Sapienza Università di Roma
Dipartimento di Scienze di Base Applicate per l'Ingegneria
PhD school in accelerator physics XXIX cycle

Design, realization and commissioning of RF power system and accelerating structures for a Gamma Source

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Outline

Gamma Sources – ELI-NP Project

- Overview and Machine Layout
- RF system of the ELI-NP Linac
- RF Sources and FAT
- RF Accelerating Structures:
  - C-band TW accelerating structures (tuning, low and high power tests and beam loading calculations)
  - RF-gun (low and high power tests)

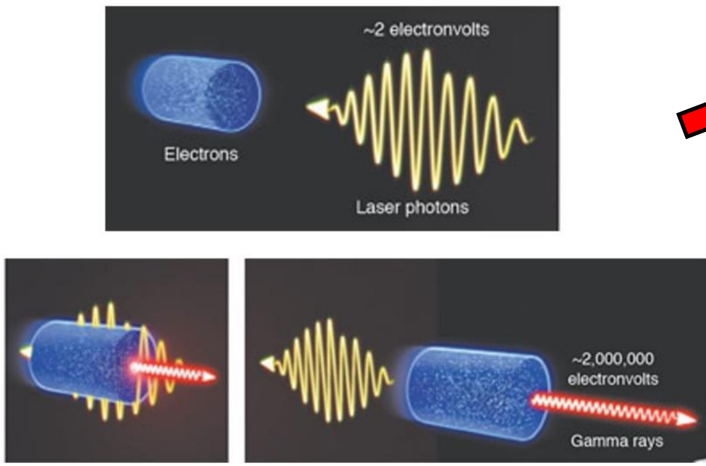
Gasket Clamping technique

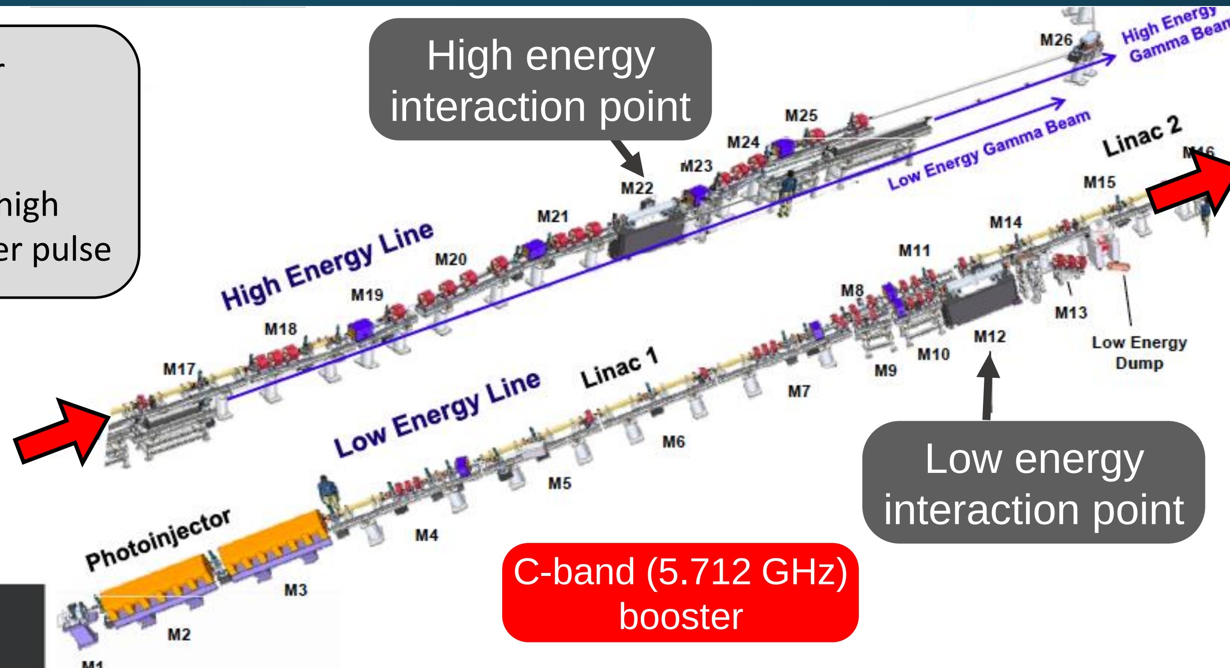
- Design of a LINAC implementing the gasket clamping technique
  - Electromagnetic design (cell, coupler and splitter)
  - Mechanical design and assembly procedure
  - 10 cell TW S-band structure prototype

Conclusion and future work

ELI-NP Gamma Beam Source

- **Source of Gamma-ray photons** under construction in Magurele (RO)
- ɣ-rays generated by **Compton back-scattering** in the collision between a high quality **e⁻** beam and a high power laser pulse





Gamma beam params	Value
Energy	0.2-20 MeV
Spectral density	0.8 – 4 • 10^4 ph/(s•eV)
RMS bandwidth	< 0.5%
Peak brilliance	> 10^{20} ph/(s•mm^2•mrad^2•0.1%)
Spot size	10-30 μm

Electron beam params	Value
Electron energy	75 - 740 MeV
Bunch charge	25 - 400 pC
N. of bunches / pulse	32
Bunch distance	16 ns
Bunch length	100 - 400 μm
Energy spread (RMS)	0.04 - 0.1%
Norm. emittance	0.4 mm•mrad
RF Rep. rate	100 Hz

RF System of ELI-NP

Increase the total flux of photons → Increase the # of collision per second:
- **100 Hz**
- **Multibunch (32 bunches)**

→
- **Damping of HOM**
- **Compensate the beam loading effects**
- Accurate thermal design

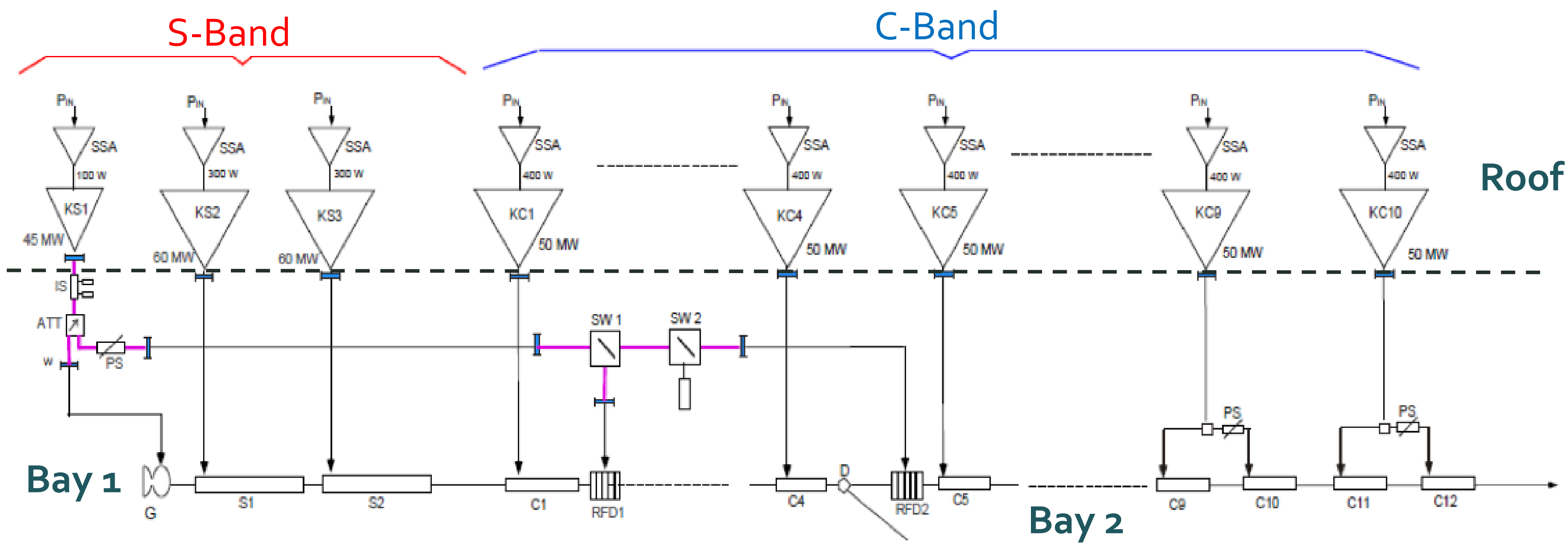
Compact system → **High gradient, high frequency** → S-band injector + C-band booster

RF Power system: 13 units (ScandiNova solid state modulators + Toshiba klystrons)
1 x 45 MW S-band RF unit;
2 x 60 MW S-band RF units;
10 x 50 MW C-band RF units.

Waveguides network: S-band: WR-284 (0.02 dB/m) C-band: WR-187 (0.03 dB/m).

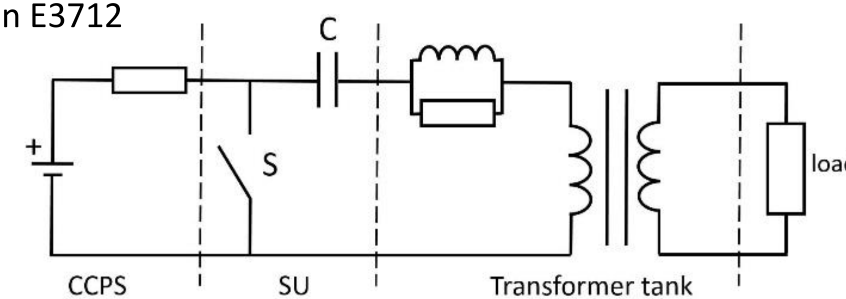
SF6 Network: Isolator, Attenuator, Phase shifter, 2 x RF switch

RF structures:
1 x SW S-band RF-GUN
2 x TW S-band SLAC type structures
2 x SW S-band RF deflectors
12 x TW C-band accelerating structures



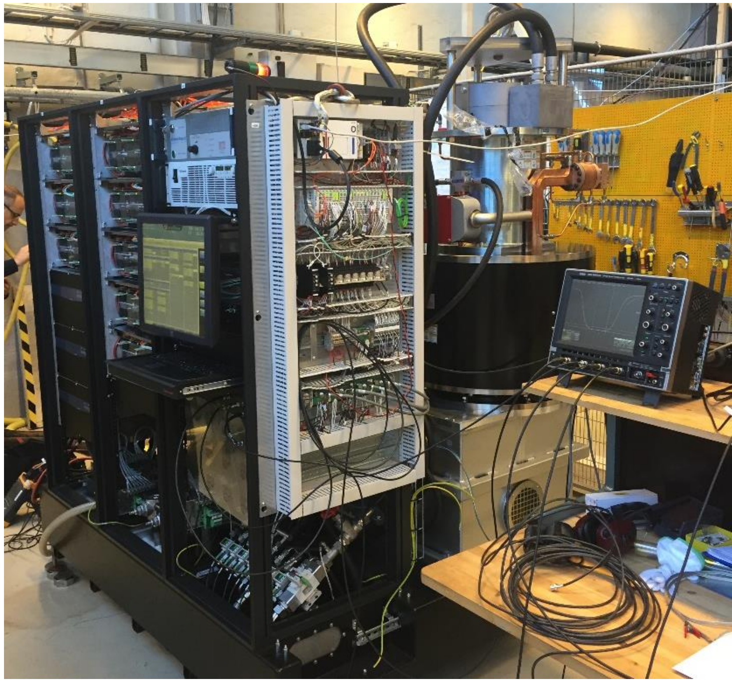
RF Sources: Klystron and Modulator

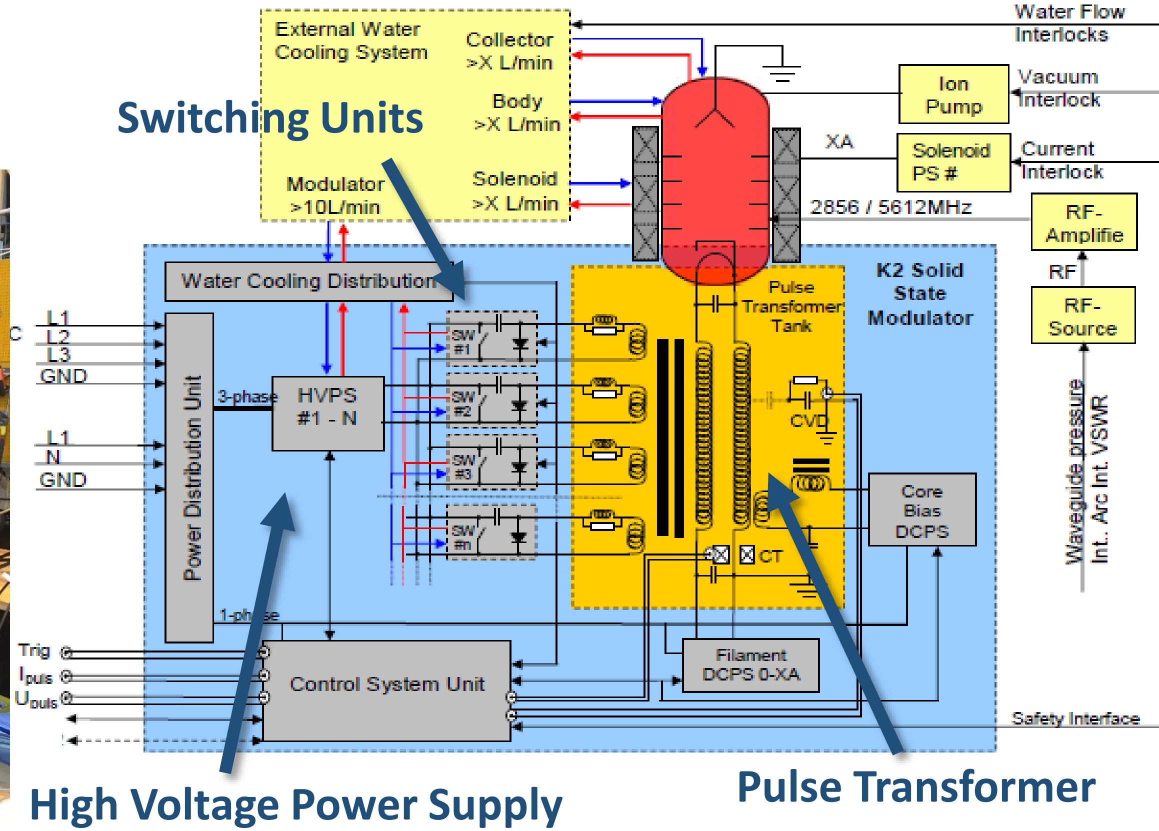
3x Solid State modulator K2-3 for 45MW and 60MW S-band klystron E3712
10x Solid State modulator K2-2 for 50MW C-band klystron E37210



Features:

- Completely in **Solid State Technology**:
    - Operating voltage 1kV (**high reliability**)
    - Personal and equipment safety
    - Improve power efficiency
- **Compact**
- **Modular** (easy to upgrade and to repair)
- **High amplitude and phase stability**





ELI-NP RF Sources: Factory acceptance tests

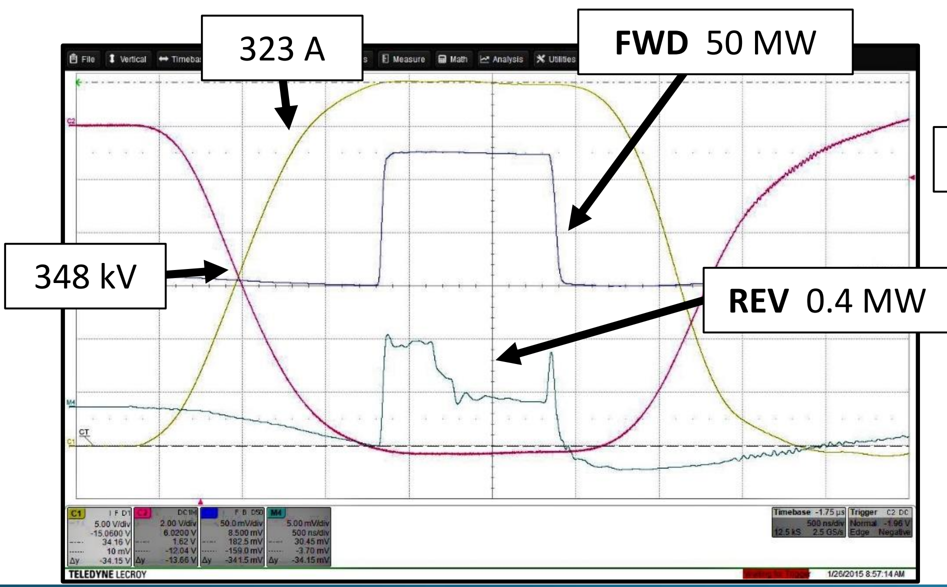
These tests were performed at the ScandiNova factory (Uppsala, Sweden).

FAT Protocol:

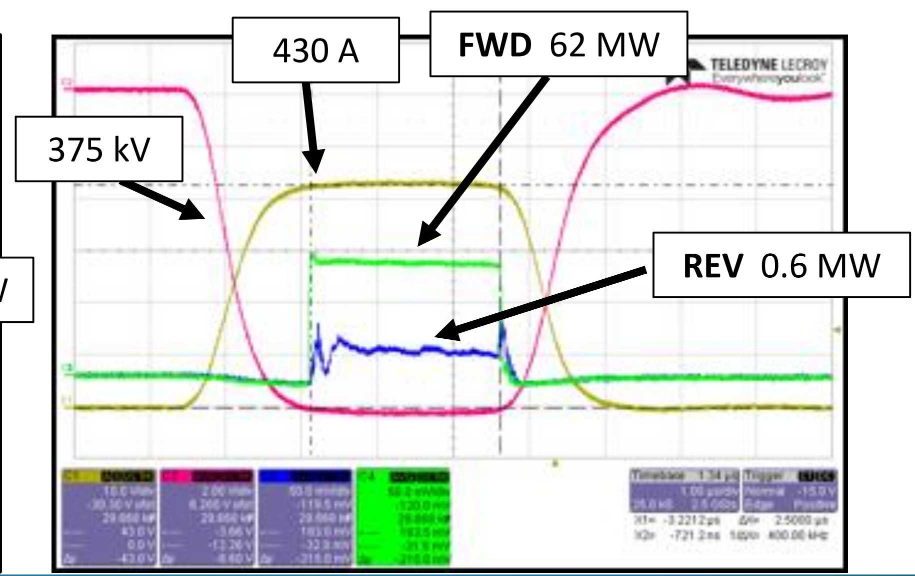
- Test in Diode Mode
- RF Test (Forward, reverse, pulse length)
- Long Run Test (8 hours)
- Interlock test (temperature, water flow, arcs, reflected power, external, emergency, filament V and I, subsystem)
- Radiation Measurements

Param.	unit	MSB1	MSB3 (45MW)	MCB3	MCB4
Output Pulse Voltage	kV	375	345	347.4	360
Output Pulse Current	A	430	371	323	324
Mod. Average power	kW	69	51	30.2	30
Peak Beam Power	MW	161	128	112	116
Pulse top flatness	%	0.58	0.47	0.73	0.74
Pulse rep. Freq.	Hz	100	100	100	100
RF Pulse length (top)	us	2.5	2.5	1	1
Pulse to pulse stability	%	0.004	0.0022	0.004	0.0033
Rate of rise	kV/us	442	423	414	431
Rate of fall	kV/us	379	405	362	366
Kly filament DC current	A	30.28	30.2	18	19.5
Kly filament DC voltage	V	11.7	11.8	15.5	17.3

C-band 50 MW unit



S-band 60 MW unit

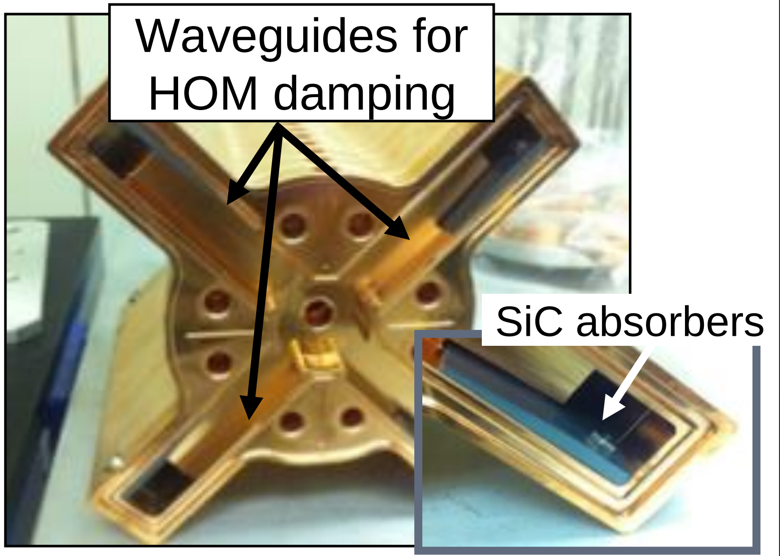


ELI-NP C-band structure

Travelling Wave (TW) C-band (5.712 GHz) sections, 2π/3 phase advance per cell, 1.8 m long:

- **HOM damping** by means of 4 waveguides + SiC absorbers [1] on each cell**;**
- Irises shaped to have a **quasi-constant gradient** [2] (38 ÷ 28 MV/m - 33 MV/m average):
    - Constant impedance (gradient in the first cells > 44 MV/m) - Breakdown rate issues;
    - Constant gradient (irises aperture too small) - increase of the dipole mode effects, reduction of pumping speed.

RF frequency	GHz	5.712
Rep. Rate	Hz	100
Number of cells	102 + in and out coupler	
Working Mode	2π/3	
Max Rf input power	MW	40
Average accelerating gradient	MV/m	33 (38-28)
Average dissipated power	kW	2.3
Unloaded Q factor	8800	
Working temperature	°C	30
Total length	m	1.8
Iris aperture	mm	6.8-5.78 (Half apert.)
Type	Quasi - Costant Gradient	
Filling Time	μs	0.31
Shunt Impedance	MΩ/m	63-67



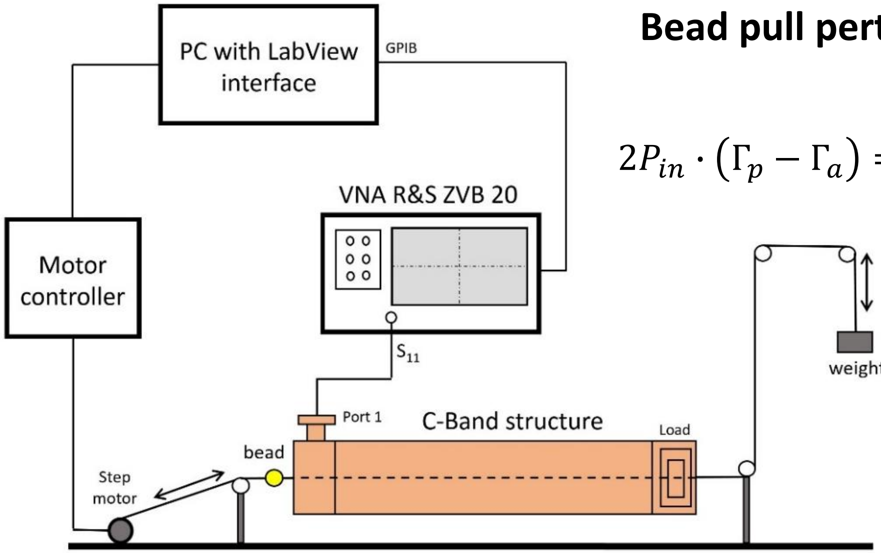
[1] D. Alesini *et al.* WEPFI013, Proceedings of IPAC2013, p.2726
[2] D. Alesini *et al.* THPRI042, Proceedings of IPAC2014, p.3856

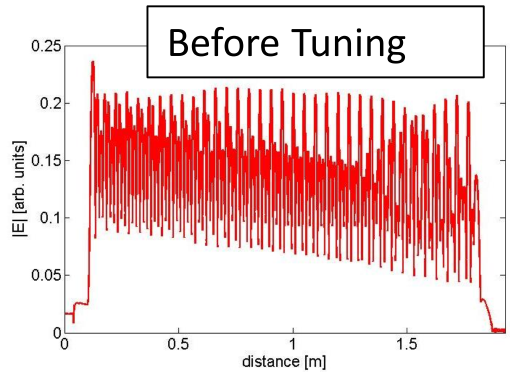
C-band structures: tuning (I)

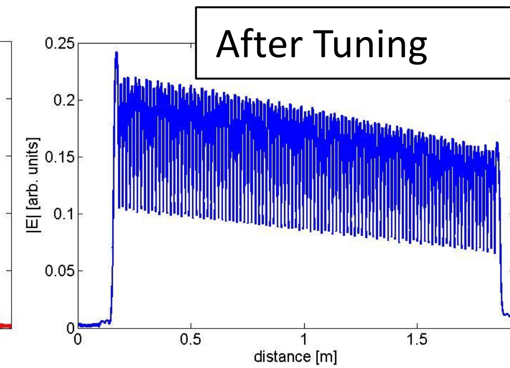
After realization structure has to be tuned (constant phase advance per cell $2\pi/3$):

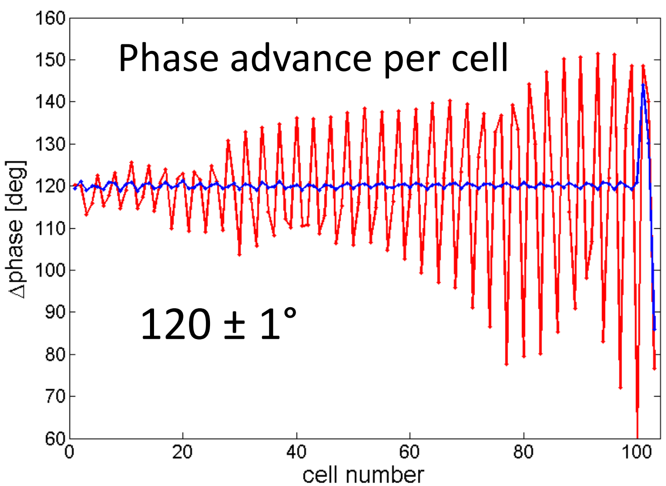
Bead pull perturbation technique (Steele [3]) + **tuning alghoritm** trough local reflection coefficient calculation [4]

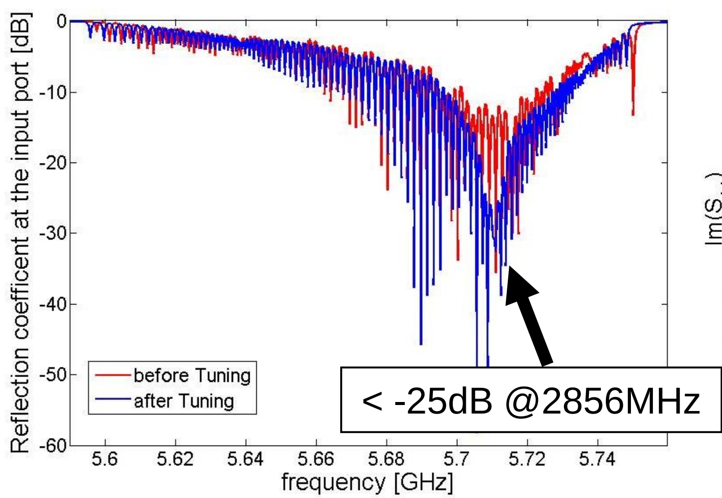
$$2P_{in} \cdot (\Gamma_p - \Gamma_a) = -j\omega k_{steele} \cdot |E_z|^2 \Rightarrow E_z \Rightarrow \Gamma_n \Rightarrow \Delta freq \text{ of each cell}$$

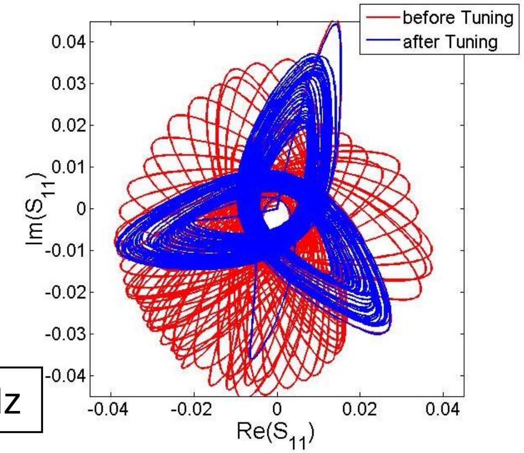






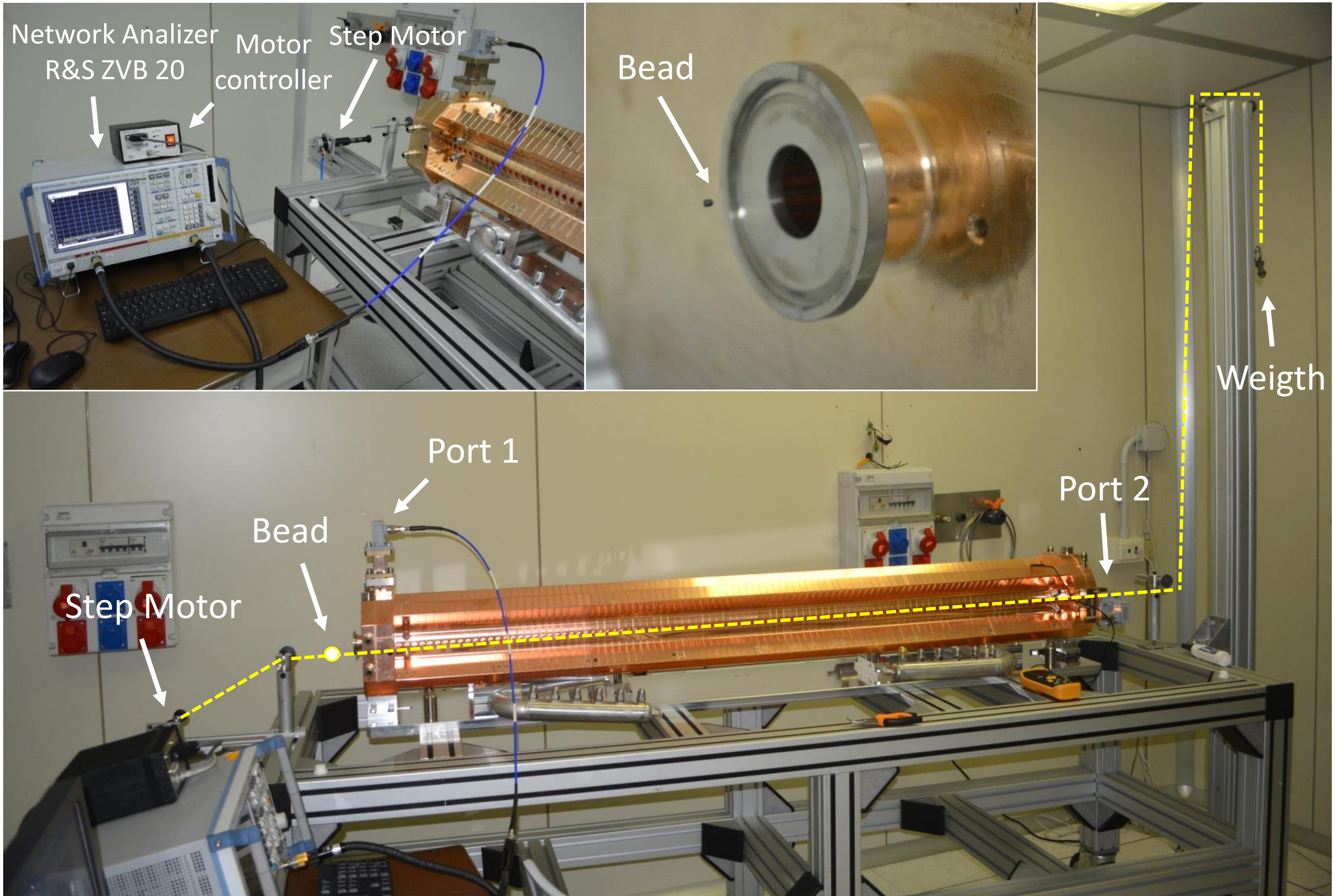






[3] C. Steele 1966 IEEE T. Microw. Theory 14 70, [4] D. Alesini *et al.* 2013 JINST 8 P10010

C-band structures: tuning (II)



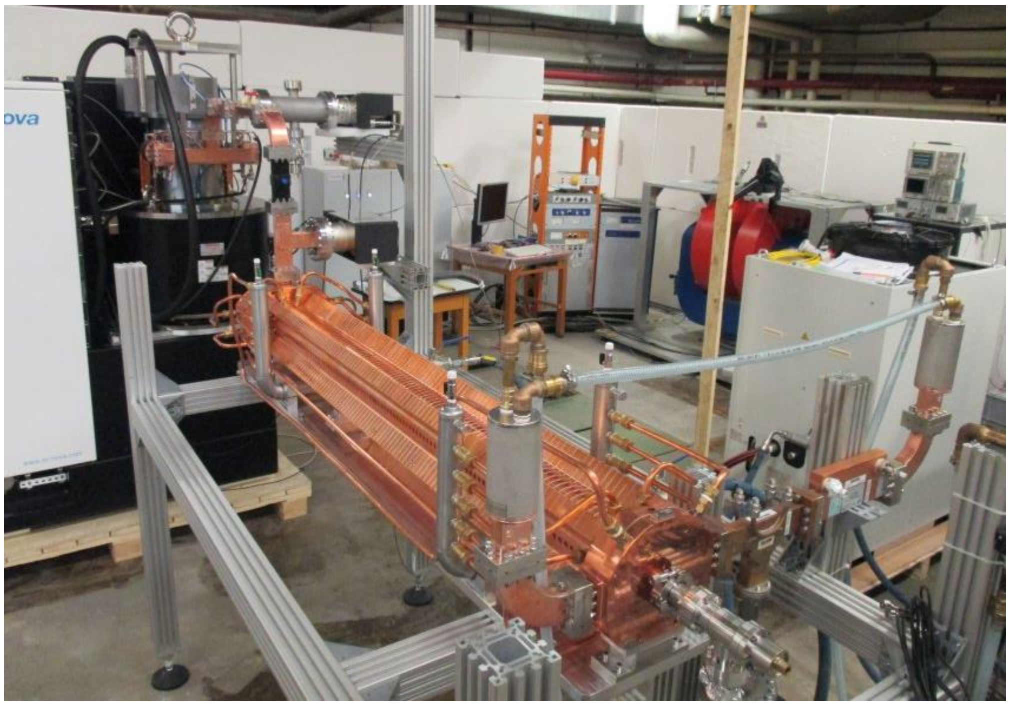
C-band structures: High power tests

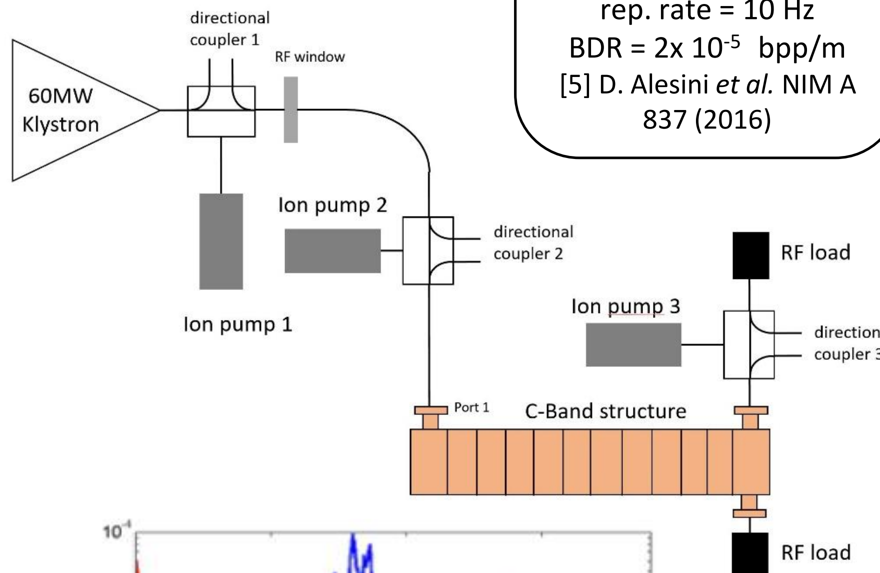
Starting conditions:
P = 0 W
pulse length = 100 ns
rep. rate = 10 Hz

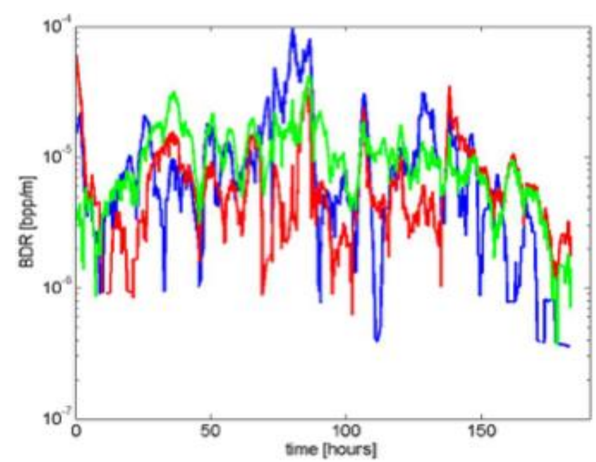
Goal:
P = 40 MW (pulsed)
t pulse = 800 ns
rep. rate = 100 Hz

Results after 4 weeks of conditioning (190 h):
P = 40 MW (pulsed); pulse length = 820 ns
rep. rate = 100 Hz
BDR = 3 x 10^{-6} bpp/m

Conditioning of the SPARC_LAB C-band structure:
P = 38 MW (pulsed); t pulse = 165 ns
rep. rate = 10 Hz
BDR = 2x 10^{-5} bpp/m
[5] D. Alesini *et al.* NIM A 837 (2016)







The current of three ion pumps connected around the structure and the RF signals from pickups were monitored.

This test has been performed at the ELSA Facility @ Bonn University (Germany).

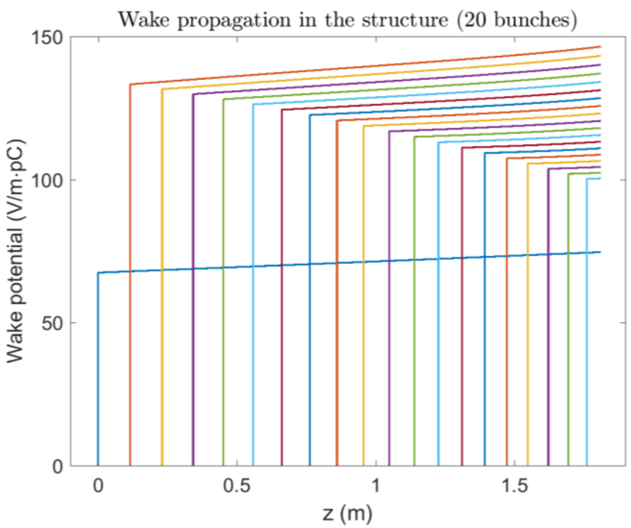
C-band structures: Beam Loading

A **first order study** on the wake-fields excited in the quasi-constant gradient C-band TW structures by the 32 electron bunches has been performed. Assuming each bunch to be a point-like charge, the **wake generated by a single bunch**

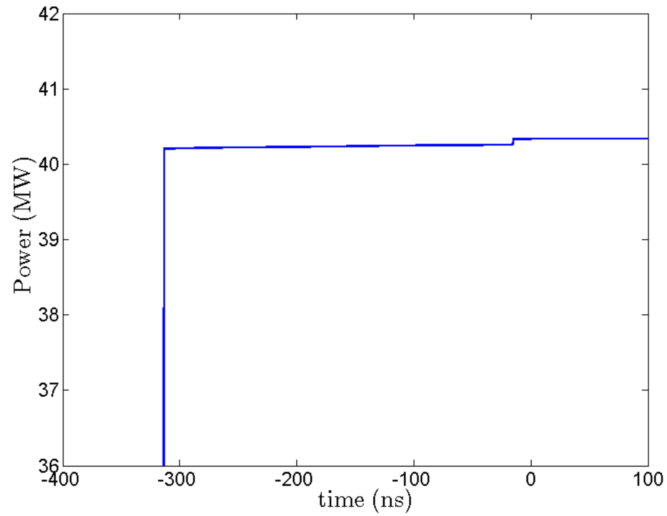
$$W(z) = \frac{1}{2}\omega_{RF}\frac{r}{Q} = \alpha v_g r \qquad r = \frac{E^2}{\left|\frac{dP}{dZ}\right|} = \frac{Z}{2\alpha}$$

Since the filling time of the structure is $\sim 314\, ns$ and the bunch separation is $T_b = 16\, ns$, the wake reaches a steady state after the passage of 20 bunches.

Every 16 ns a new bunch arrives and consequently a new wake is produced, travels and is attenuated along the structure. After the passage of 20 bunches the structure is "fully loaded"



Input pulse shape



In order **to have a net average accelerating field of 33 MV/m** (design value), the structure has to be pre-loaded with a tailored power pulse to compensate for the BL transient effects.

Bandwidth limitations (backend -16 MHz, klystron/modulator - 10 MHz) might limit compensation effectiveness, which has to be studied by means of a integrated test of LLRF-Modulator-Klystron system.

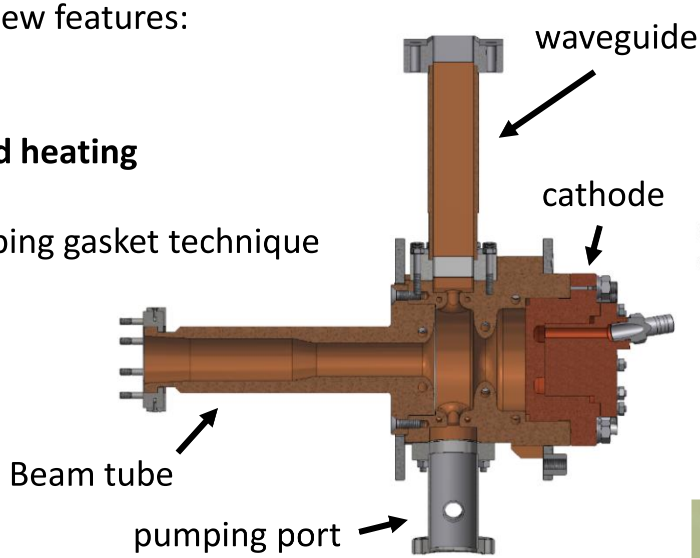
[6] L. Piersanti *et al.*, proceedings IPAC16, Busan, Korea, May 2016, MOPMW006.

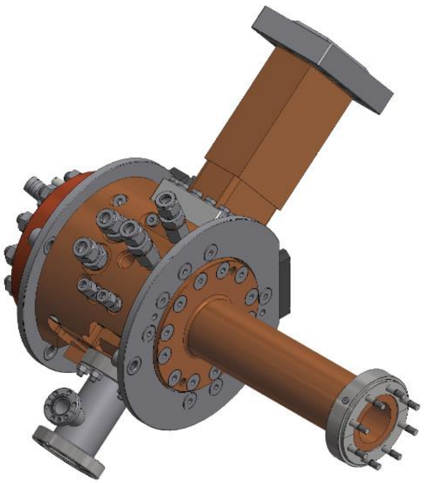
ELI-NP RF Gun

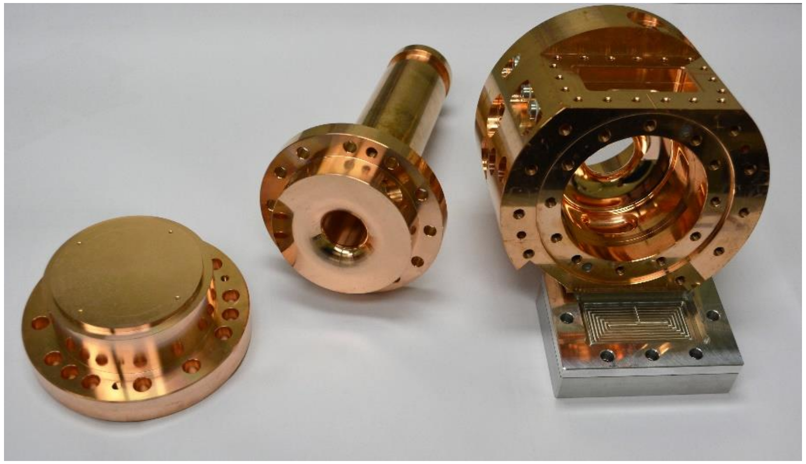
1.6 cell gun of the BNL/SLAC/UCLA type with new features:

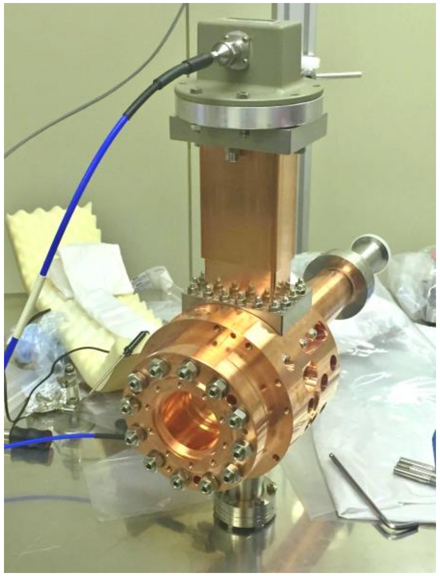
- elliptical shaped irises with larger aperture
- tunable by deformation
- coupling hole rounded to **reduce** the **pulsed heating**
- **cooled cathode**
- fabrication **without brazing** using the clamping gasket technique

RF frequency	GHz	2.856
Rep. Rate	Hz	100
Working Mode	π mode (SW)	
Max Rf input power	MW	16
RF peak field at the cathode	MV/m	120
Average dissipated power	kW	1.5
Unloaded Q factor	15000	
Coupling coefficent β	3	
Working temperature	°C	33-34
Filling time	ns	420
Shunt Impedance	MΩ/m	1.64
Type of cathode	copper	





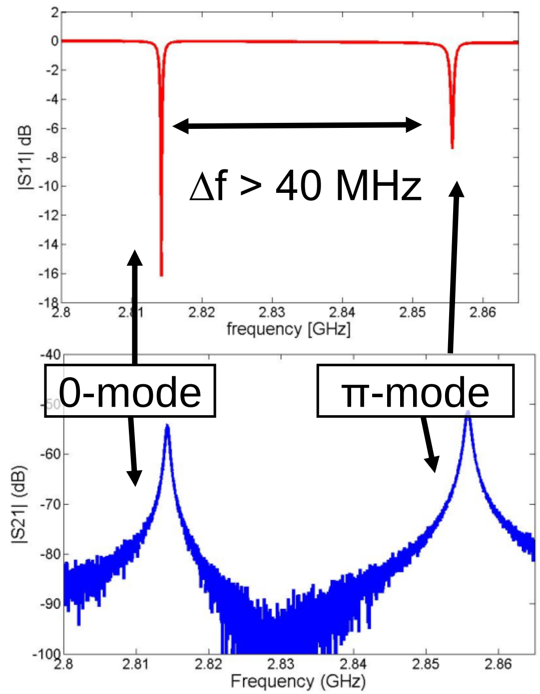




[7] D. Alesini et al., PRST-AB 18, 092001 (2015)

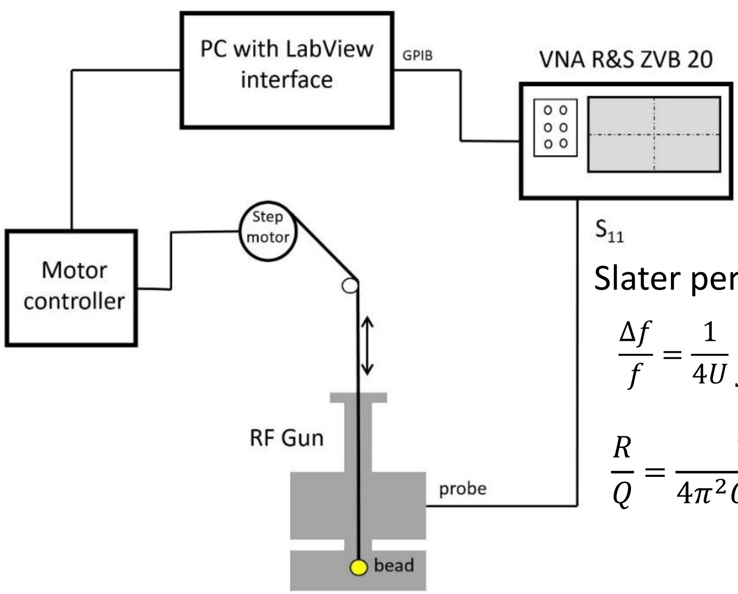
RF Gun: low power measurements

Parameters	Design	Measured
Working π-Mode freq.	2856 MHz	2855.62 MHz
0-Mode freq.	2816 MHz	2814.26 MHz
Q_0	15000	14990
Q_L	3625	4115
Coupling β	3	2.643
Freq. Separation	40 MHz	41.3 MHz
Field flatness	< 3%	~2%
Temperature	34°C	22.9°C
Conditions	Vacuum	Air



Measurements ambient conditions:

$$T_{air} = 22.9°C$$
$$T_{gun} = 21.8°C$$
$$P = 995{,}2\ hPa$$
$$H = 52{,}4\%$$

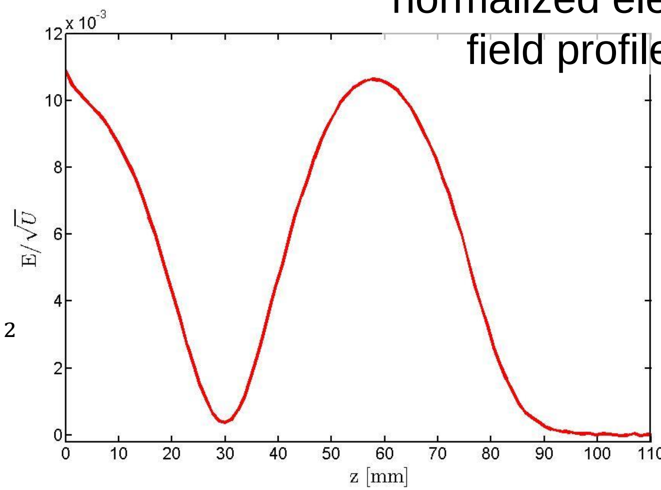


Slater perturbation technique

$$\frac{\Delta f}{f} = \frac{1}{4U}\int_{\Delta V}\left(\mu_0 H_0^2 - \varepsilon_0 E_0^2\right) \mathrm{dV}$$

$$\frac{R}{Q} = \frac{1}{4\pi^2 G l^3 f^2}\left|\int_0^L |\Delta f(z)|^{1/2} e^{\frac{j\omega z}{c}} dz\right|^2$$

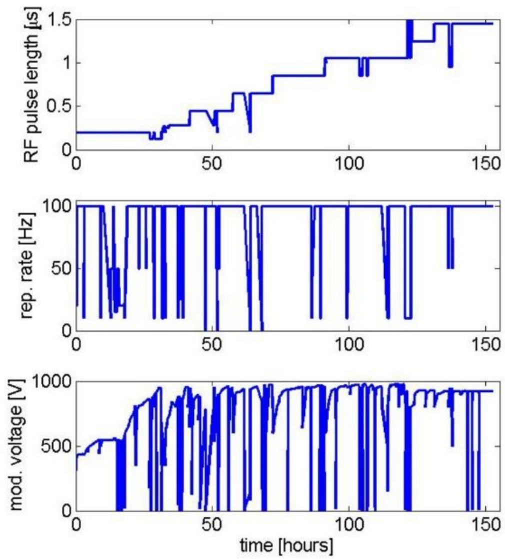
π-mode normalized electric field profile

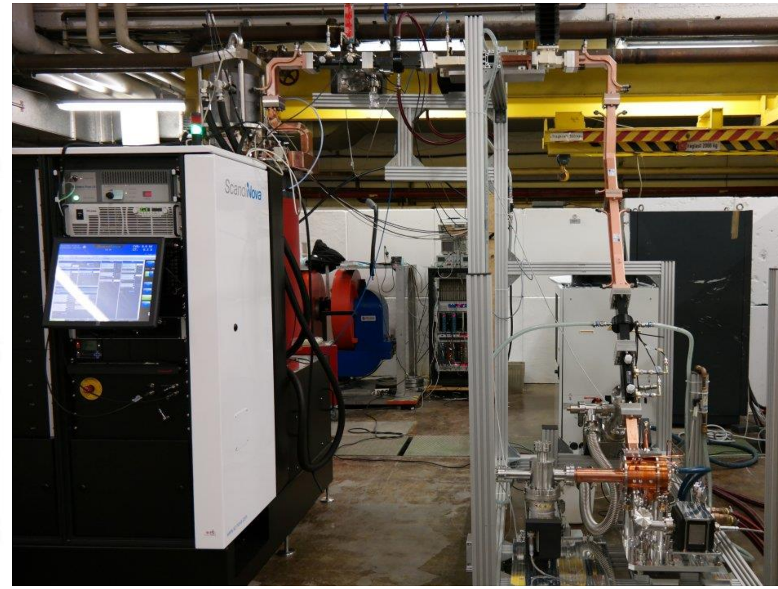


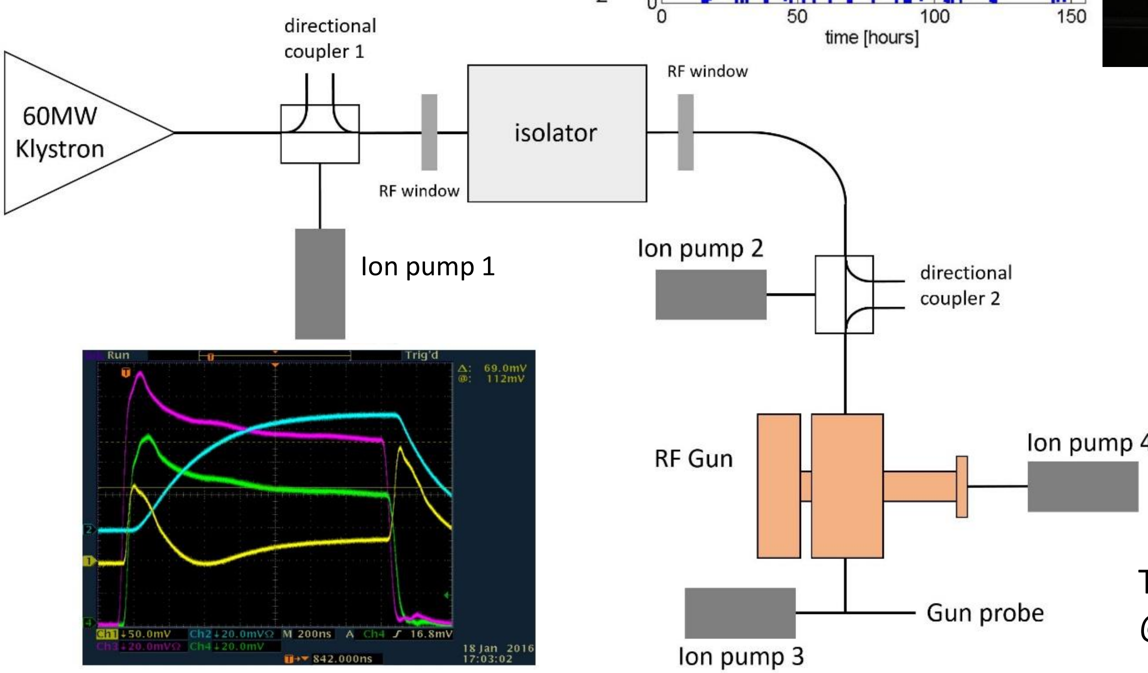
RF Gun: High power test

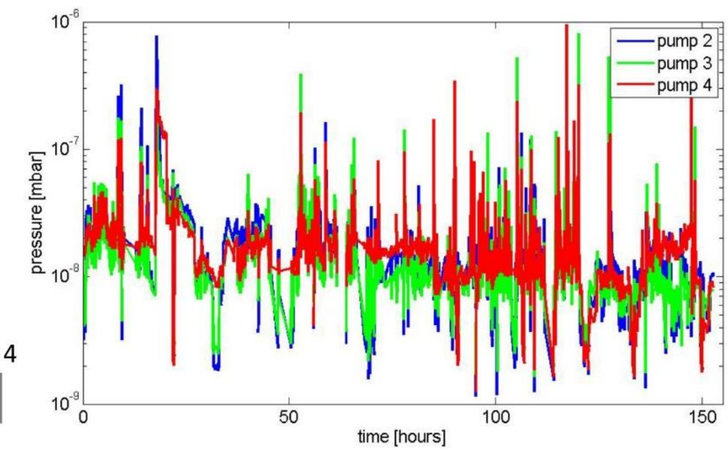
Starting conditions:
P = 0 W
pulse length = 100 ns
rep. rate = 10 Hz

Goal:
P = 16 MW (pulsed)
120 MV/m on the cathode
t pulse = 1.5 us
rep. rate = 100 Hz









This test has been performed at the ELSA Facility @ Bonn University (Germany).

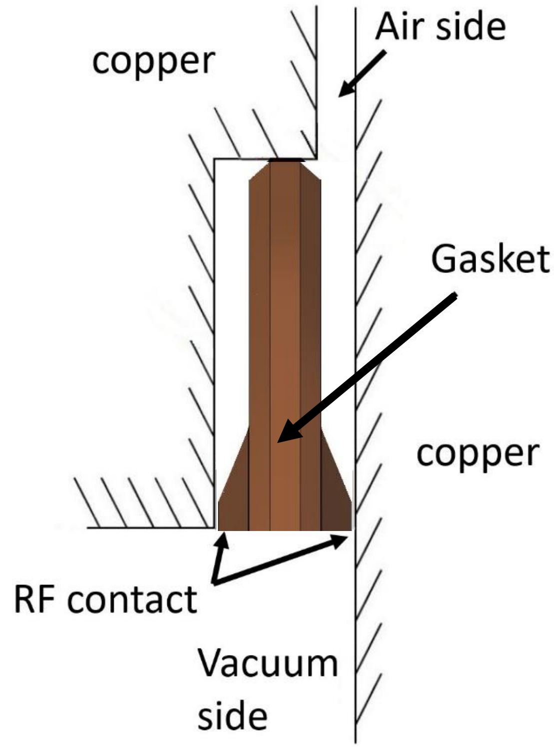
Gasket-Clamping technique

The accelerating structures generally are realized by a **brazing process** following all **cleaning procedure of the high gradient technology**. But brazing process:

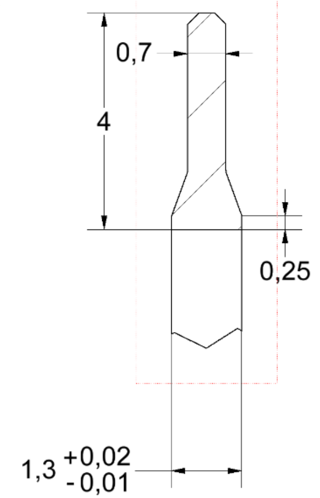
⇒ requires large vacuum furnace
⇒ is very expensive
⇒ poses a not negligible risk of failure.
⇒ at the end of the process the copper is "soft".
⇒ Avoiding it is possible to decrease the BDR

New technology developed at INFN-LNF and used for the realization of two S-band RF Gun:

- Gasket made of **copper**, realized with high precision lathe
- Compression of 0.2 mm after clamping
- Simultaneously guarantees **the vacuum seal and the RF contact** avoiding sharp edges and gaps.



Mechanical tolerances



⇒ **Realization of an entire Linac (S/C/X band) without brazing**

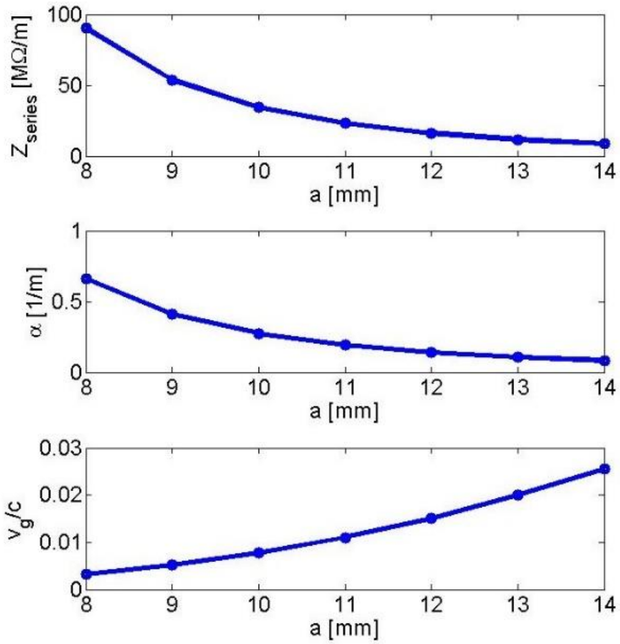
[8] Int'l patent application PCT/IB2016/051464, D. Alesini et al. ''Process for manufacturing a vacuum and radio-frequency metal gasket and structure incorporating it'' assigned to INFN

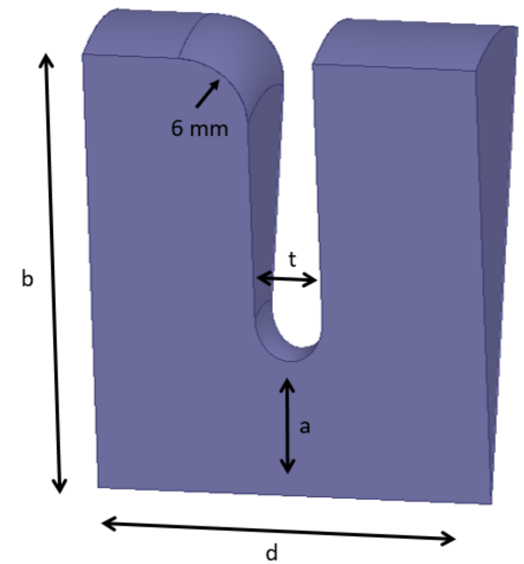
Design and realization of an S-band prototype:
1) Electromagnetic and mechanical design → 2) Gasket test (vacuum) on a single copper cell → 3) Low power electromagnetic test on a symplified prototype made of aluminum or brass → 4) Vacuum, low and high power tests on a OFHC copper structure

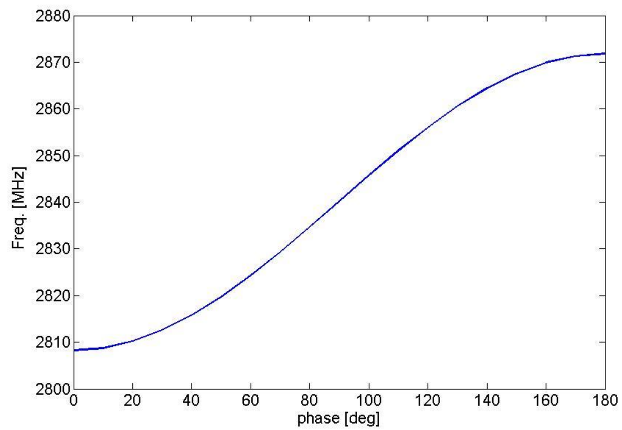
LINAC electromagnetic Design: Single cell

Single cell design:

- Parametric analysis of the single cell through **Ansys HFSS**
- **Iris half aperture 13 mm** for good pumping speed and performace comparable to a SLAC-type section
- **Internal edge rounded** to increase the Q factor and simplify the mechanical realization
- **Elliptical shape of the iris** with 4/3 aspect ratio to decrease the peak surface field
- **Costant impedance** (CI)
- 2pi/3 phase advance: **d=34.99mm**





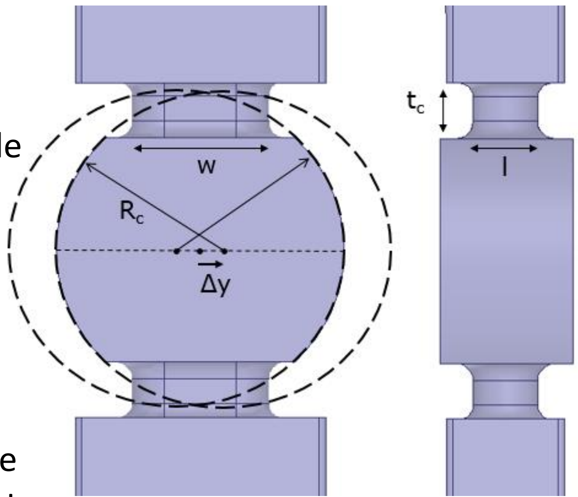


Parameter	Sensitivity
Cell radius	-80 kHz/um
Iris radius	22 kHz/um
Cell length	-5 kHz/um
Iris thickness	10 kHz/um

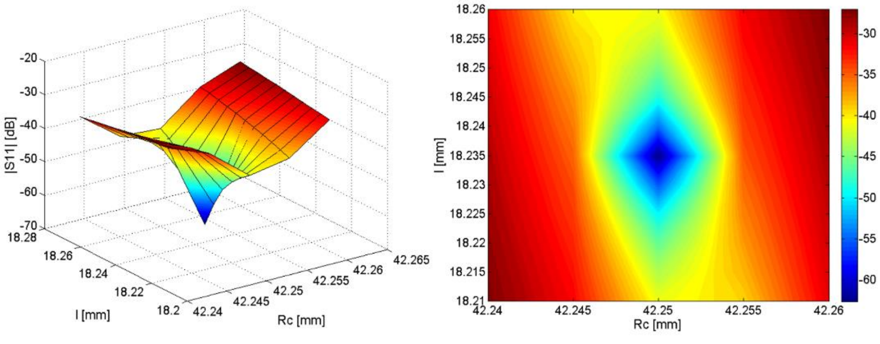
LINAC electromagnetic design: Coupler

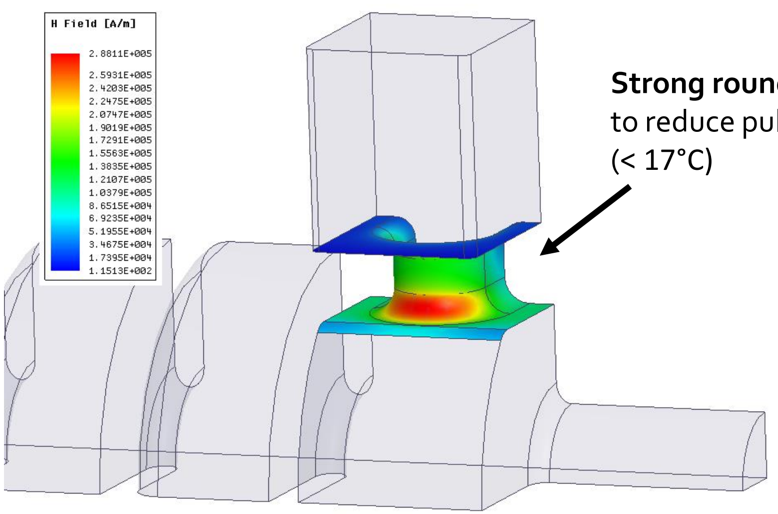
Input/Output coupler:

- Coupling through an aperture
- **Rc, w and l optimized** to match the waveguide mode TE10 to the accelerating one TM01-like
- **Pulsed heating** evaluation
- **Dual feed** (no dipole field)
- **Racetrack profile** with a 'cut' to facilitate the machining and compensate the quadrupole component



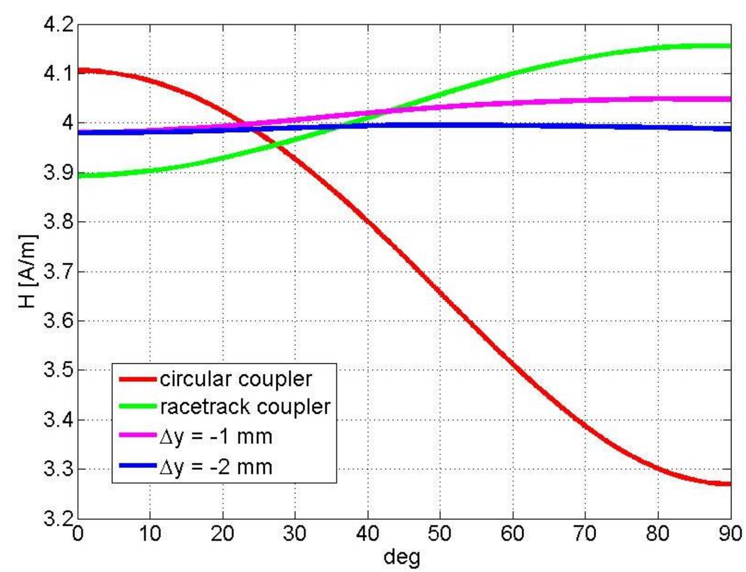
Coupler tuning through the «short circuit» method[9] using l, w and Rc





Strong rounded coupler to reduce pulsed heating (< 17°C)

Compensation of the **quadrupole field component**

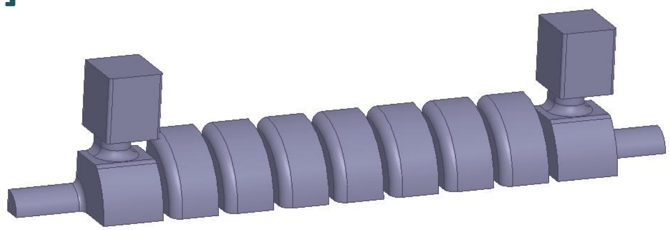


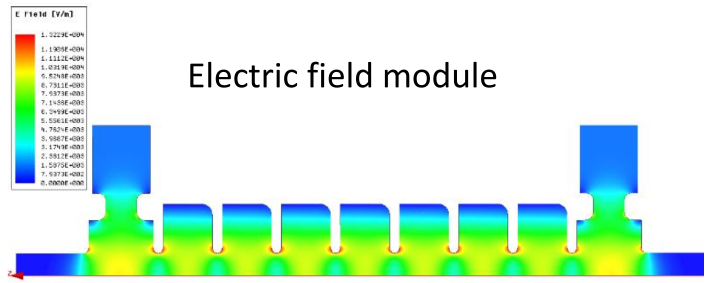
[9] D.Alesini *et al.*, Journal of Instrumentation 8,10, (2013).

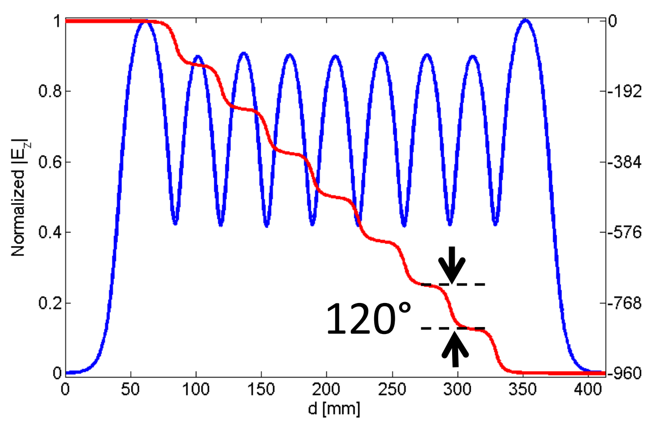
LINAC electromagnetic design: Results

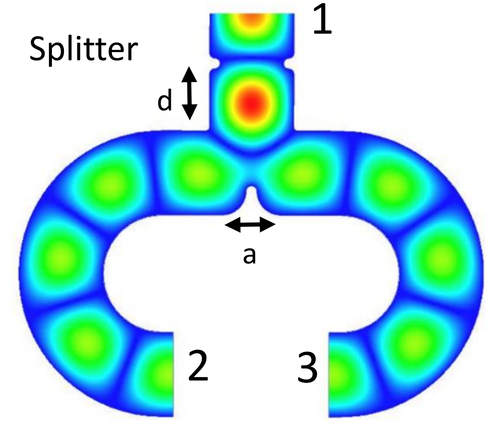
10 cells TW S-band prototype[10]:

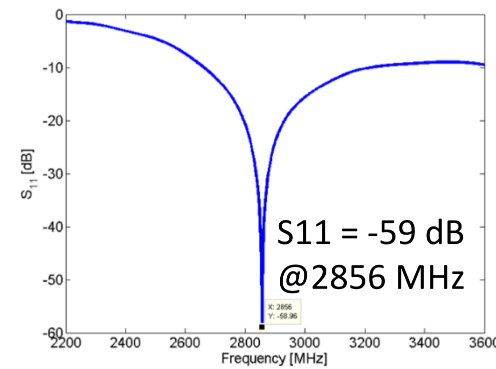
Parameter	Value
Frequency	2856 MHz
Cell phase advance	2π/3
Structure type	CI
Number of cells	10 + 2
Period	34.99 mm
Structure length	55 cm
Iris Radius	13 mm
Q_0	14200
Group velocity (vg/c)	0.02
Field attenuation	0.11 m^{-1}
Shunt impedance	55 MΩ/m
Series impedance	11.67 MΩ/m
$E_{acc}/\sqrt{P_{in}}$	3.4 $MV/m/\sqrt{MW}$
Pulsed heating (@ 40MW and 1μs pulse length)	< 17 °C

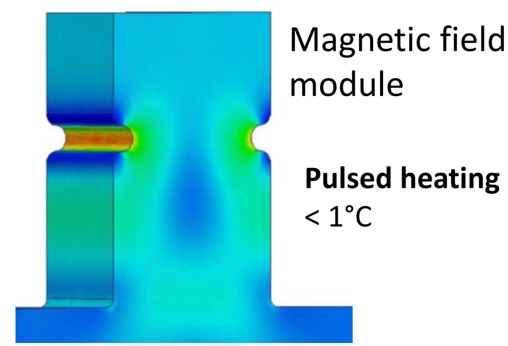










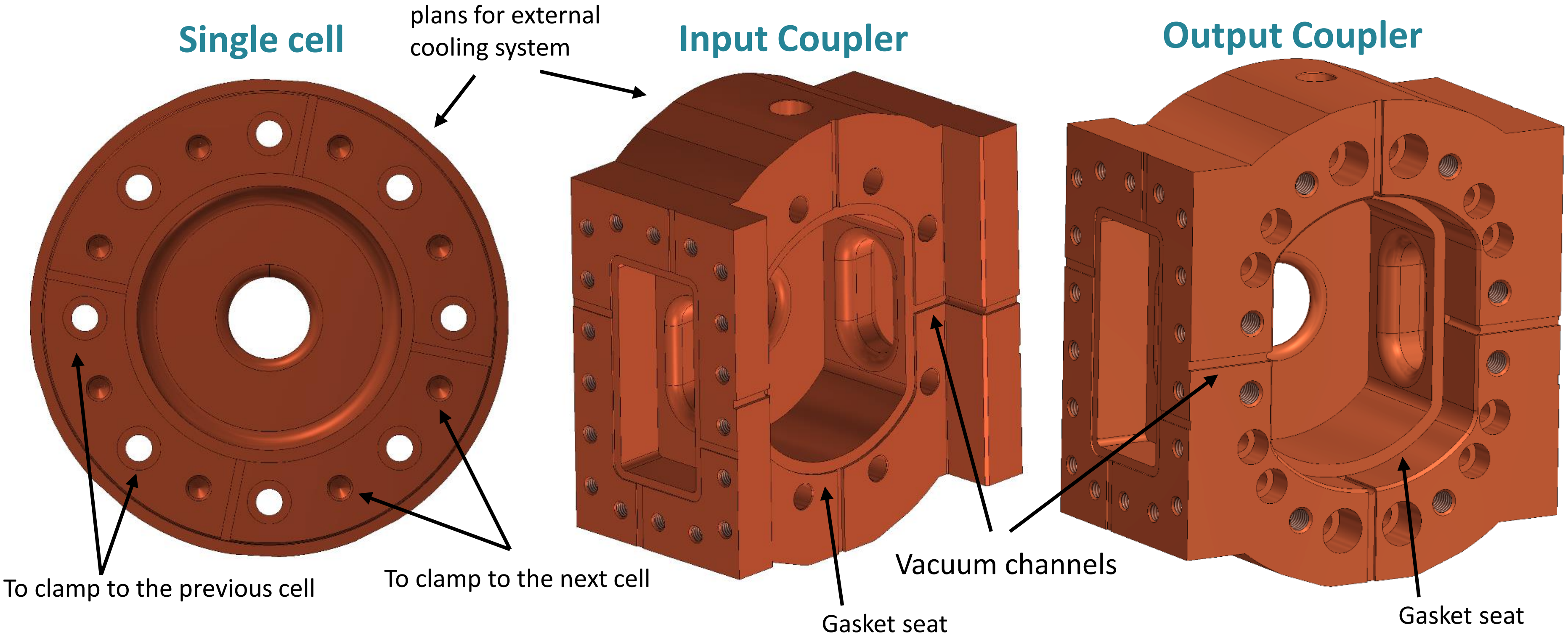


[10] F. Cardelli *et al.*, proceedings IPAC16, Busan, Korea, May 2016, MOPMW005.

LINAC mechanical design

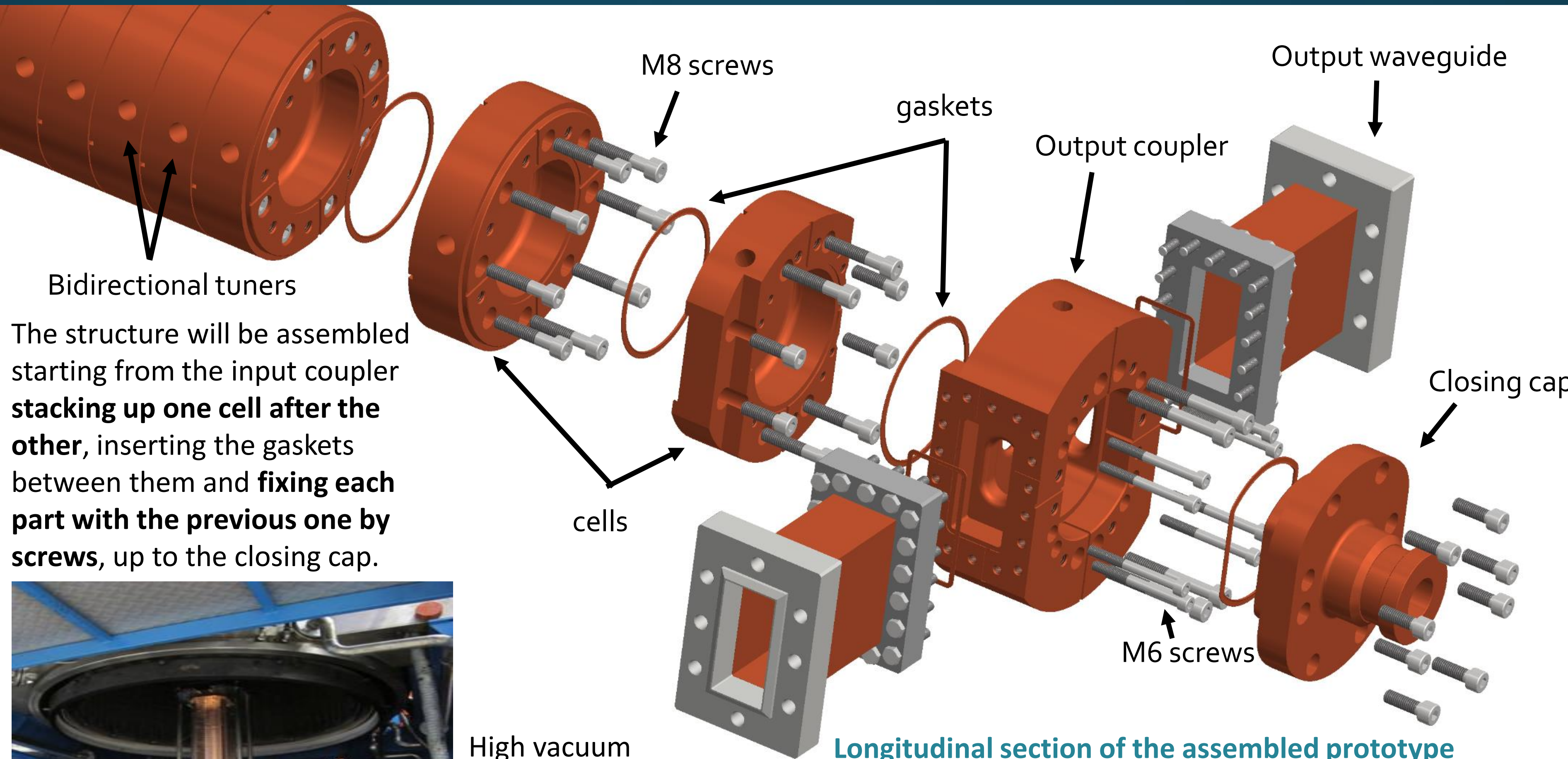
In the overall design a continuous **feedback between the electromagnetic design and the mechanical model** has been necessary to match electromagnetic and mechanical constraints.

The prototype is composed by an input coupler, ten accelerating cells and an out coupler with the final closing cap.
Each cell has eight screw holes disposed at 45° to one another to **provide homogeneous force on the gasket** when the cells are clamped together.
Each parts will be **fabricated from cylinders of Oxygen Free High Conductivity (OFHC) copper** using high precision lathe and milling machines. The Mechanical design is ready for the machining. The manufacturing will be done at mechanical workshop of INFN-Roma1.



Mechanical design with Autodesk Inventor.

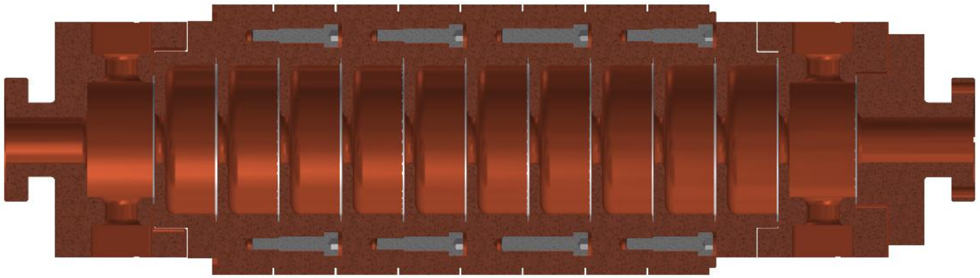
LINAC assembly procedure



The structure will be assembled starting from the input coupler **stacking up one cell after the other**, inserting the gaskets between them and **fixing each part with the previous one by screws**, up to the closing cap.

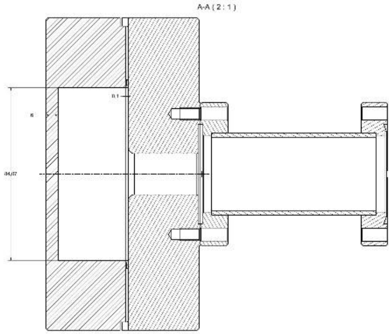
High vacuum oven used for structure brazing (INFN- LNL)

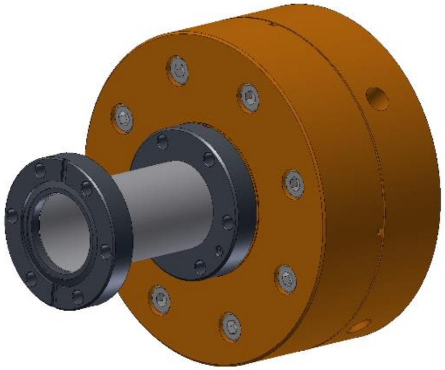
Longitudinal section of the assembled prototype



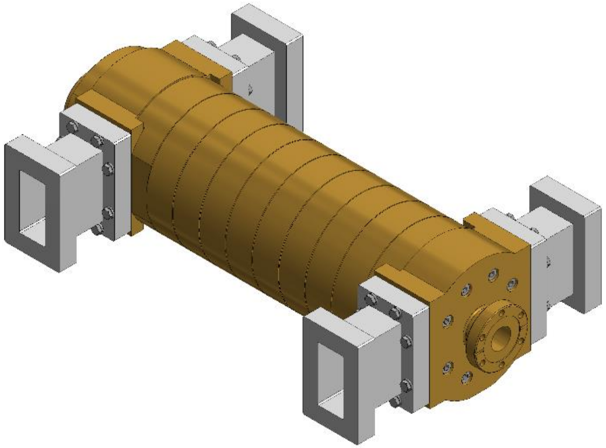
Next steps

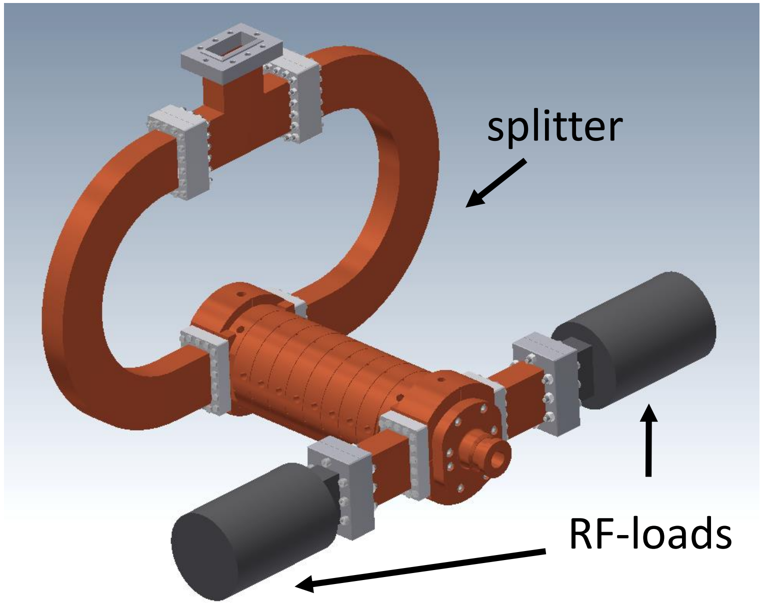
1) Vacuum and tuner test on a single cell





2) Low Power RF measurements on a brass/Al simplified prototype





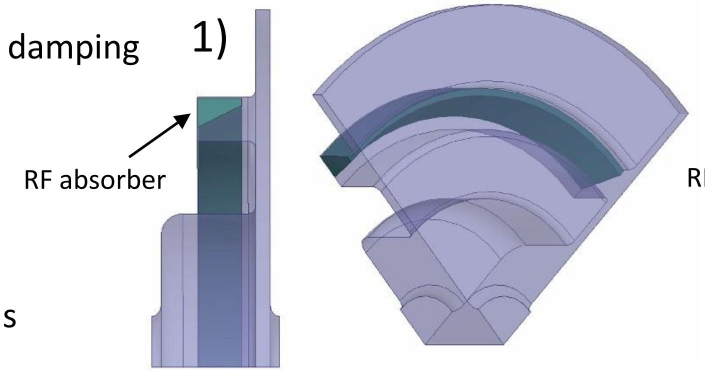
3) Vacuum and high power test

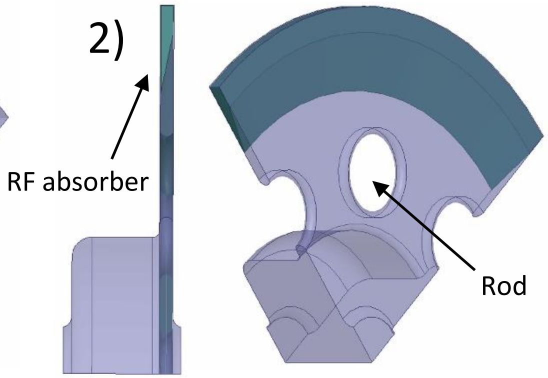
4) Extention of this technique to C-band structures with HOM absorber integrated for multibunch operation

Is not possible to use waveguides for HOM damping
Structures under study:

1. Choke mode structure (modified)
2. Rods structure

Electromagnetic and wakefields simulations with HFSS and CST Particle studio.





Conclusions and Future Work

Gamma sources based on RF linacs require **high gradients, high repetition rate** and **multibunch operation** this implies a challenging design for the overall RF system and accelerating structures

This work has been done in the frame of activities of the RF and Vacuum group of the Frascati laboratories of INFN and in particular in the scope of the ELI-NP GBS project.

The actual state of the commissioning of different RF devices and components has been presented:

- **Modulators and klystrons**: Factory acceptance tests
- **C-band sections**: Realization, tuning, low power tests and conditioning, beam loading calculations
- **RF-Gun**: design, realization and low and high power tests

The **gasket clamping technique** is a new technique for the realization of RF structures that allows to avoid brazing process and all his drawbacks. This technique has been succesfully used for the realization of two S-band RF gun.

- The possibility to **extend the use of this technique to the realization of a Linac (S/C/X band)** has been investigated through the design and realization of a prototype.
- The **electromagnetic** (cell, coupler and splitter) and **mechanical design** of a **10 cell TW S-band prototype** have been presented together with the assembly procedure.
- This prototype is ready for machining. Each parts will be realized at INFN Roma1 workshop. Next steps are:
    - Vacuum and tuning test on a single OFHC copper cell clamped
    - RF test on a 10 cells symplified Brass/Al prototype
    - Low and High power tests on a OFHC copper 10 cells prototype
- The design of a **C-band TW structure** realized with the clamped-gasket technique implementing **HOM absorber** for **multibunch operation** has been started.

Thank you for the attention.