Funded by the
European Union

Compact

X-band linac and optimized accelerating structures of the CompactLight project

14th workshop on breakdown science and high gradient technology (HG2022)

16-19 May 2022

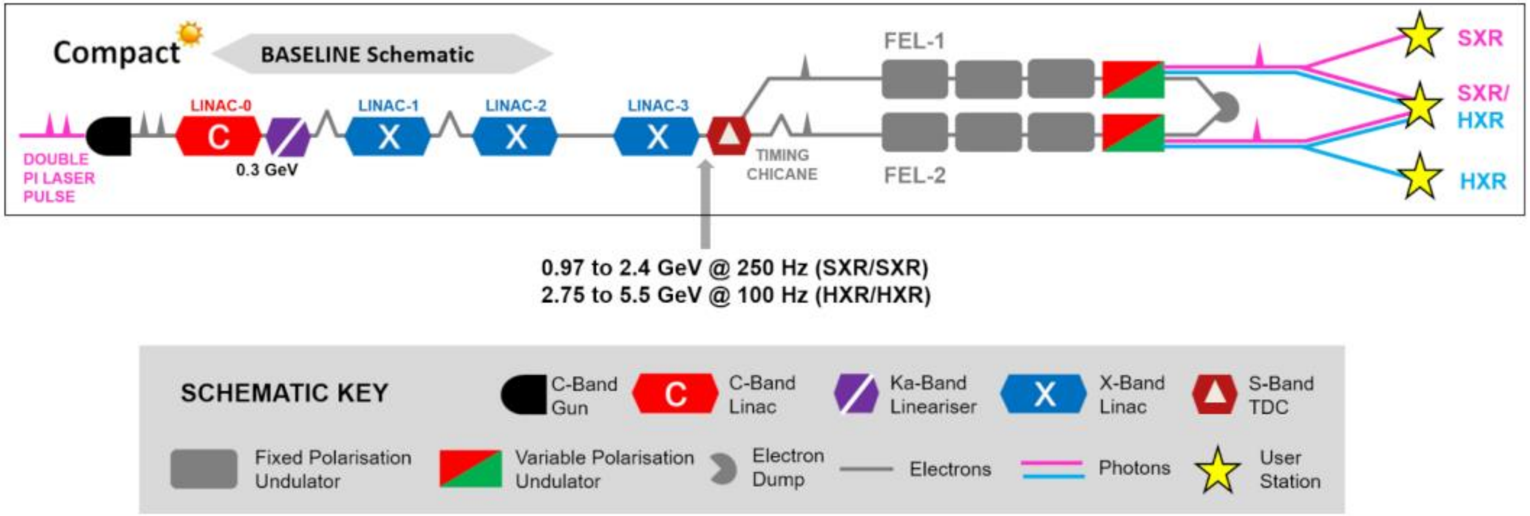
M. Diomede (DESY)

On behalf of the INFN-LNF RF and LINAC teams and of the CompactLight partnership

Funded by the
European Union

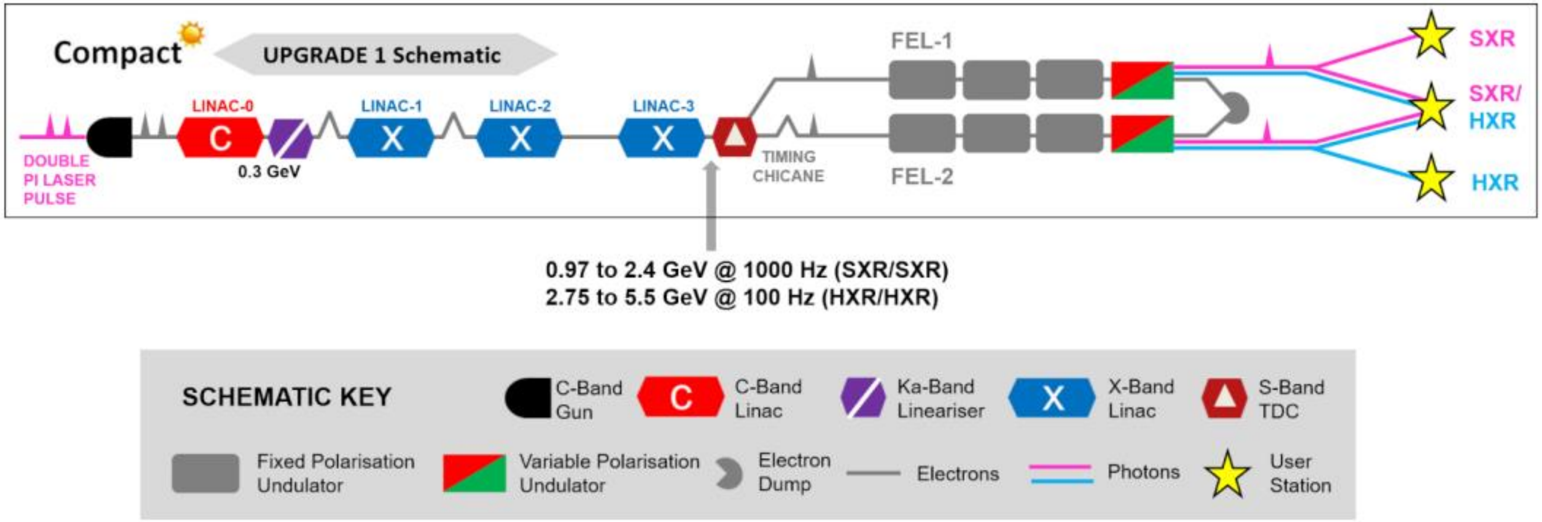
The CompactLight project

- The **flexibility in operation (100 – 1000 Hz rep. rate)** is a major innovation of CompactLight and allows a wide range of experiments to be carried out.
- 3 different machine layouts are foreseen:
  - **Baseline** (the module consists of a single RF source that can run in **dual mode**: high-energy at repetition rates of 100 Hz and low-energy at 250 Hz.)



The CompactLight project

- The **flexibility in operation (100 – 1000 Hz rep. rate)** is a major innovation of CompactLight and allows a wide range of experiments to be carried out.
- 3 different machine layouts are foreseen:
    - **Baseline** (the module consists of a single RF source that can run in **dual mode**: high-energy at repetition rates of 100 Hz and low-energy at 250 Hz.)
    - **Upgrade I** (**dual source**: a second klystron, with 10MW output power and a 1 kHz repetition rate, is added and connected to the waveguide system via a high-power switch)



The CompactLight project

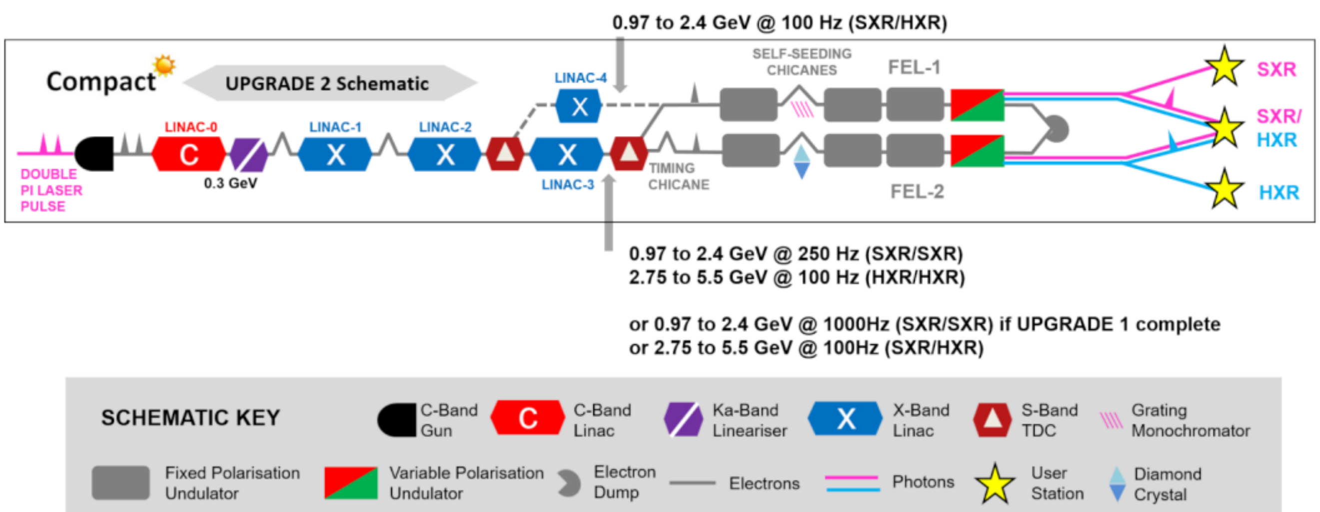
- The **flexibility in operation (100 – 1000 Hz rep. rate)** is a major innovation of CompactLight and allows a wide range of experiments to be carried out.

- 3 different machine layouts are actually foreseen:

  - **Baseline** (the module consists of a single RF source that can run in **dual mode**: high-energy at repetition rates of 100 Hz and low-energy at 250 Hz.)

  - **Upgrade I** (**dual source**: a second klystron, with 10MW output power and a 1 kHz repetition rate, is added and connected to the waveguide system via a high-power)

  - **Upgrade II** (**dual linac**: a 100 Hz kicker is introduced to separate LINAC1-2-4 equipped with a 10MW/1kHz klystron and LINAC3 equipped with the 50MW/100Hz klystron)



More on this at G. D'Auria's talk on Wed.

Funded by the
European Union

The CompactLight project - Acceleration schemes

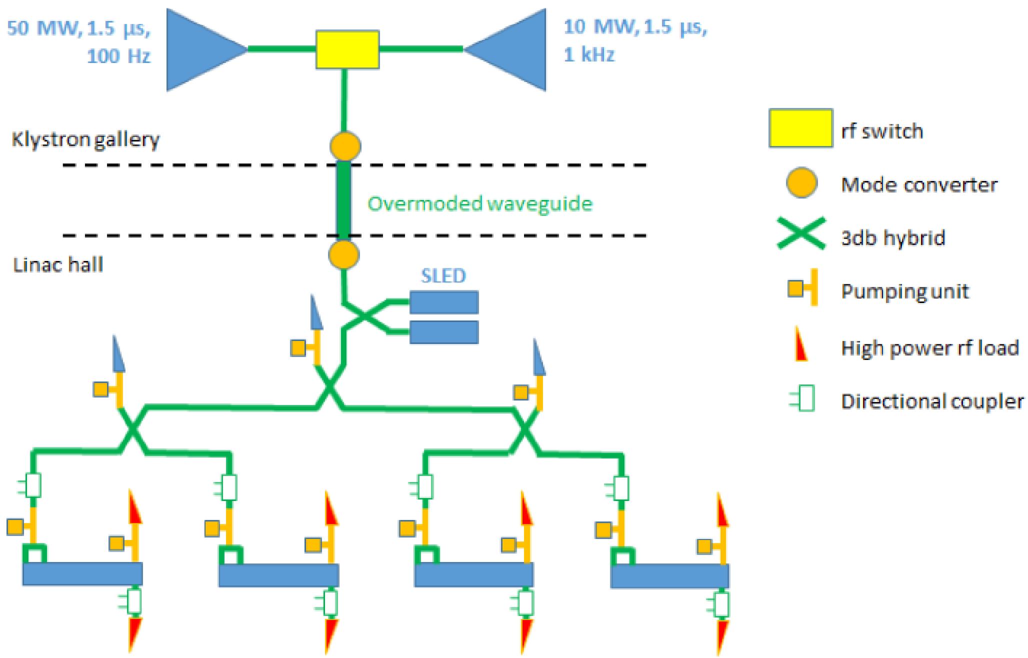
- The **CompactLight linac** is composed of **24 X-band RF** modules which provide a beam energy of up to **5.5GeV** at a repetition rate of **100 Hz** and an energy of **2.4GeV** at a repetition rate of **1 kHz**. Each module is made up of 4 TW structures and a SLED pulse compressor.

- The **linac** begins at the output of the injector and first bunch compressor. At this point the beam is fully relativistic, with an energy of **300MeV**.

RF module parameters

Repetition rate [Hz]	**100**	**250**	**1000**
Average acceleration gradient [MV/m]	65	30	30
RF pulse length [μs]	1.5	0.15	1.5
Available klystron output power [MW]	50	50	10
Net klystron power [MW]	44	44	9
SLED	ON	OFF	ON
Energy gain per module [MeV]	234	108	108

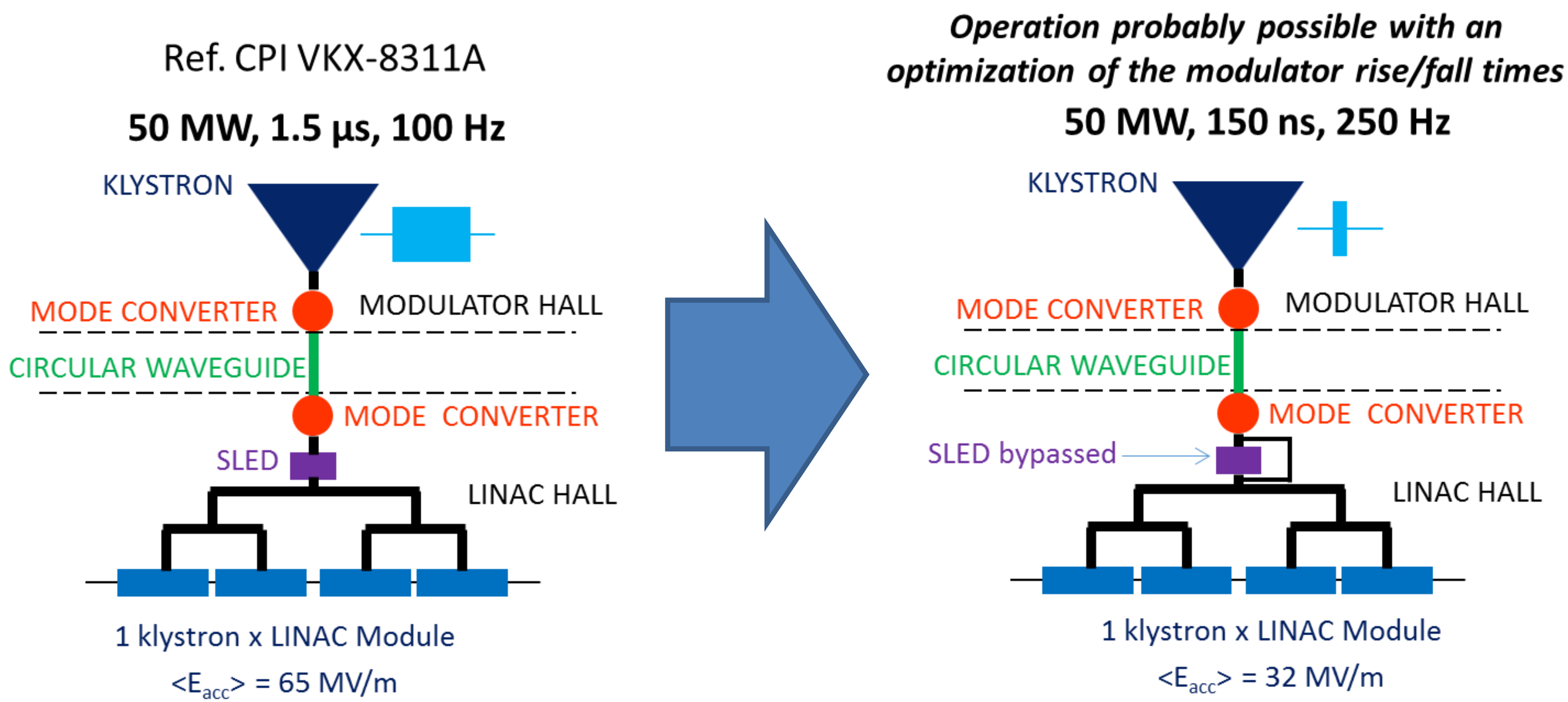
DUAL SOURCE RF module



Funded by the
European Union

RF power sources

- The main RF source adopted for the RF module is the **CPI VKX-8311A klystron**. It is a pulsed klystron operating at **11.994 GHz**, **50MW** peak power, **5kW** average power.
- This RF power source can run up to **250 Hz** by shortening the pulse length to **150 ns**. In that case, the pulse compressor would be bypassed. The max rep. rate strongly depends on the **modulator rise/fall times**. The accelerating gradient and linac energy are reduced by a factor ~2 @ 250 Hz rep. rate.



RF power sources

- For the high repetition rate, the actually available option is represented by the **Canon E37113**. It provides an **output power of 6MW, 5us pulse length and a rep. rate of 400 Hz**. 2 klystrons of this type per module would be needed in order to guarantee the 30 MV/m gradient at 1 kHz.

- Direct consequences of the activities of the CompactLight collaboration are the **R&D activities necessary for the 1 kHz repetition rate 10MW klystron** which are now underway at the companies.

X-band klystrons in development

Parameter	CPI 6MW	CPI 10MW	Canon 8MW	Canon 20MW	Units
Frequency	11994	11994	11994	11424	MHz
Peak out. pwr	6	10	8 (10 max)	20	MW
RF pulse width	5 (max)	5 (max)	5 (max)	1.5 (max)	μs
Pulse rep. rate	1000 (max)	400 (max)	400 (max)	400 (max)	Hz
Beam voltage	155 (165 max)	185 (195 max)	155 (175 max)	265 (290 max)	kV
Beam current	98 (107 max)	127 (138 max)	94 (115 max)	170 (195 max)	A
Drive power	46 (200 max)	40 (200 max)	120 (400 max)	120 (400 max)	W
Efficiency	43	43	56	44	%

Accelerating structure – Main parameters

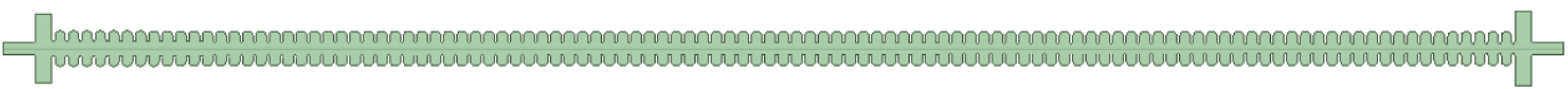
The accelerating structures are **90 cm long** (109 cells) with an **average iris radius** of **3.5 mm**. The iris radius is **optimized with beam dynamics simulations** to give acceptable levels of **emittance growth due to short-range wakefields**.

In order to minimize the contribution of the long-range transverse wakefields that can adversely affect two-bunch operation, the accelerating structures have a **modulation of the iris geometry** along the propagation axis that involves both **the iris thickness and the iris radius**.

The **iris radius** goes from **4.278 to 2.722mm** while the **iris thickness** from **2.0 to 2.24 mm**. The **wakefield** of the accelerating structure was calculated with **GdfidL** by **X. Wu**.

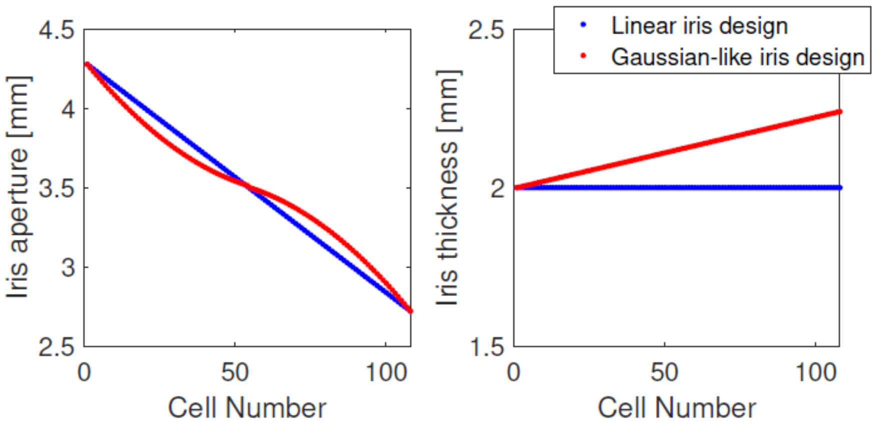
Frequency [GHz]	11.994
Phase advance per cell [rad]	$2\pi/3$
Waveguide power attenuation [%]	$\approx$10
Average iris radius **<a>** [mm]	3.5
Iris radius **a** [mm]	4.3 - 2.7
Iris thickness **t** [mm]	2.0 - 2.24
Number of cells per structure	109
Accelerating cell length [mm]	8.332
Structure length $\mathbf{L}_s$ [m]	0.9
Unloaded SLED Q-factor Q_0	180000
External SLED Q-factor Q_E	23200
Shunt impedance **R** [MΩ/m]	85 - 111
Effective shunt impedance $\mathbf{R}_s$ [MΩ/m]	349
Group velocity v_g/c [%]	4.7 - 0.9
Filling time [ns]	146

Max. Mod. Poy. Vec. [W/um^2]	3.4
Max. Mod. Poy. Vec. - 10^{-6} bpp/m limit [%]	-30

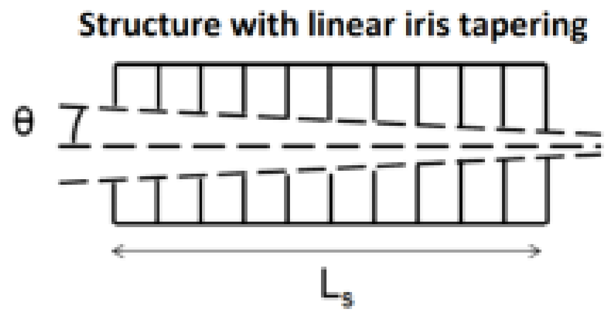


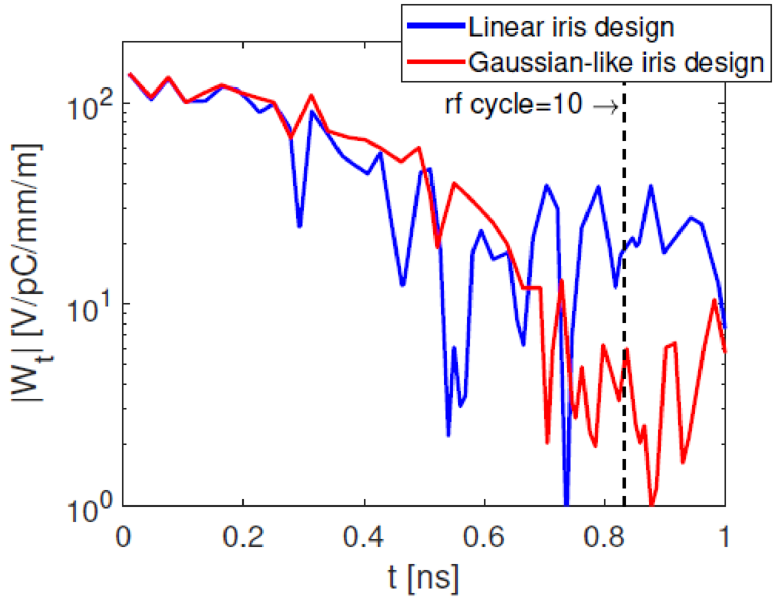
Accelerating structure – Wakefield optimization

- Optimization of the long-range transverse wakefield



Baseline design's aperture:
from 4.278 mm to 2.722 mm

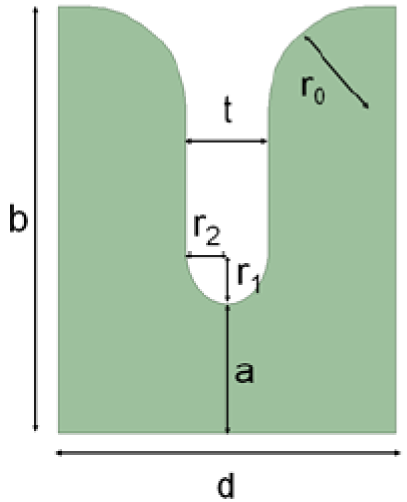


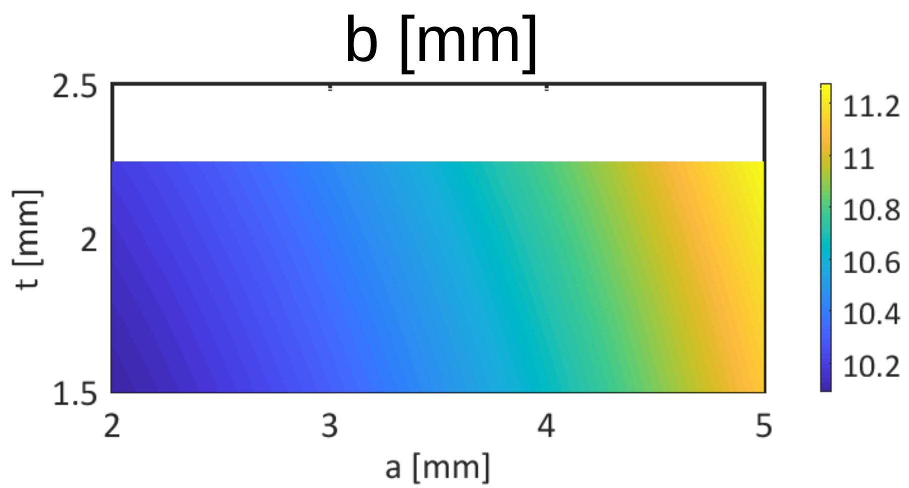


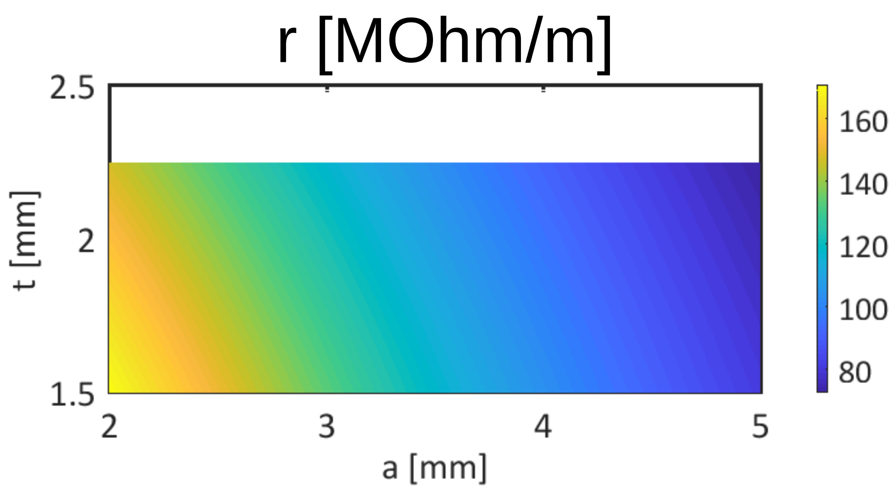
X. Wu

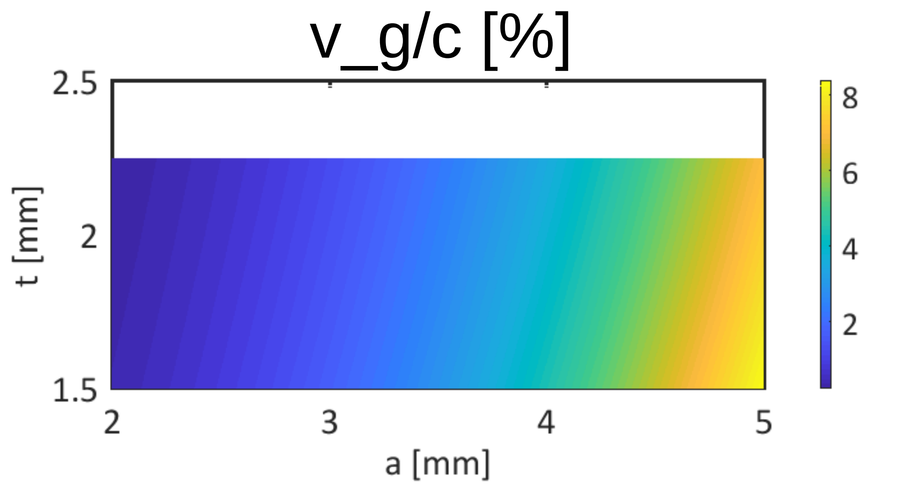
CELL PARAMETERS

- As a function of iris radius a and iris thickness t



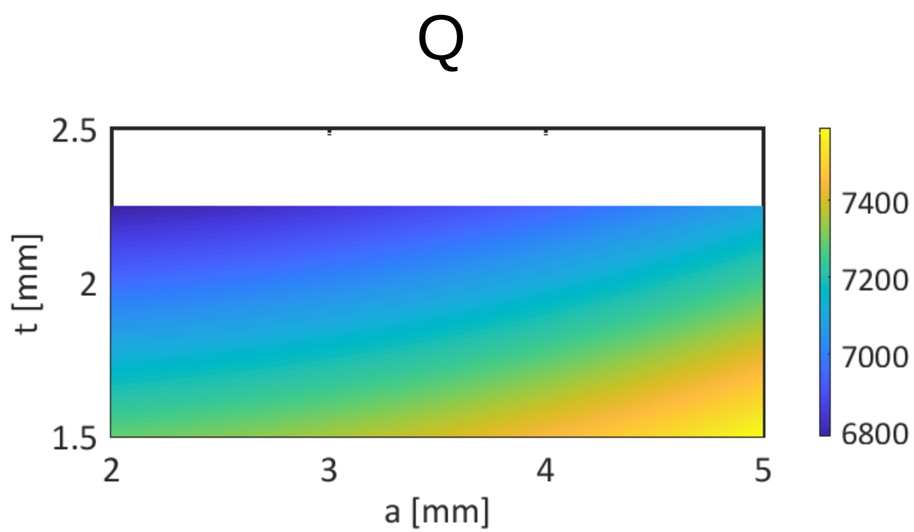


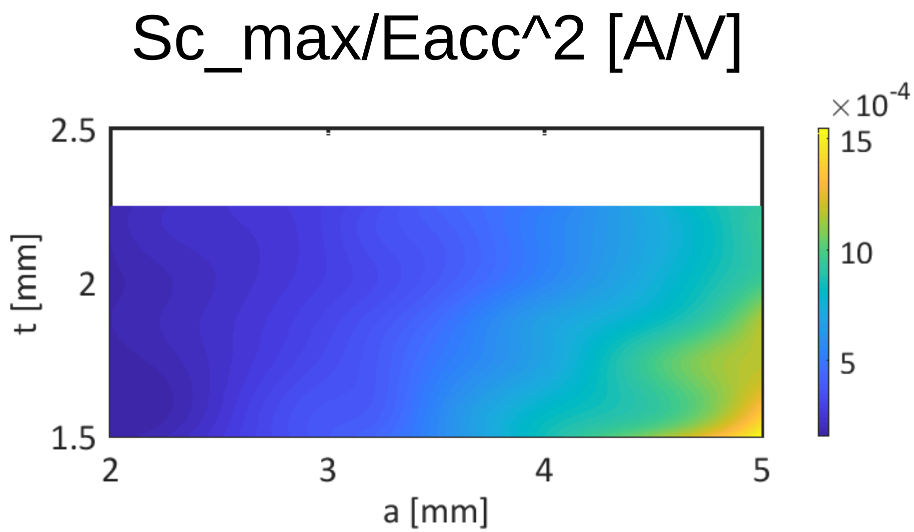




CELL PARAMETERS

- As a function of iris radius a and iris thickness t





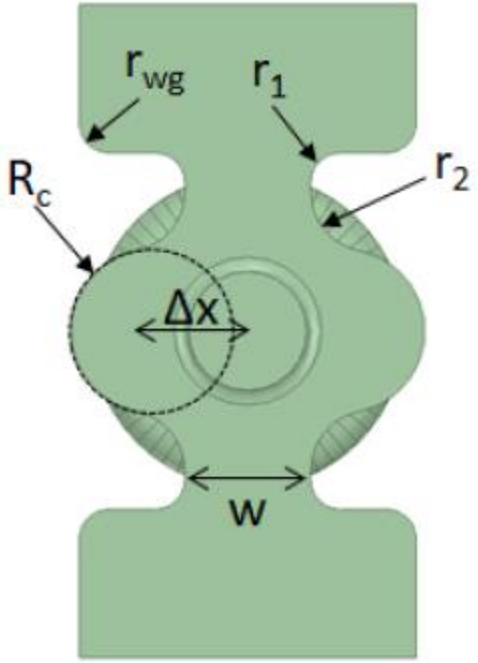
- This data has been imported into a **MATLAB tool** that can calculate the **main structure parameters** as a function of the **structure length and iris modulation** (A. Grudiev, V. Dolgashev, G. D'Auria, D. Alesini, A. Gallo, B. Spataro)

M. Diomede et al, Preliminary RF design of an X-band linac for the EuPRAXIA@SPARC_LAB project, NIM A 909 (2018) 243–246
M. Diomede et al., RF DESIGN OF THE X-BAND LINAC FOR THE EUPRAXIA@SPARC_LAB PROJECT, JACoW-IPAC2018-THPMK058 (2018)
M. Diomede, High-gradient structures and RF systems for high-brightness electron linacs, PhD thesis (2020)

Input and output RF power couplers

- **Magnetically-coupled z-type input and output power couplers** were selected because of **compactness**. In order to **minimize the quadrupolar field component of the magnetic field**, a so-called **racetrack geometry** has been implemented in the design.

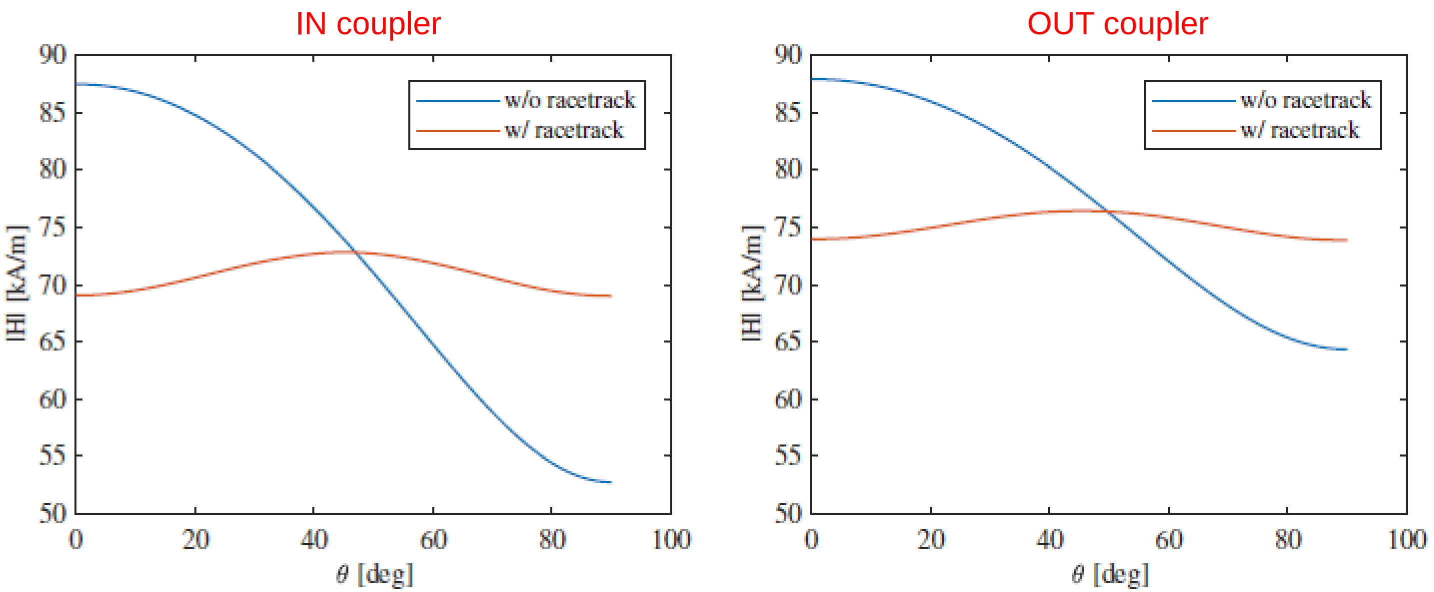
- The **calculated reflection coefficient** at the input port is **-45 dB for the input coupler** and **-37 dB for the output one**. For the **input coupler**, there is a pulsed heating of **24 C deg**. This value can be considered absolutely **safe for high-field operation**.



Parameter	Units	Input coupler	Output coupler
Waveguide rounding r_{wg}	mm	2	
Waveguide-slot rounding r_1	mm	2	
Slot-matching cell rounding r_2	mm	4	
Matching cell radius R_c	mm	5.063	6.308
Off-axis circle center Δx	mm	8.359	4.765
Slot width w	mm	9.017	7.819

Input and output RF power couplers

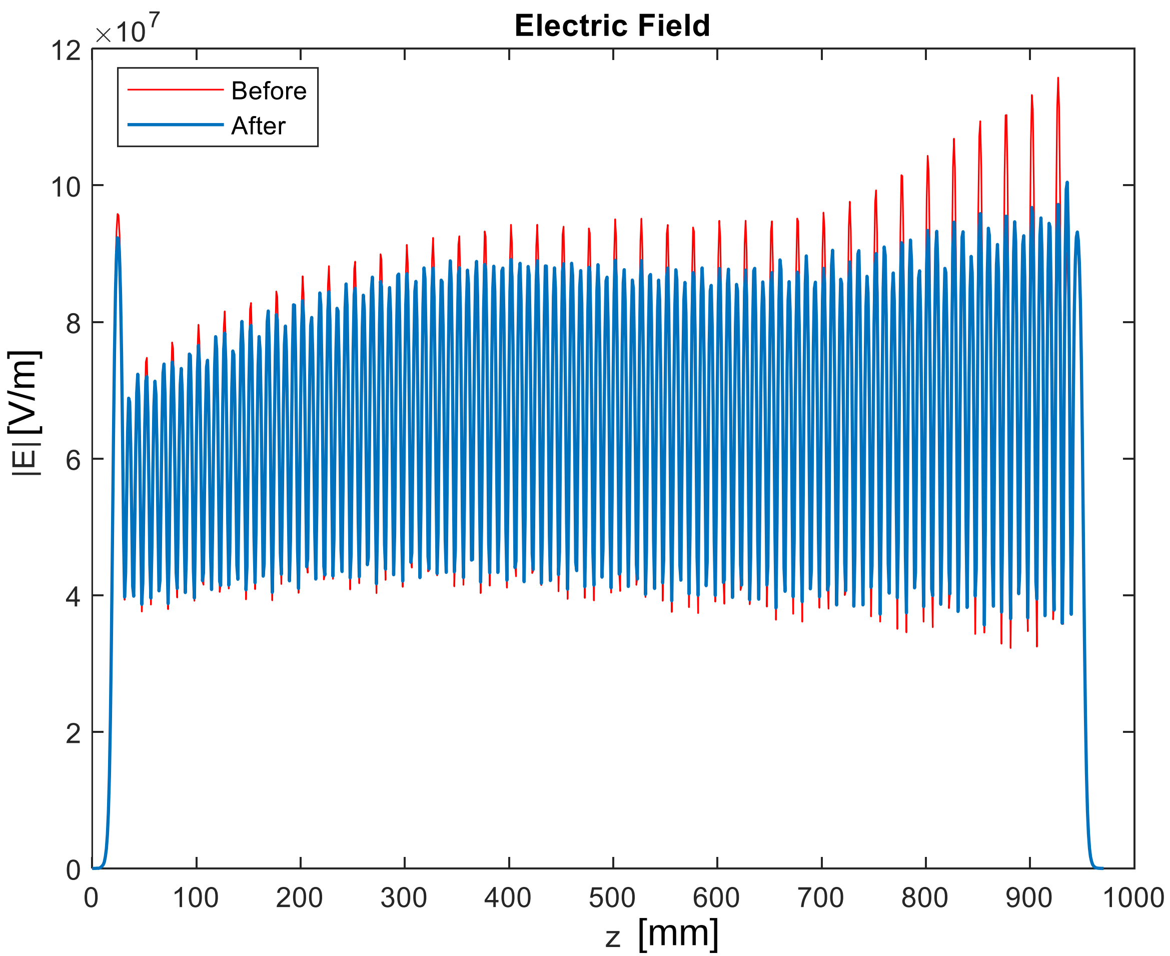
- The **racetrack geometry** allows the **quadrupolar component of the magnetic field** to be minimized. For the **input coupler**, the **integrated equivalent quadrupole gradient** has been minimized to **4mT**, while without racetrack it is **30mT**.
- Results are referenced to an **arc of 2mm radius** placed at the longitudinal center of the coupler.



Funded by the
European Union

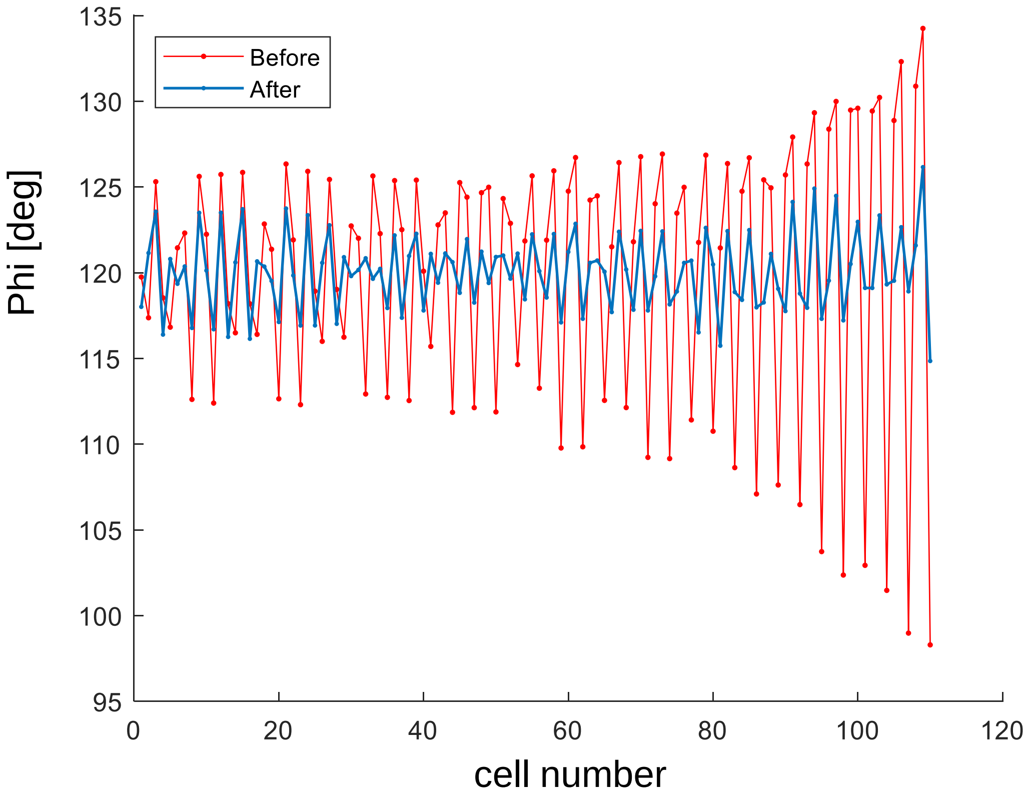
Compact

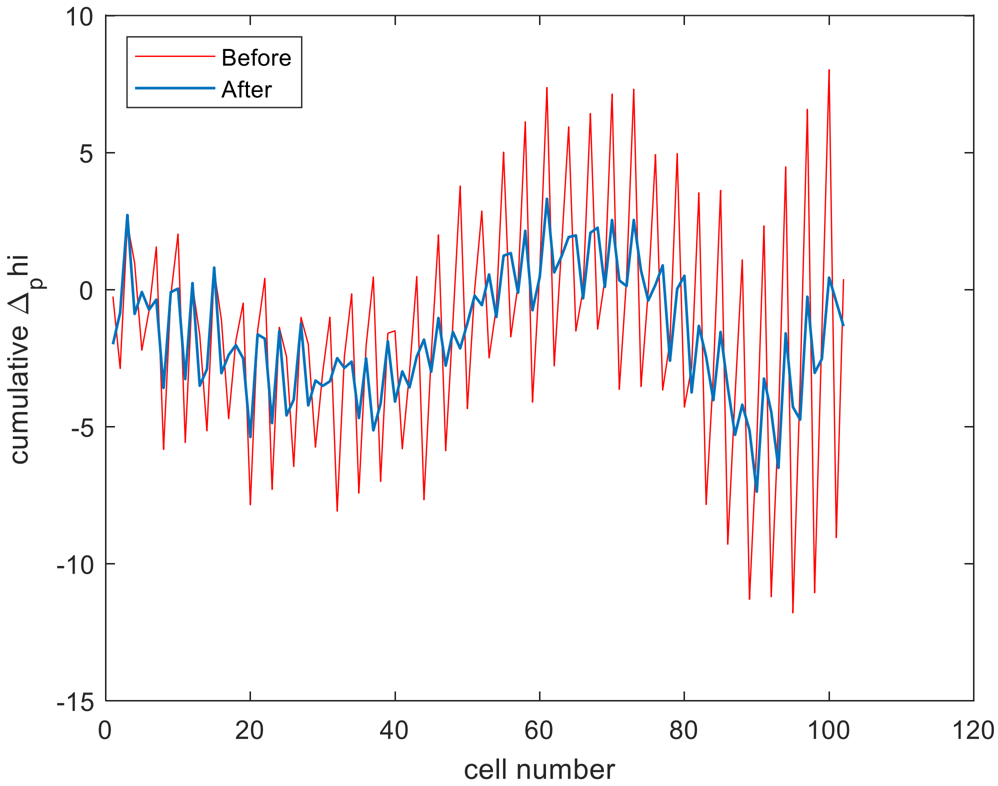
(Partially) tuned structure



- Tuned the output coupler together with the last 3 cells

(Partially) tuned structure





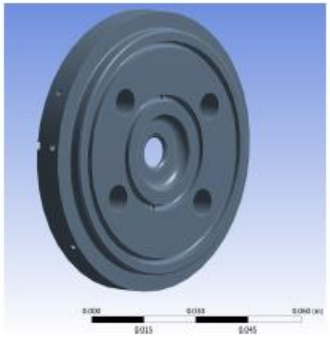
- More needs to be done for the **I.FAST prototype** (Task 7.5 - CompactLight Prototype Accelerating Structure)

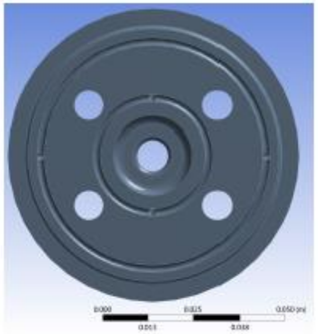
Funded by the
European Union

Compact

Mechanical and Thermal design

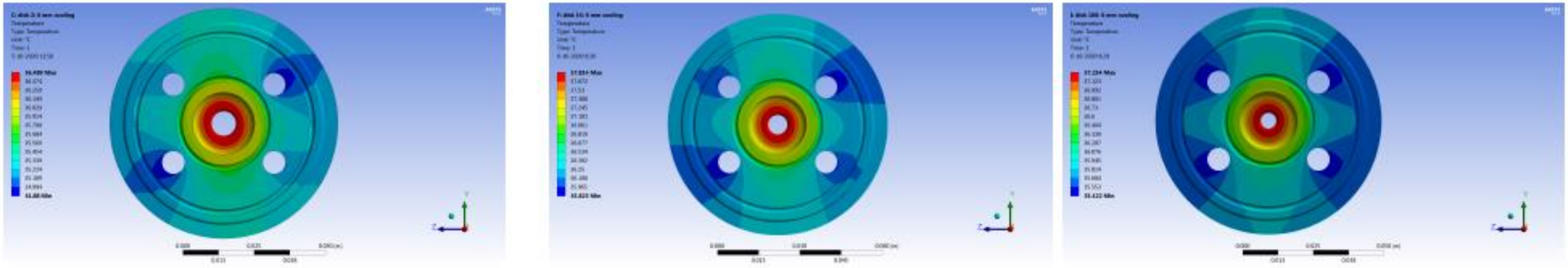
- **VDL** performed a **mechanical and thermal design/simulation** of the structure
- For the baseline cooling design, a geometric design of a cell with **four cooling channels** is taken. Due to **space constraints** given by the RF power couplers, **the cooling channels are not evenly distributed**.
- Main parameters:
  - **Cooling channel diameter: 6mm**
  - Symmetric routing in the structure
  - **Water flow: 3 l/min**
  - Convective heat transfer coefficient to ambient: 5 W/(m^2K)
  - Water temperature difference max. 2 deg C
  - Water cooling heat transfer coefficient: 5 kW/(m^2K)
  - **Water inlet temperature: 30 deg C**
  - Water outlet temperature: 32 deg C
  - Room temperature: 22 deg C
  - Water pressure: $6*10^5$ Pa



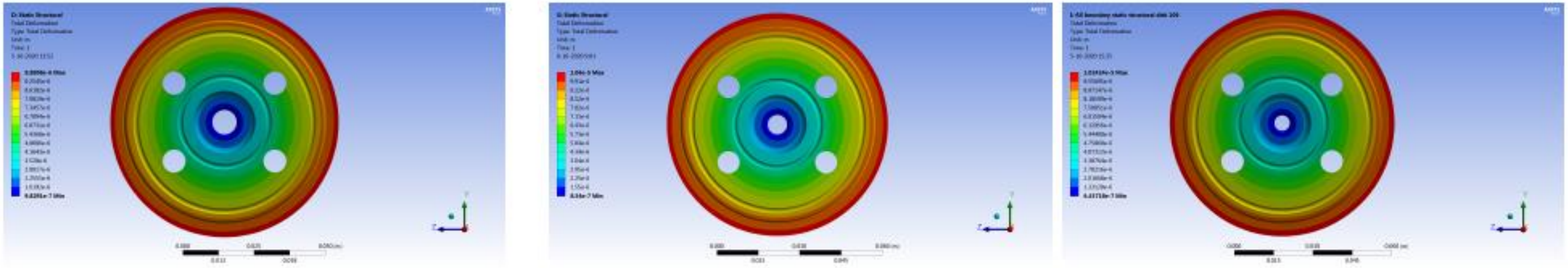


Mechanical and Thermal design

- With these inputs and the worst case heat load provided by the RF calculations (**1000 Hz** repetition rate leading to **2.2kW dissipated power in the structure**), the **temperature profile** and respective **deformation of three disks** are calculated:



Temperature profile of the disks (2, 54 and 106)



Total deformation of the disks (2, 54, 106)

Mechanical and Thermal design

- At **100 Hz**, the heat load of **1000W** (instead of 2.2 kW) with the same distribution profile was used, and **the water temperature was raised to compensate for the lower heat load**. The water temperature of **34.5 deg C** leads to the same temperature at the iris for the last disks in the structure.
- At the **beginning** of the structure the temperature is **0.4 deg C higher**, while in the **middle** of the structure the temperature at the iris is **0.4 deg C lower**.
- **Preliminary design**, further disk design optimization can be done.
- More can be found in the recently published **CompactLight CDR**

Conclusions

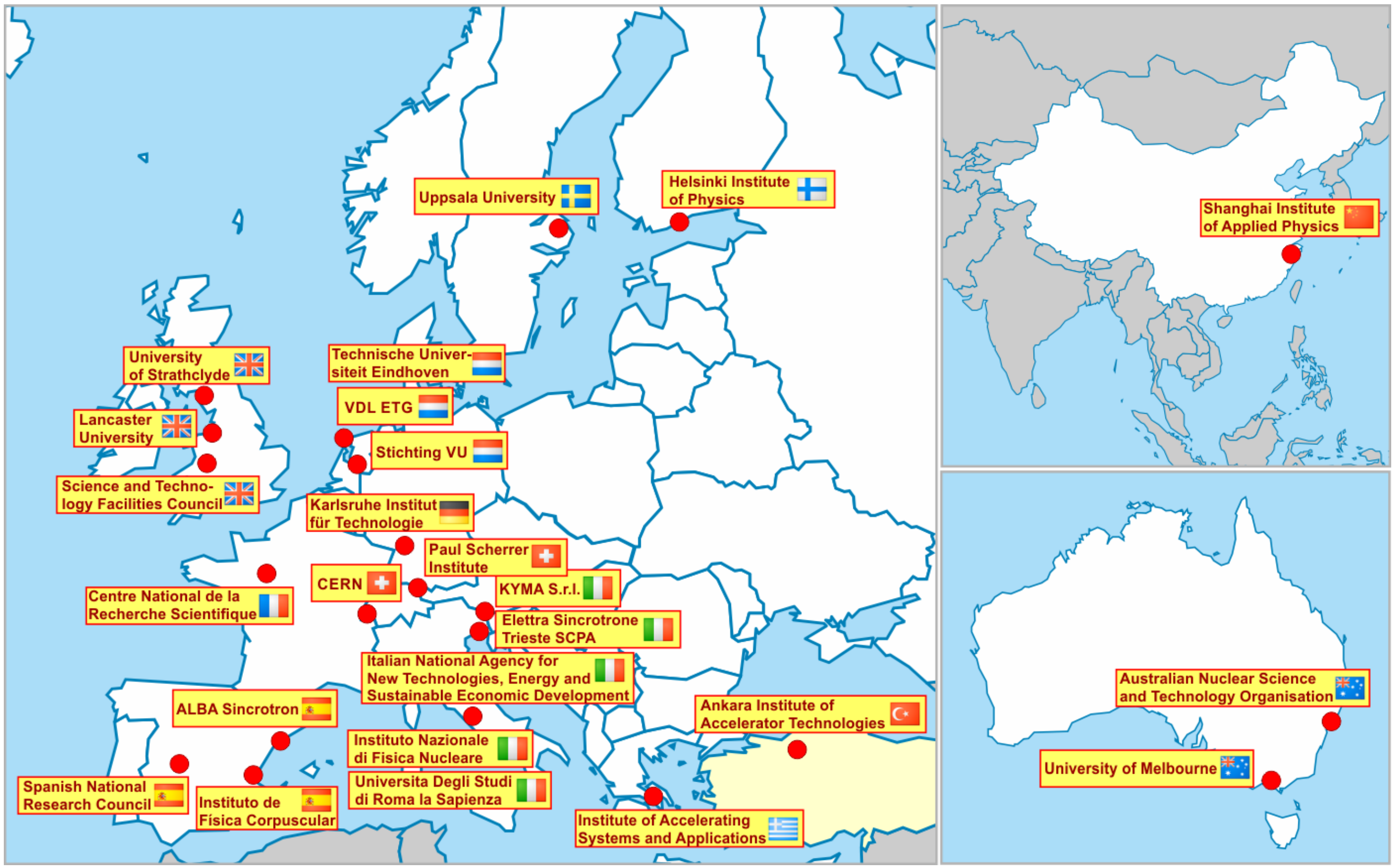
- A **preliminary design of the CompactLight X-band linac and the TW acc. structures** has been performed
- The linac has been designed for **3 different operating modes/schemes (100, 250, 1000 Hz)**
- **R&D activities in collaboration with klystron manufacturers** are ongoing to achieve high output power/rep. rate
- The structure design aims to **minimize transverse wakefields and breakdown rate**
- **EM simulations** of the whole structure + 1st tuning has been performed
- **VDL** has performed **thermomechanical simulation at different heat loads/rep. rates**
- More can be found in the recently published **CompactLight CDR**

Funded by the European Union

Compact

Thank you!

CompactLight@elettra.eu www.CompactLight.eu



CompactLight is funded by the European Union's Horizon2020 research and innovation programme under Grant Agreement No. 777431.