

Business and Industrialization Plan

- The industrial nature of the proposal lays a strong foundation for an effective commercial exploitation of the results. There are **two industrial partners, i.e. Scandinova AB and Exir Broadcasting AB** with strong commercial interests into the particle accelerator business. Both offer a unique expertise to the project and will contribute with knowhow and equipment, for instance:
  - Scandinova will lend the M200 for the demonstration part
  - Exir will contribute with waveguides and advanced manufacturing capabilities for high power microwave sources.
- The good completion of the project will bring them an edge into future commercial competitions, representing a great competitive advantage.
- **FREIA** is leading research into particle accelerators and a well established academic institution with expertise ranging from semiconductors to machine learning and accelerator development.
- **CERN** is also contributing with expertise in vacuum tube development.

The consortium possesses not only the **background expertise** but also the **critical infrastructure** to carry out this very ambitious and rewarding project.

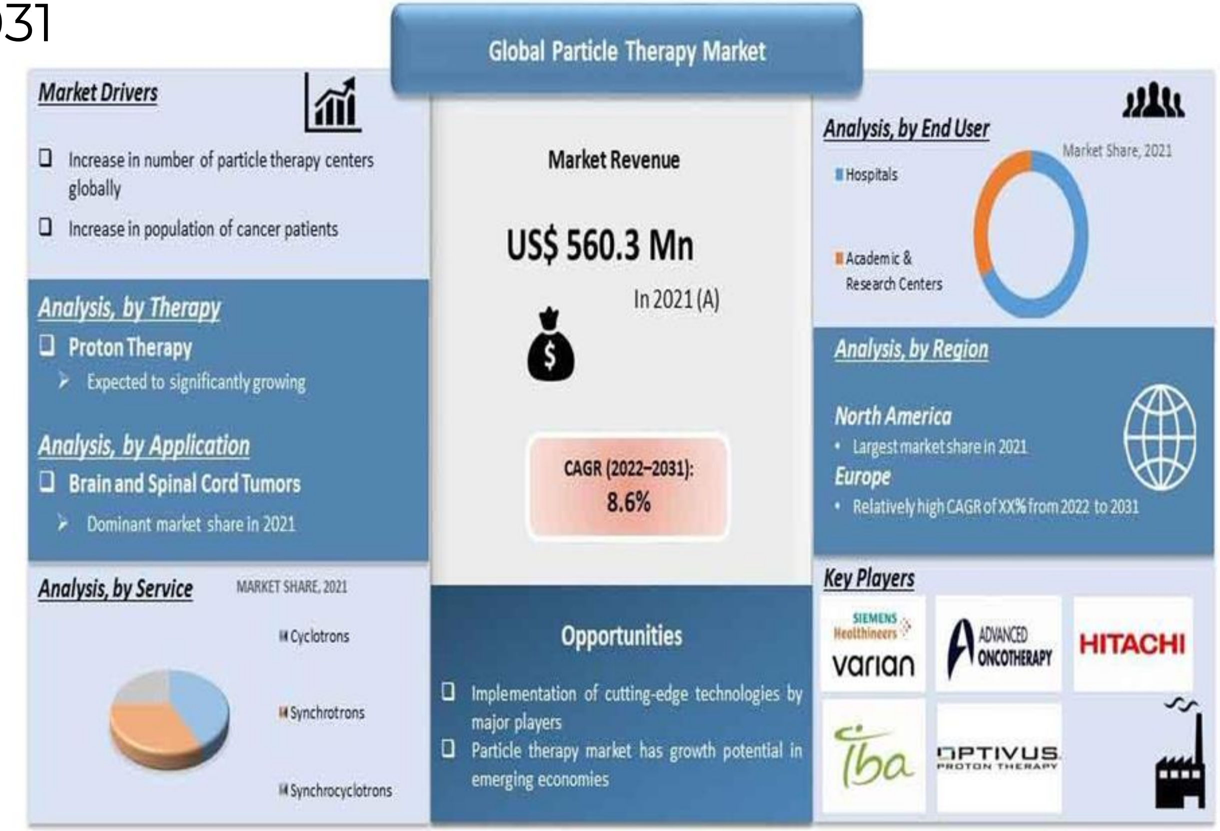
Business and Industrialization Plan

- **An exploitation roadmap**
  - The results from the project that can be used and exploited will be identified:
    - High gain and long life slow wave structure with high efficiency and phase stability
    - Compact and reliable CFA architecture at megawatt level
  - Potential markets and customers will be identified:
    - Including accelerator for scientific research and <u>radiological treatment for cancer patient, i.e. particle therapy</u>, RADAR transmitters and industrial heating.
  - Exploitation and business roadmaps will be investigated
    - The intention is of reducing the acquisition and operating cost
    - The estimated cost with life cycle assessment will be made
    - RF generation Cost/Watt followed by space requirement estimations
  - A roadmap beyond the duration of the project will be developed
    - With the experience of the CFA development, multiple solutions for accelerator applications as for industrial microwave processing

- **Intellectual Property rights**
  - Identify and update background knowledge
  - Continuous identification of foreground knowledge
  - Assessment of potential for patent filing
  - Patent filing

Particle Therapy Market

- Particle Therapy Market Outlook 2031
- The global particle therapy market was valued at US$ 560.3 Mn in 2021
- The global market is projected to expand at a CAGR of 8.6% from 2022 to 2031
- The global particle therapy market is anticipated to exceed the value of US$ 1.2 Bn by 2031



ENEFRF Eurostars project
Collaboration UU and GE Healthcare on new RF power sources for radioisotopes production. Cyclotron worldwide production in Uppsala. CERN's 750 MHz RFQ considered as a viable alternative.

GE Healthcare

eurostars™

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Resources and budget

Funded by I.FAST: 200 k€

- **Research personnel salaries: 140 k€**
  To undertake the scientific and technical development of the idea a Postdoctoral researcher will be hired at 80% occupancy during two years. The salary cost is evaluated at 130 k€ and 10 k€ are reserved for travel costs .
- **Equipment: 50k€**
  - Oxide-coated cathode CPI Y-646 - 6 k€
  - Vacuum pump - 12 k€
  - CFA manufacturing including material - 15 k€
  - Waveguides - 2 k€
  - Diagnostic instruments - 5k€
  - RF window 1.5 k€
  - Magnets and pole pieces - 1.5 k€
  - Operational costs using existing infrastructure, e.g. furnace - 7 k€
- **Intellectual property (IP): 10 k€**
  - patentability search

In addition, two Researchers at FREIA, funded by **two Marie Skłodowska-Curie Individual Fellowship Actions** will participate to this project:

- **Dr. Alireza Mohadeskasaei**, with an Individual fellowship Grant 2021 entitled: “Green SSPA”
- **Dr. Anshu Singh** with a an Individual fellowship Grant 2022 entitled: “Micro-magnetron”

Project Deliverables and Milestones

Deliverable (D)/ Milestone(M)	**Month**
D1 - Design reports, Particle in Cell codes	Sixth (6^{th})
a) Design of Slow wave structures, RF propagation study and its interactions to e-beam using PIC codes b) b) Magnetostatic design and simulation, development of pulse power diagnostic system	
M1 - CFA design ready for manufacturing	
D2 - Development of SSPA and CFA amplifier including RF subsystems	Eighteenth (18^{th})
a) Feasibility study using cold test and beam wave interaction testing of non-process tube with cold cathodes b) Implementation of design correction and countermeasure, if any mismatch c) Assembling of tube, processing and Device prototype testing d) Matched rf amplifier prototype incl. versatile control	
M2 - SSPA unit with CFA and Power supply unit ready	
D3 –Testing Reports and demonstration of operational usage and demonstration of phase coherence and high power	Twenty fourth (24^{th})
a) Development of SSPA driven CFA based RF system b) Testing of RF system and implementation of diagnostic strategies	
M3 - System commissioning and Innovation Pilot demonstrated	**Desired Goals** **Peak RF power 1 MW** **Efficiency >80%, Gain ~30dB** **Duty cycle 0.1 % and PRF 1 kHz**

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Parameters that will be measured in the final tests, values expected to be achieved and industrialisation

Parameter	Testing	Expected value	Risk	Remedy
RF output power and efficiency	RF power fundamental and harmonics pulse shape and droop measurement	> 1 MW ~85 %	1.Low RF power 2.Oscillations in RF pulse	RF input low Voltage and magnetic field desync
Frequency	Frequency measurement Fundametal and Harmonics	750 MHz	1.frequency shift in beam present condition 2.Harmonics generation	Voltage magnetic field adjustment Coupled cavity based SWS will be implemented
Gain	Investigation of gain compression and expansion	>30 dB	Drive power and gain should support the excitation of secondary emission and interaction	nonuniform input pulse operation in backoff region
Longevity	Characterization Anode vanes and Cathode surface		Erosion of Anode vane tip Wearout/erosion secondary emitter surface Erode tip can lead breakdown	Molybdneum Tungsten mix copper implementation reduction of pulse width
Phase sensitivity	Phase measurement against the varying voltage, and current	Phase variation <5° for 1% V_b 1° for the 1% I_b	Phase nonlinearity beyond limit	VSWR adjustment using tuner Drive Power increment

<u>CFA Desired Goals</u>

Peak RF power 1 MW at 750 MHz
Efficiency >80%, Gain ~30dB
Duty cycle 0.1 % and PRF 1 kHz

<u>Industrialization</u>

The cold cathode would be commercially available.

The slow wave structure remains to be developed within the project and will be industrialized by the project partner Exir broadcasting AB. Exir has its core expertise in such developments.

The high voltage modulator is provided by Scandinova AB, the second industrial partner of the project.

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