C-BAND ACCELERATION ACHIEVEMENTS, USE AND APPLICATION

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OUTLINE

- **C-Band accelerating structures for SPARC** (e^- acc. TW single bunch)

- **C-Band structures for multi-bunch RF LINACS: ELI_NP proposal** (e^- acc. TW multi bunch)

- C-Band structures for hadrontherapy (SW ions) (few slides)

- *PSI*

- *SPRING-8*

SPARC_LAB

(Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams)

Multi-purpose radiation/acceleration laboratory at LNF-INFN

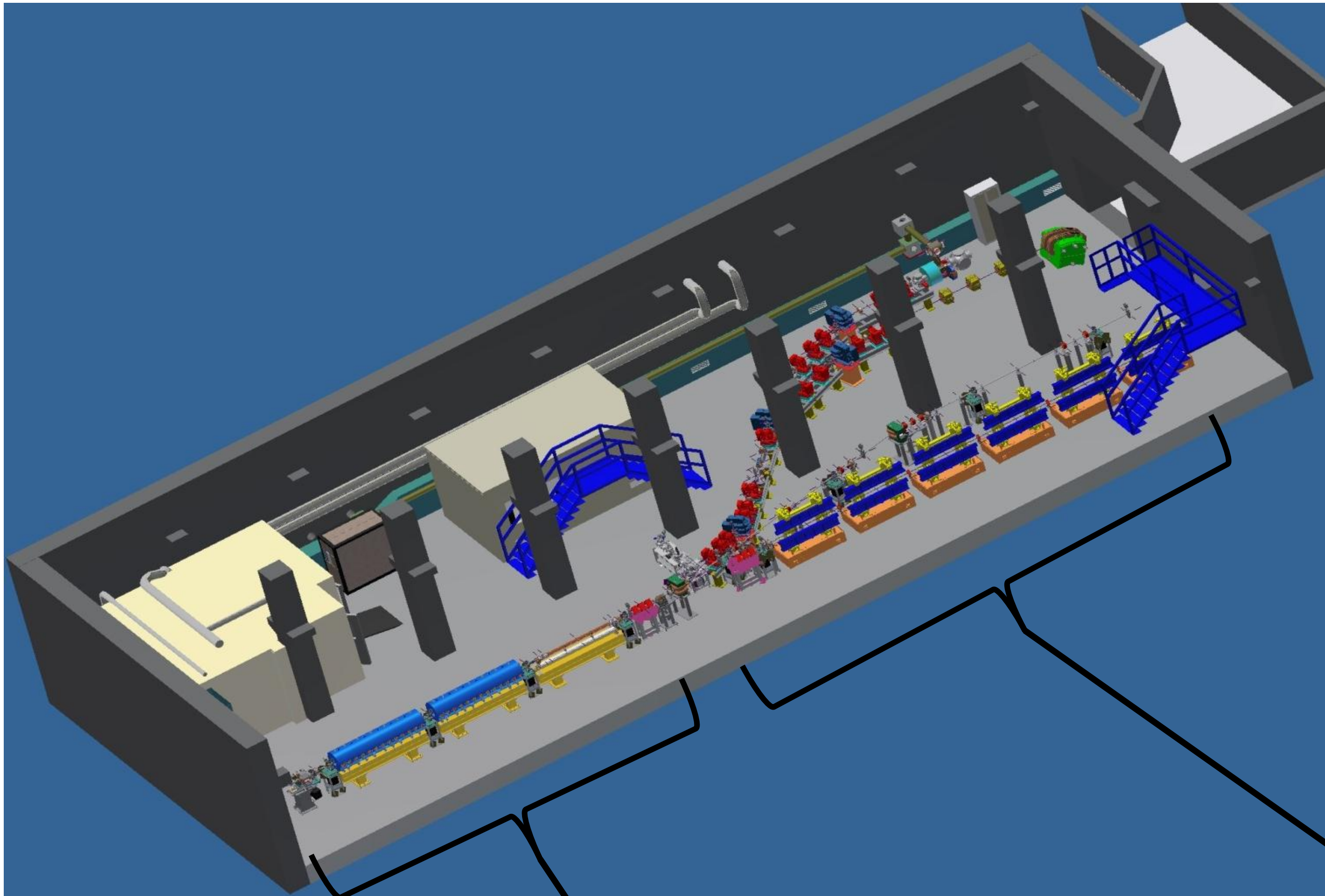
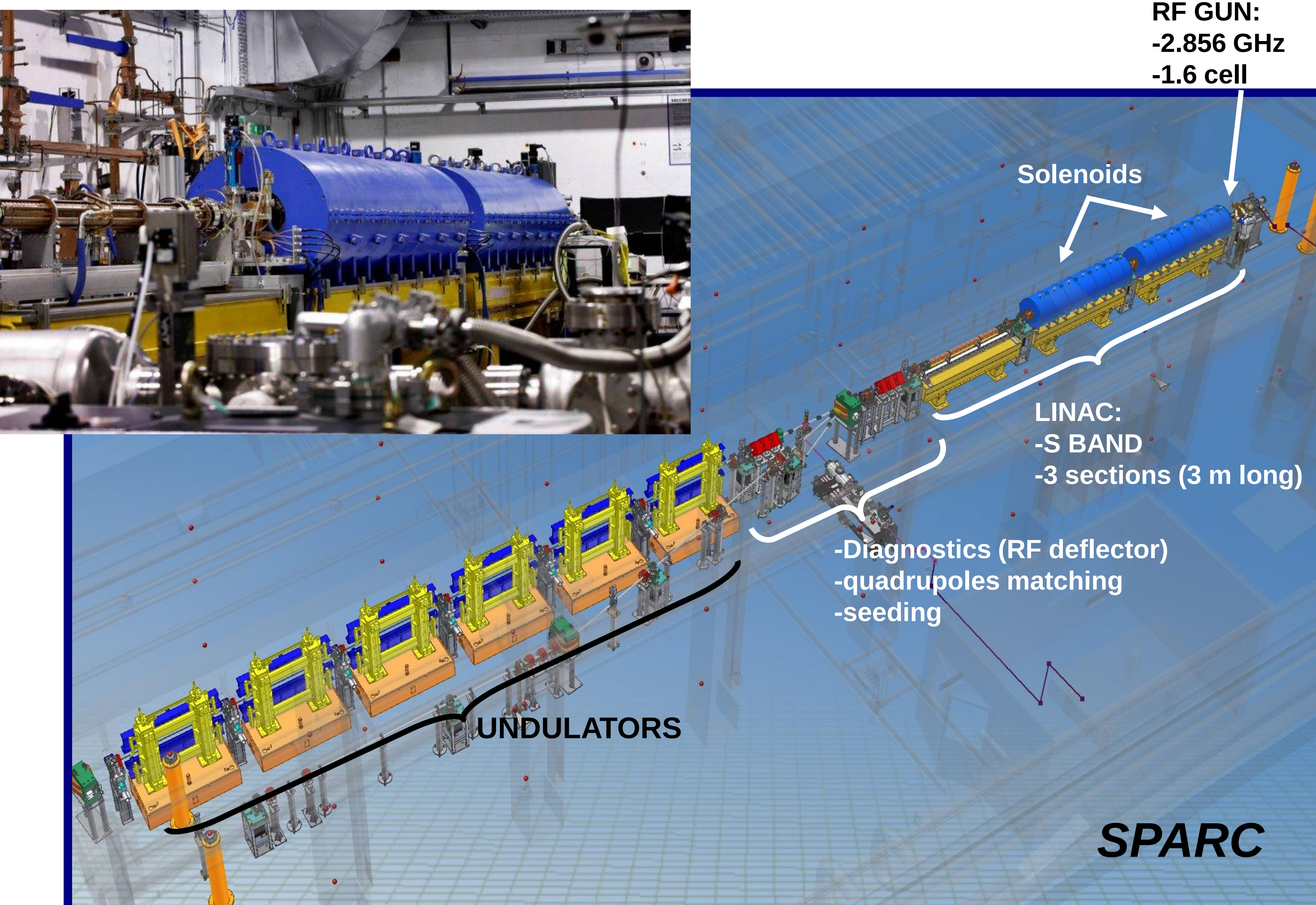


Photo-injector

Experimental beam lines for FEL,
Laser plasma acceleration, THz radiation,
Compton source,…

SPARC PHOTO-INJECTOR



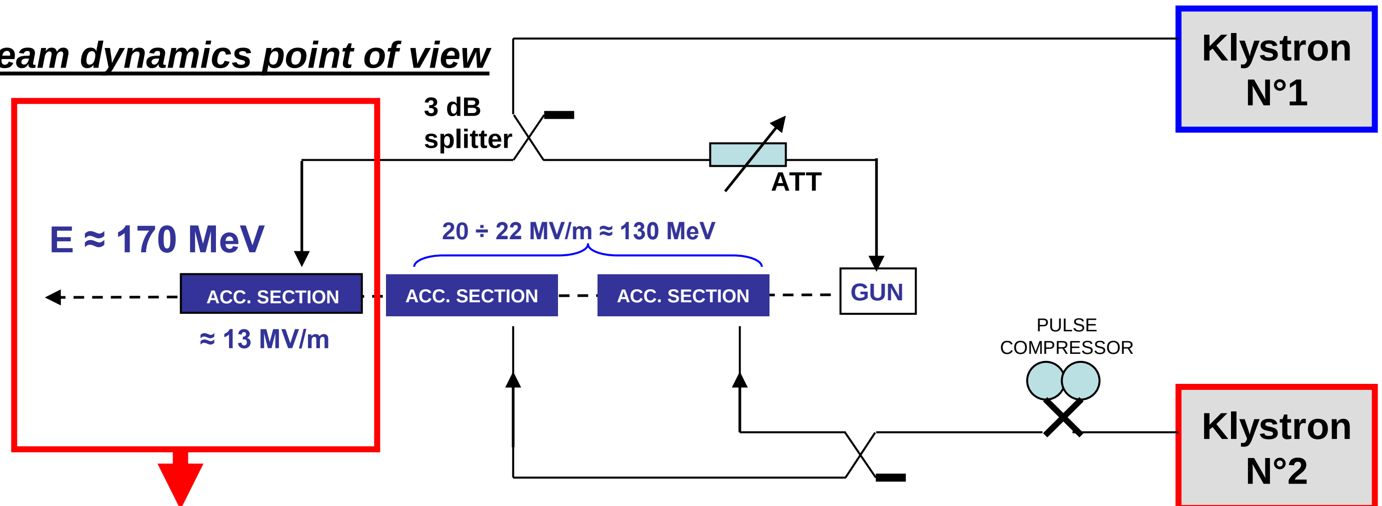
SPARC ENERGY UPGRADE WITH C BAND SYSTEM: MOTIVATION

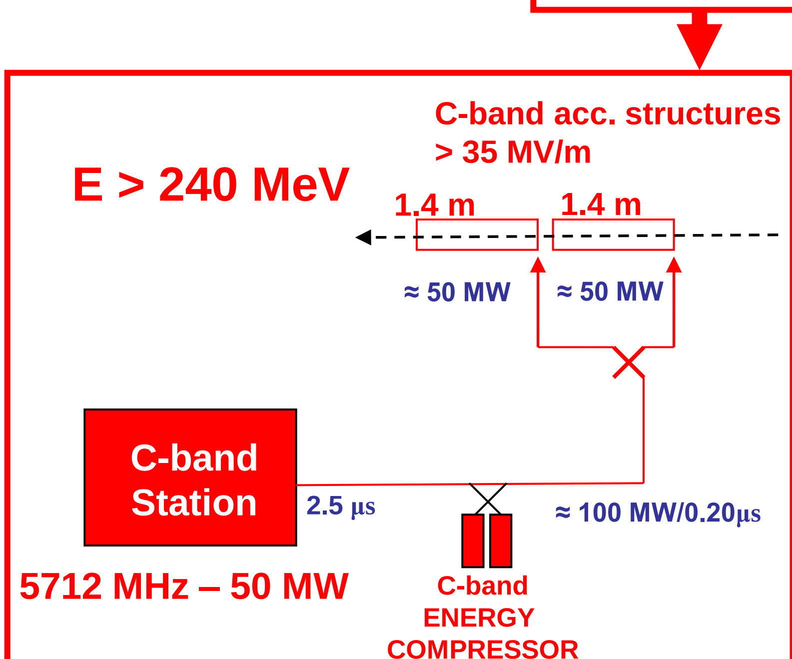
The SPARC energy will be upgraded from ≅170 to >240 MeV by replacing a low gradient S-band traveling wave section with two C-band units.

We decided to implement this system at SPARC to explore the C Band acceleration (RF components, construction at LNF TW sections, SLED, syncronization) **in hybrid scheme with S Band**:

-***<u>Higher gradients</u>***

-***<u>Very promising from the beam dynamics point of view</u>***





The new C-band system consists mainly of:

⇒ **2 accelerating sections** (1.4 m long)

⇒ 1 C-band **klystron** (50 MW), by Toshiba Ltd (JP)

⇒ 1 **Pulsed HV modulator** supplied by ScandiNova (S)

⇒ WR187 waveguide system

⇒ **400 W solid state driver** supplied by MitecTelecom (CDN)

⇒ **SLED**

DESIGN OF C BAND TW STRUCTURES FOR SPARC

(D. Alesini, et al, SPARC Note RF-11/002, 01/02/11)

Structure design (CI)

The structure has been designed in order to:

-**simplify the** fabrication (Constant Impedance)

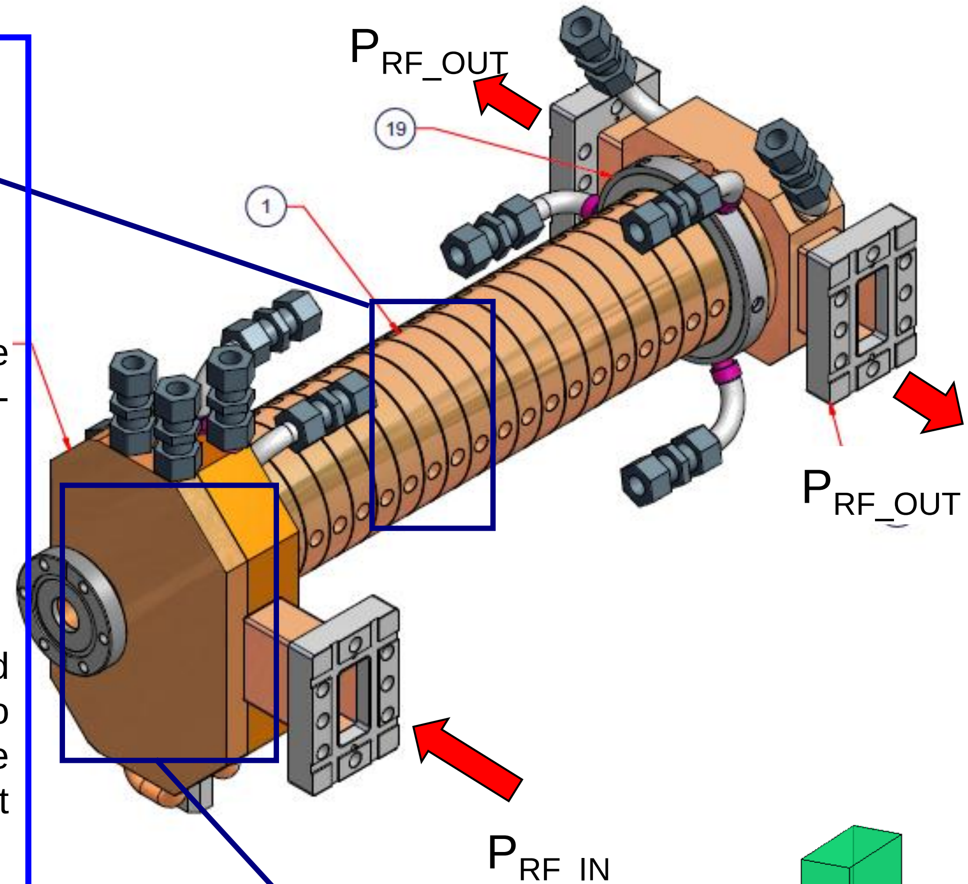
-**reduce the peak surface field** on the irises when the structure is feed by the SLED pulse (large irises-Constant Impedance)

-obtain **an average accelerating field >35 MV/m** with the available power from the klystron;

-**reduce the unbalance** between the accelerating field at the entrance and at the end of the structure, due to the combination of power dissipation along the structure and SLED pulse profile (Constant Impedance).

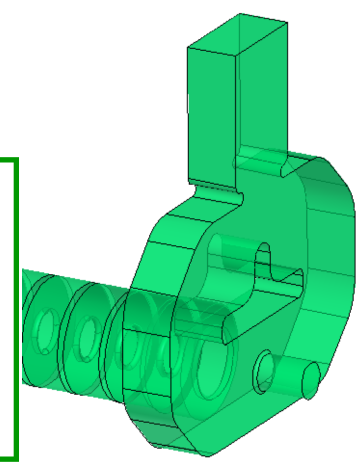
-**reduce the filling time** of the structure to input pulse length and, consequently, to reduce to the BDR (large irises)

-**increase the pumping speed** (large irises)



Coupler design

Based on the “new generation” of couplers for high gradient operation proposed at SLAC for high gradient X Band structures (waveguide couplers)



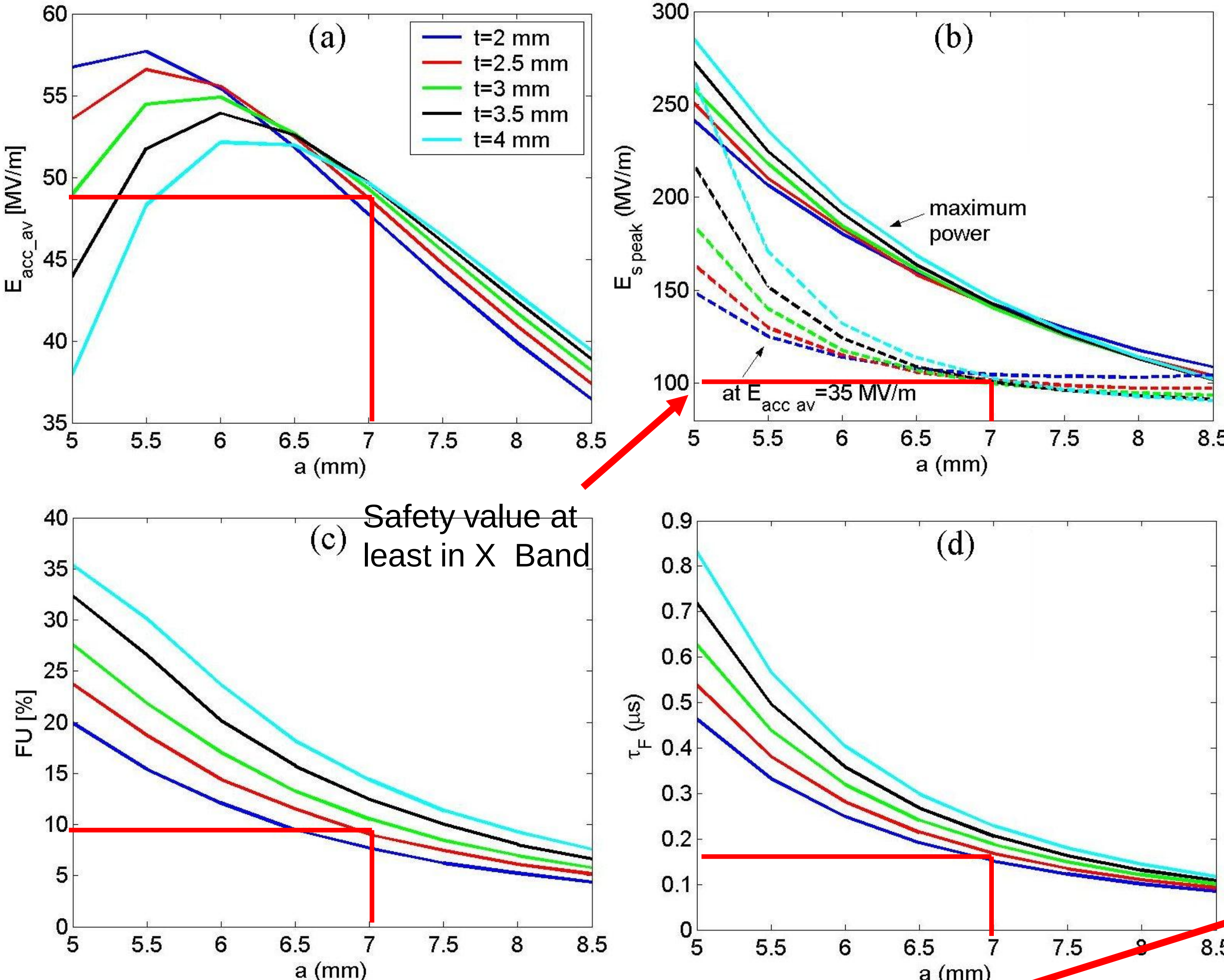
ACCELERATING STRUCTURE OPTIMIZATION

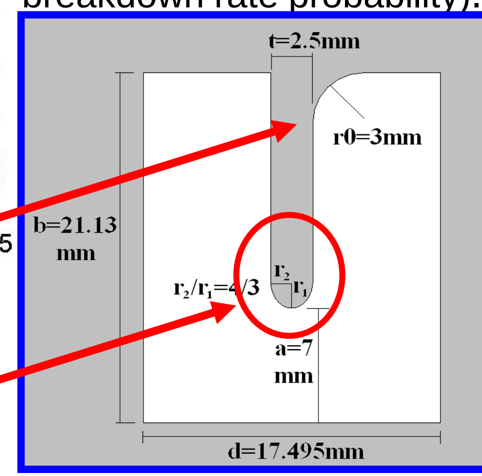
The dimensions of the single cell have been optimized to simultaneously obtain:

-**lowest peak surface** electric field on the irises with the SLED input pulse;

-**an average accelerating field of, at least, 35 MV/m** with the available power from the klystron;

-the **largest iris aperture** for better pumping, reduced wakefields contribution and reduced filling time of the structure (related to the breakdown rate probability).





Reduction of the Attenuation
Reduction of the magnetic field (pulsed heating)

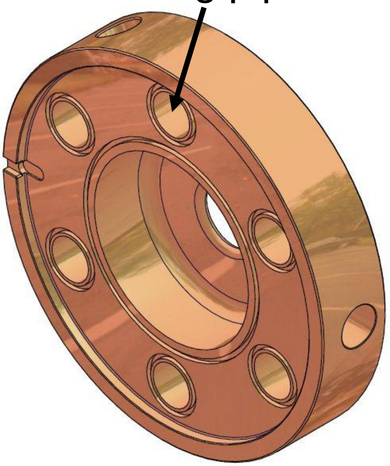
Elliptical shape

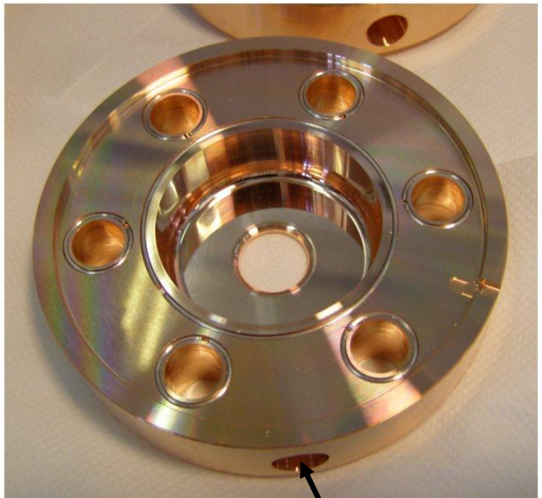
ACCELERATING STRUCTURE PARAMETERS

PARAMETER	prototype	Final structure
Frequency (f_{RF})	5.712 [GHz]	
Phase advance per cell	$2\pi/3$	
Number of accelerating cells (N)	22	71
Structure length included couplers (L)	0.54 [m]	1.4 [m]
group velocity (v_g/c):	0.0283	
Field attenuation (α)	0.206 [1/m]	
series impedance (Z)	34.1 [$M\Omega/m^2$]	
Filling time	50 [ns]	150 [ns]
Power flow @ E_{acc}=35 MV/m	36 [MW]	
$E_{s\ peak}/E_{acc}$	2.17	
$H_{s\ peak}$ @ E_{acc}=35 MV/m	87.2 [kA/m]	
Pulsed heating @ E_{acc}=35 MV/m	<1 ^{o}C	
Average Accelerating field with SLED input pulse and after one filling time	60.2 [MV/m]	51.6 [MV/m]
Peak surface field with SLED input pulse at the beginning of the pulse (max and @35 MV/m)	140 (96) [MV/m]	
Energy gain (max and @ 35 MV/m)	23.2 [MeV]	64.1 (42) [MeV]
Output power	$0.85{\cdot}P_{in}$	$0.60{\cdot}P_{in}$
Average dissipated power @ 10 Hz with SLED pulse length equal to one filling time	7.6 [W]	59.6 [W]

REALIZATION OF THE PROTOTYPE (@LNF+Local firm (COMEB))

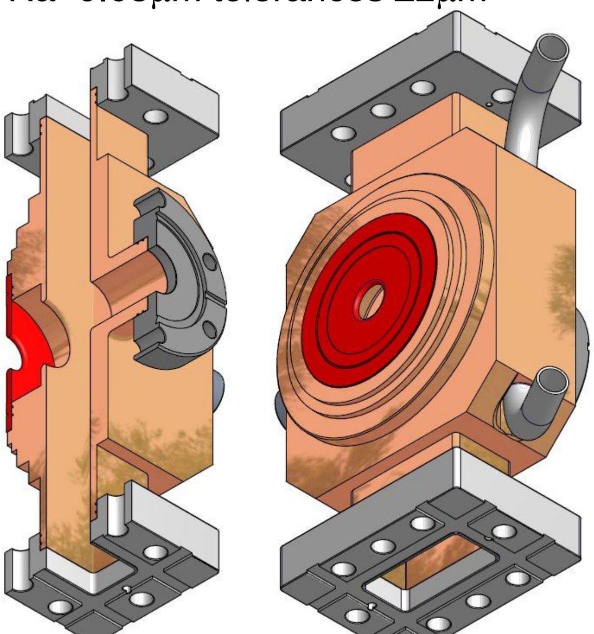
Cooling pipes

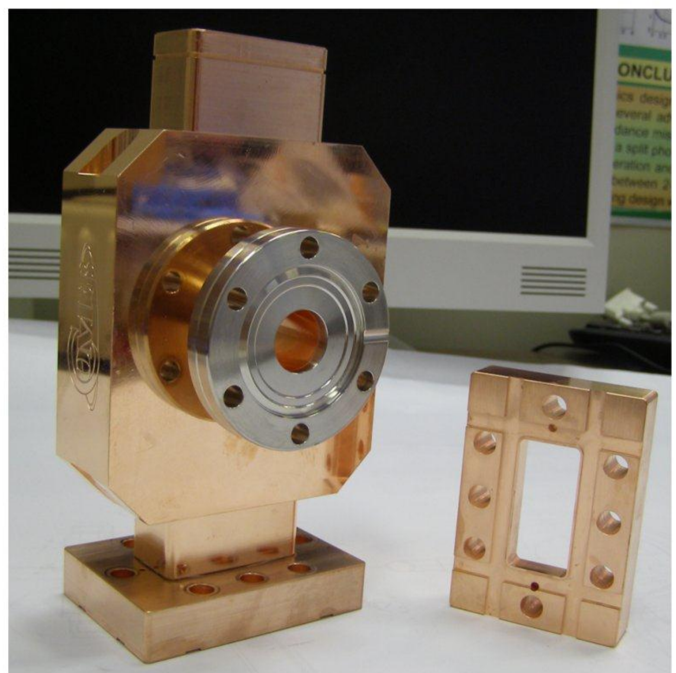




Cells
Turning machine
Cell Ra<0.05μm tolerances ±2μm

Tuning by deformation

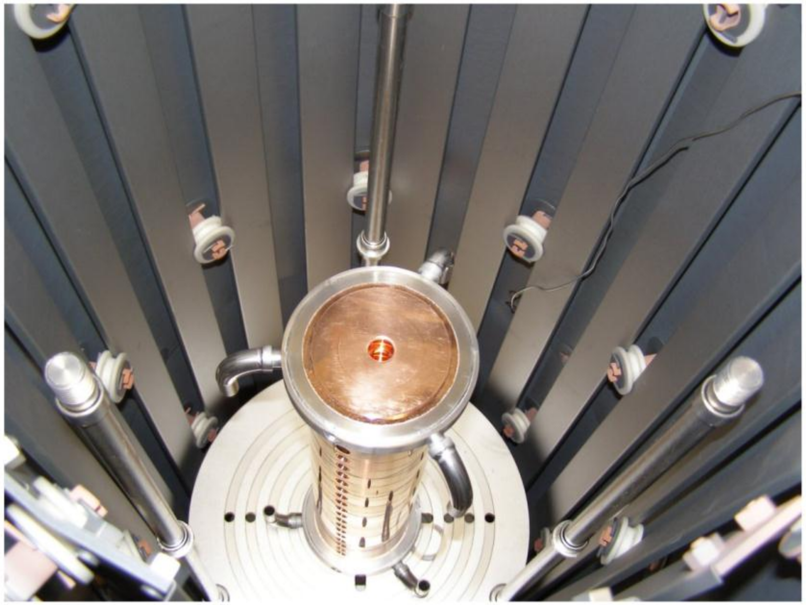


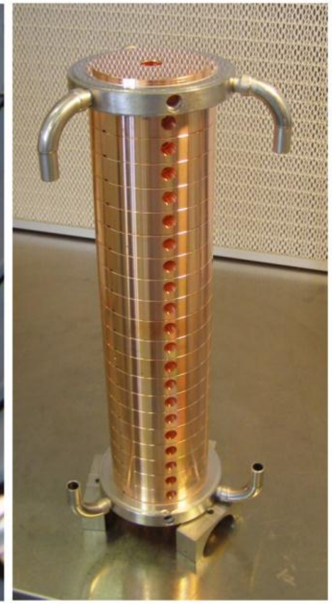


Input coupler
cumputer controlled
milling machine
Ra<0.2μm tolerances ±20μm

Output coupler:
Electro discharge machining
Ra<1μm tolerances ±20μm

REALIZATION OF THE PROTOTYPE (@LNF+Local firm (COMEB))





The structure has been brazed @ LNF in several steps:

-*Cells*

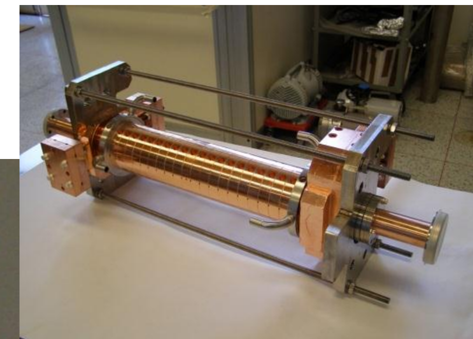
-*Couplers*

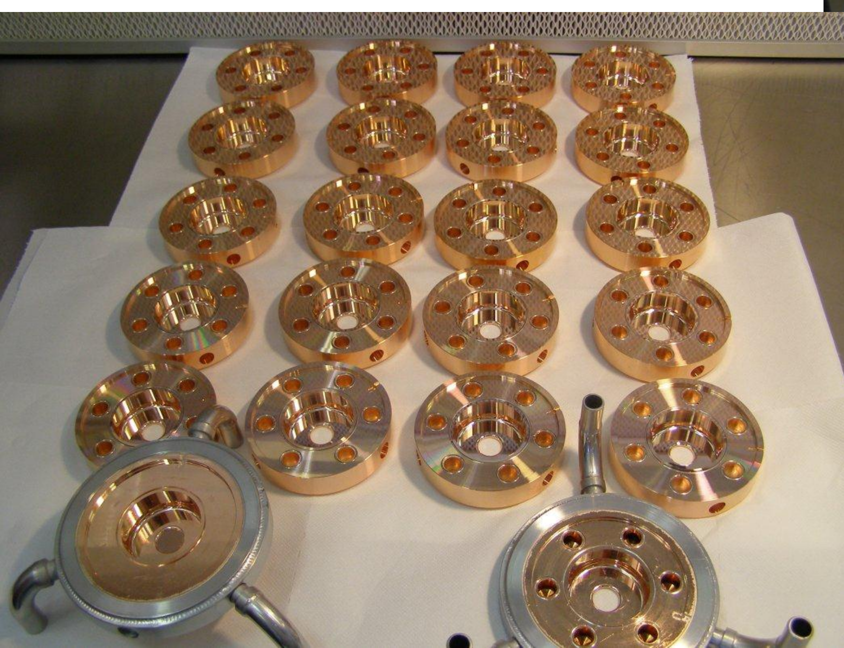
-*Final brazing*

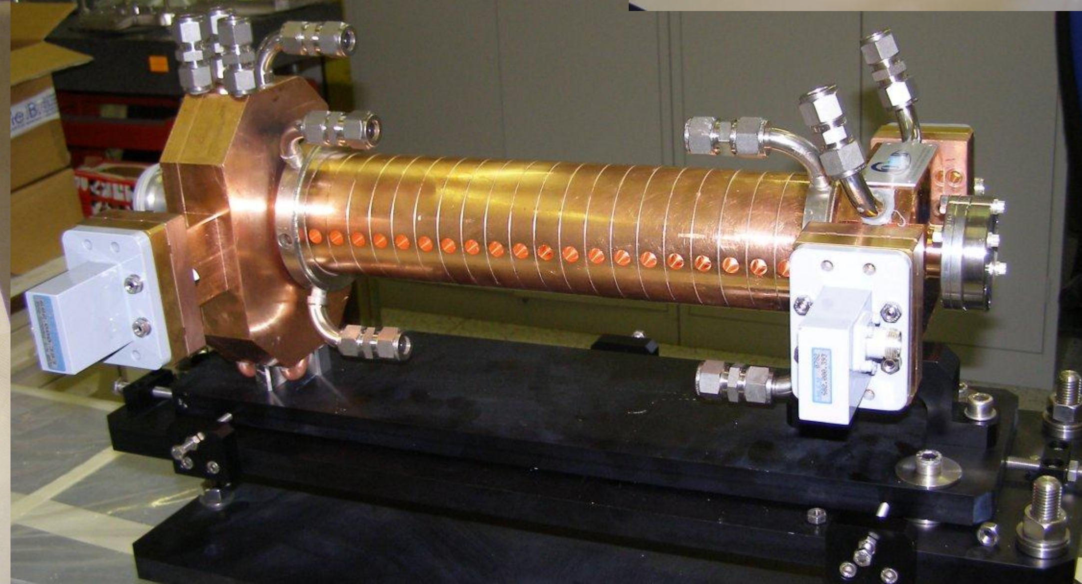
Intermediate RF measurements have been done during realization

Main problem during the realization:

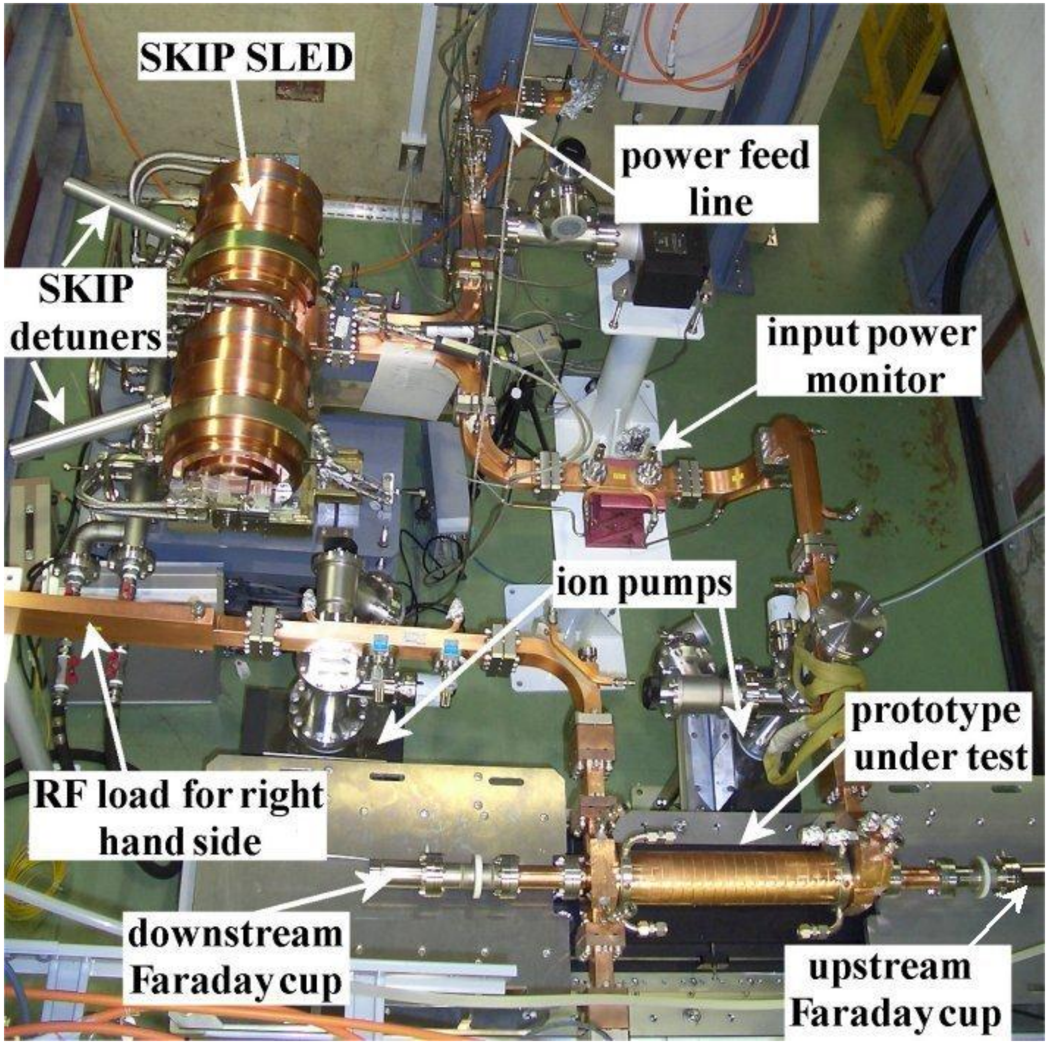
-alignment of coupler and cells in the final brazing process





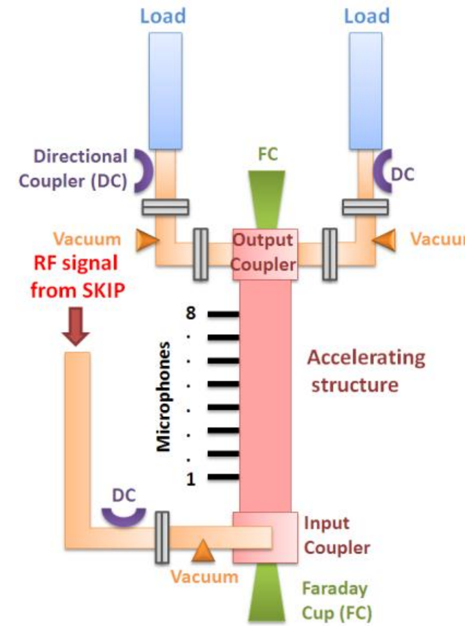


TEST AT HIGH POWER (KEK) OF THE PROTOTYPE: THE SETUP

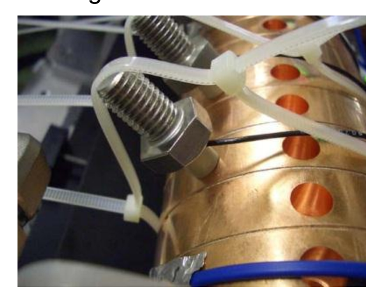


The input power was monitored by the **directional coupler** located between SKIP and the accelerator structure.
The transmitted power was monitored in front of each RF load.

The currents emitted from the accelerator structure were monitored in both directions. Pipes with an inner diameter of 40 mm were connected from the beam ports of the accelerator structure with ceramic insulation in front of the **Faraday cups**.

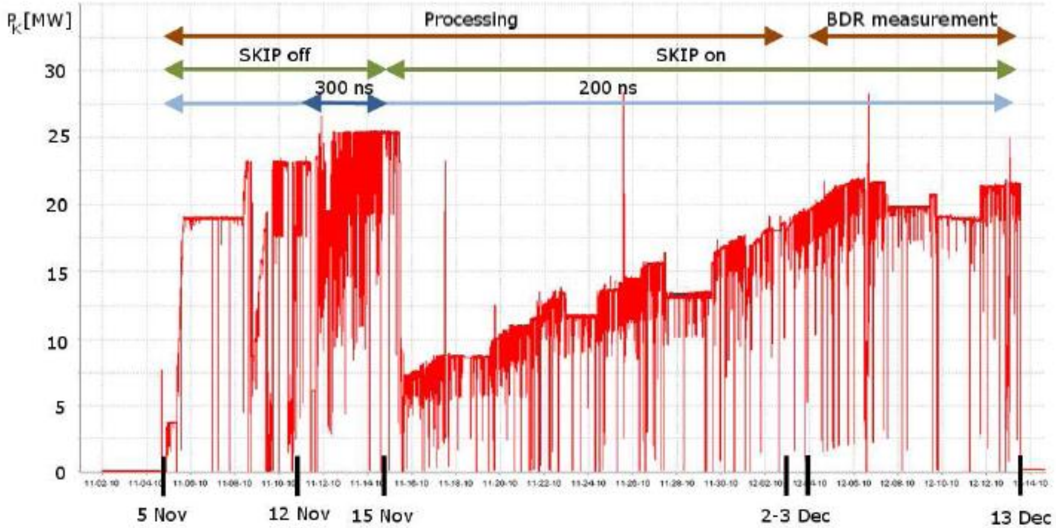


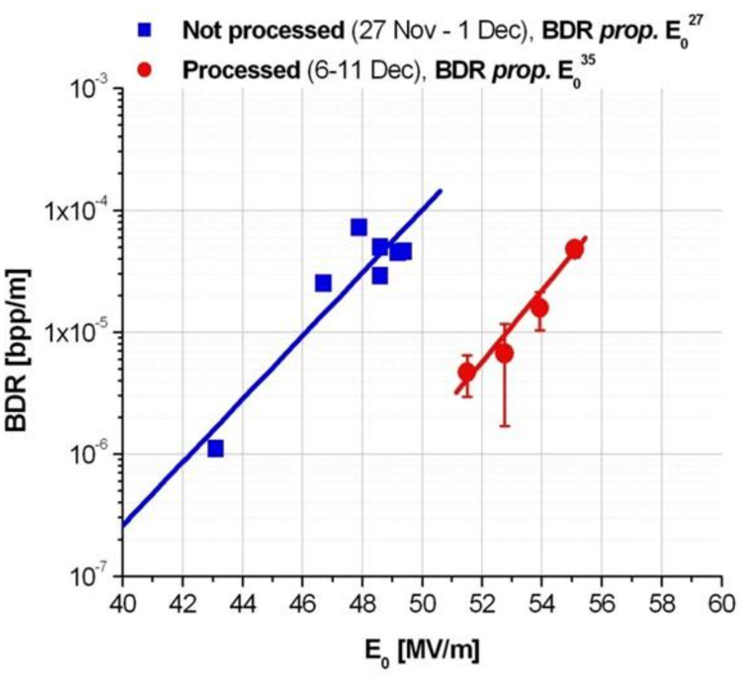
Acoustic sensors were mounted on the test structure and various parts of the waveguide. These were pressed against the surfaces by using fasteners.



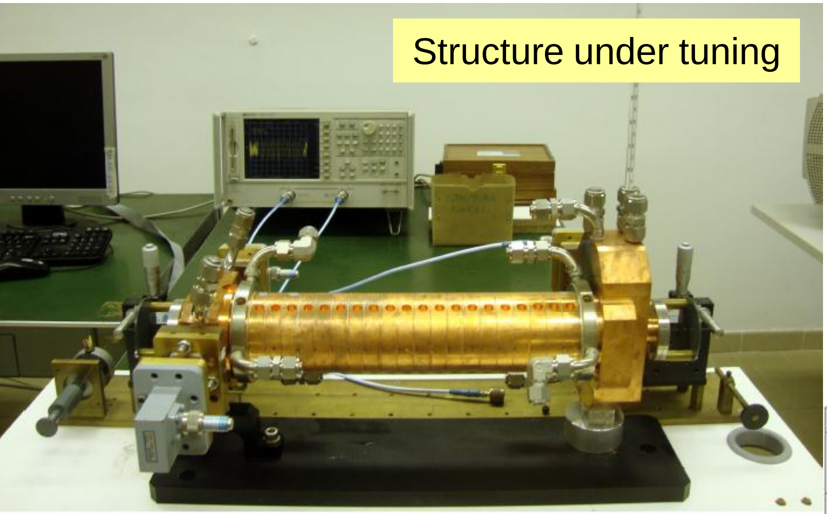
HIGH POWER TEST: PROCESSING HISTORY

The high-power test started on November 5 and was completed on December 13, 2010. For almost one month of processing, from November 5 until December 2, more than **10^8 RF pulses of 200 ns** width were sent into the structure with a repetition rate of **50 Hz**. For a couple of days the RF pulse length was changed to 300 ns and for one day (November 12) the repetition rate was decreased to 25 Hz. On November 15, SKIP was switched on.

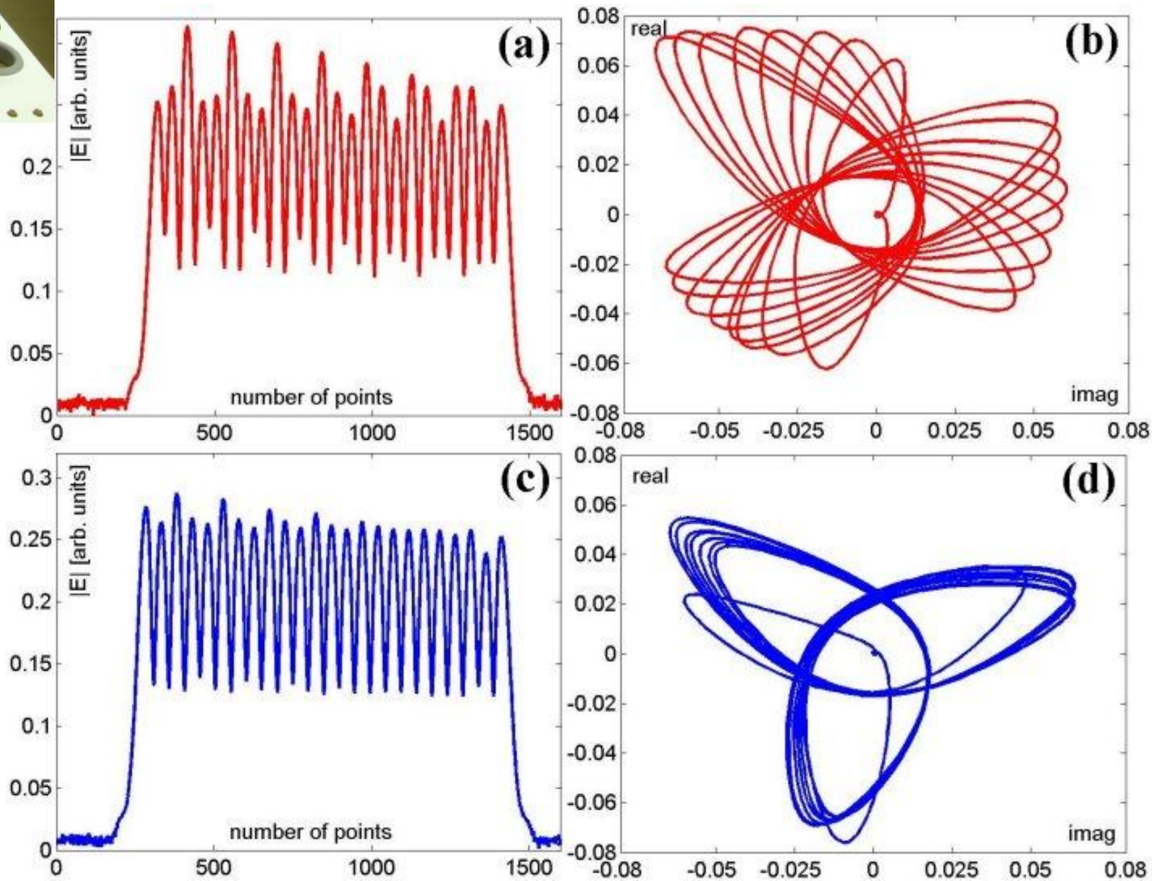




TUNING OF THE PROTOTYPE (IN COLL. WITH UNIV. LA SAPIENZA)



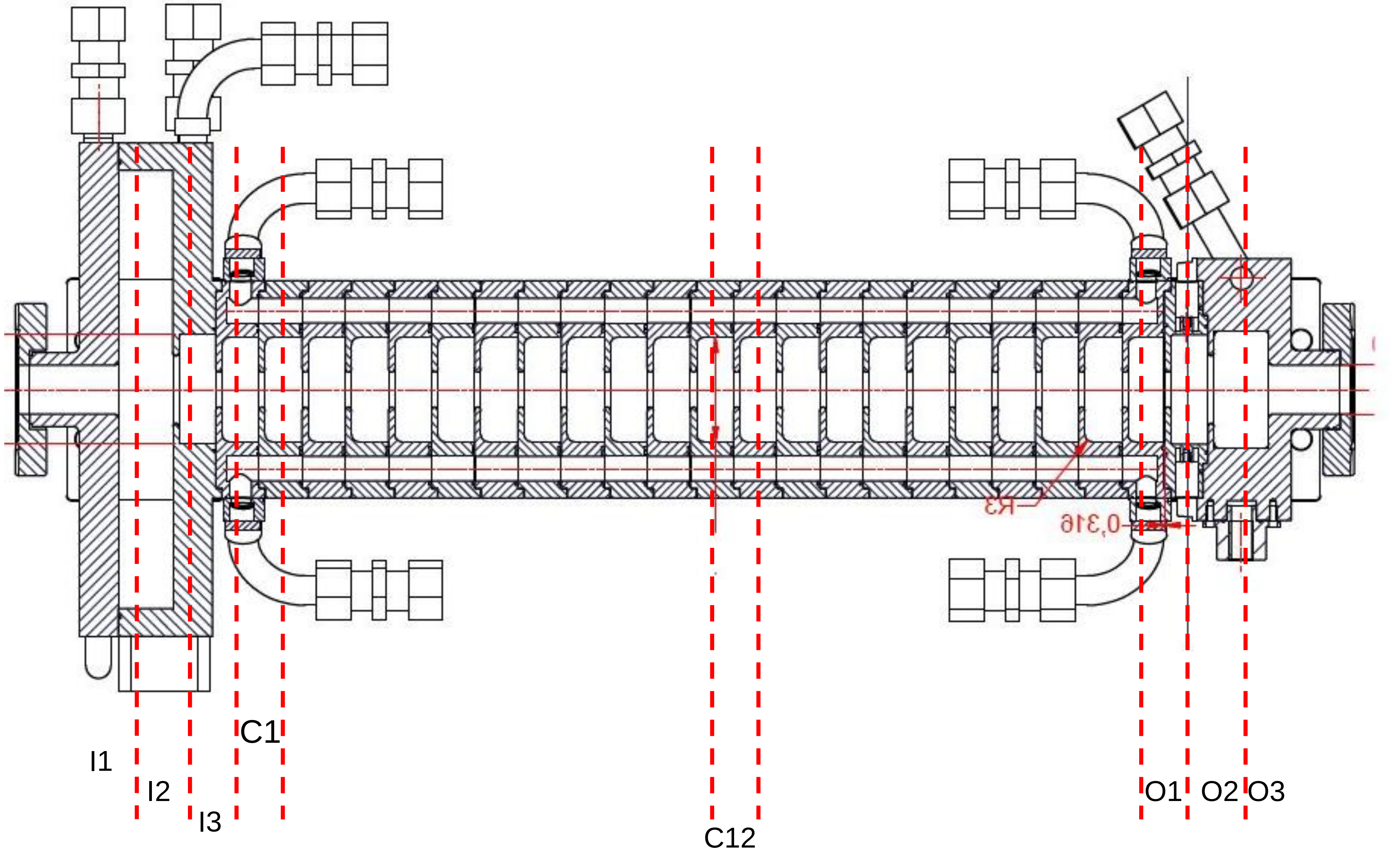
Tuning results



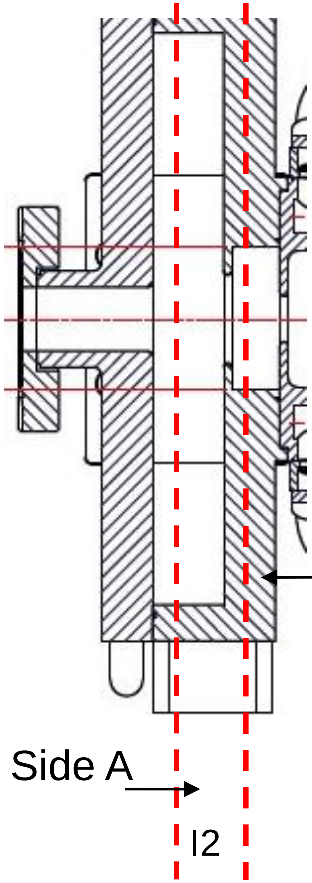
The technique we used has been derived from a well know technique (J. Shi, et al., proc. of LINAC 08, 2008). Only imaginary parts of the local reflection coefficient can be compensated. A residual real part (irises?) cannot be compensated.

A strong detuning of the coupler has been found.

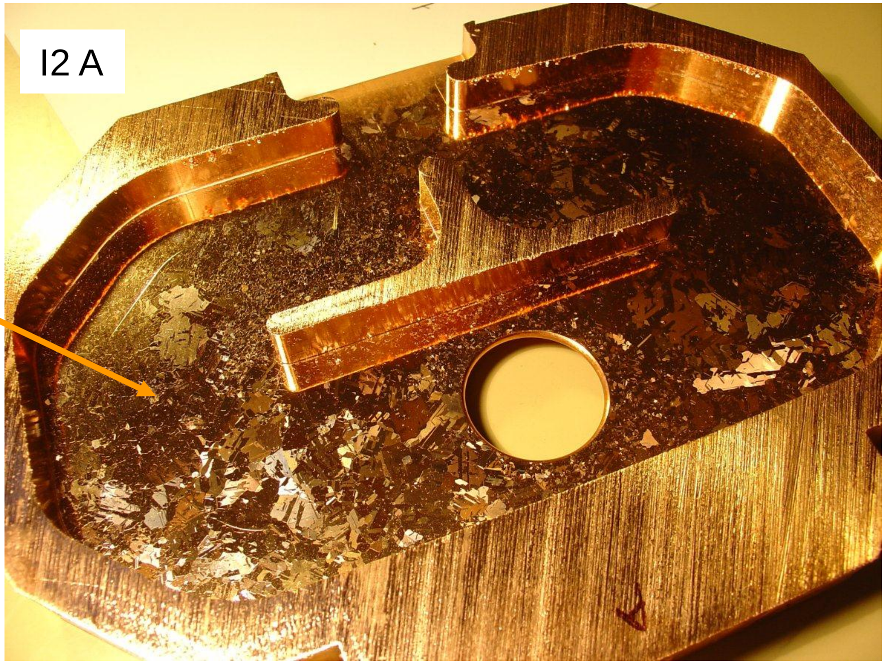
PROTOTYPE INTERNAL INSPECTION



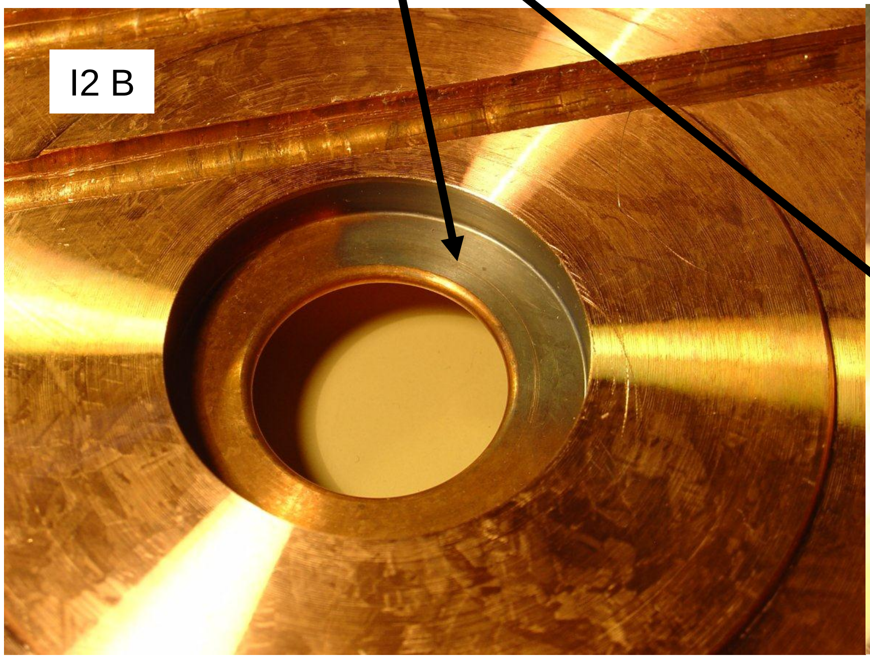
INPUT COUPLER INSPECTION

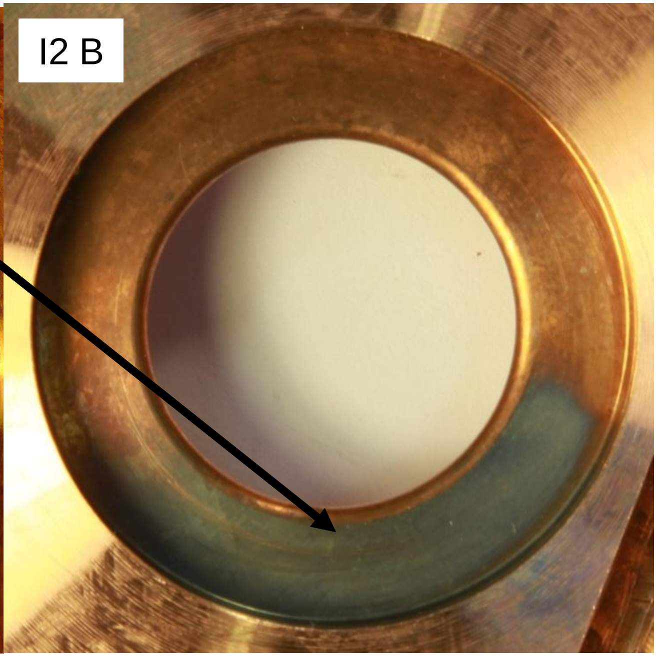


Reflective, macro-crystals, Clean, not signs of discharges or damages



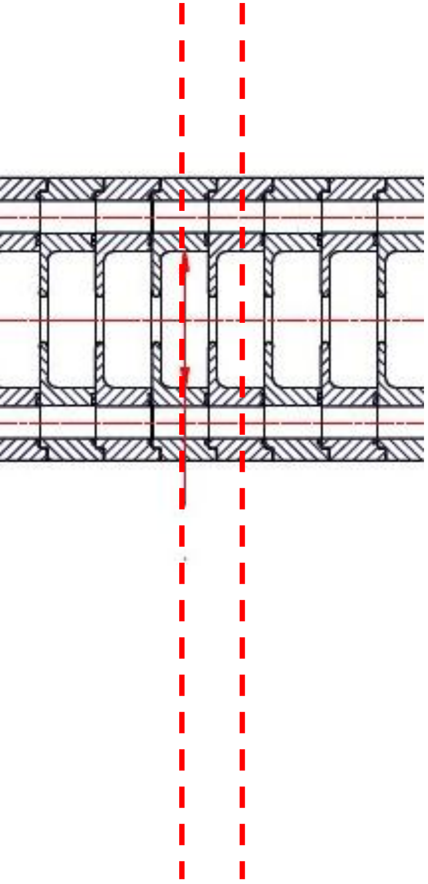
Opaque, not reflective, presence of oxidation, Colored part, what happened? Contamination? (SEM micro-analysis in progress…)

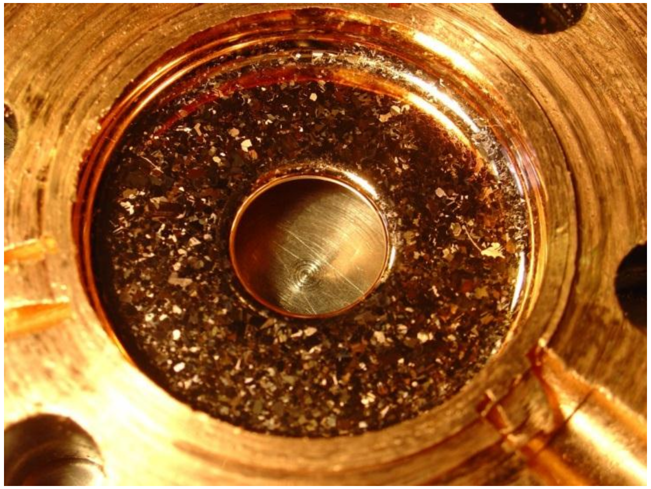


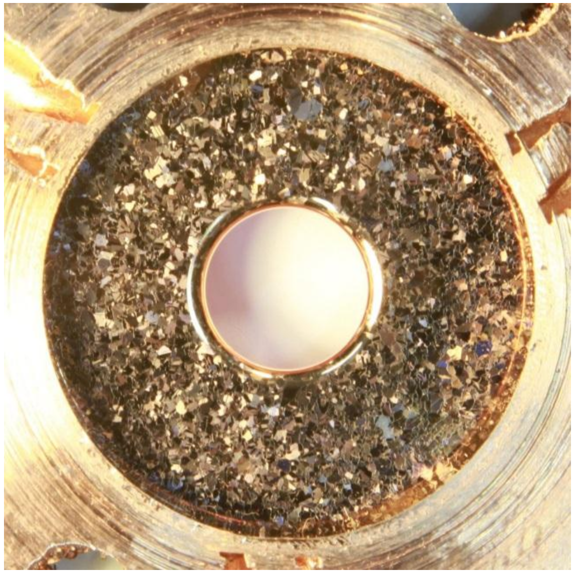


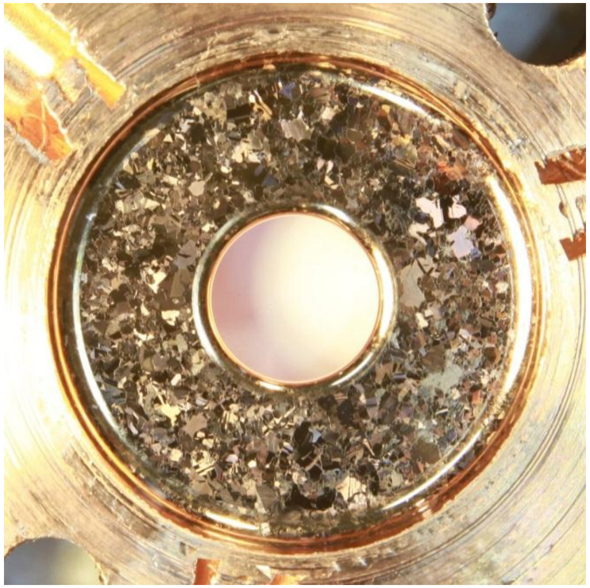
CENTRAL CELLS

-For all cells no visible pits or signs of discharges
-Presence of macro-crystals
-The cells are perfectly reflective, no oxidation

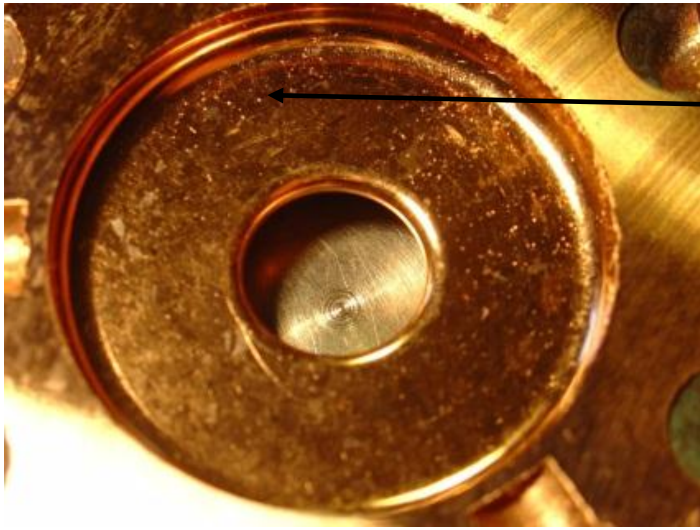


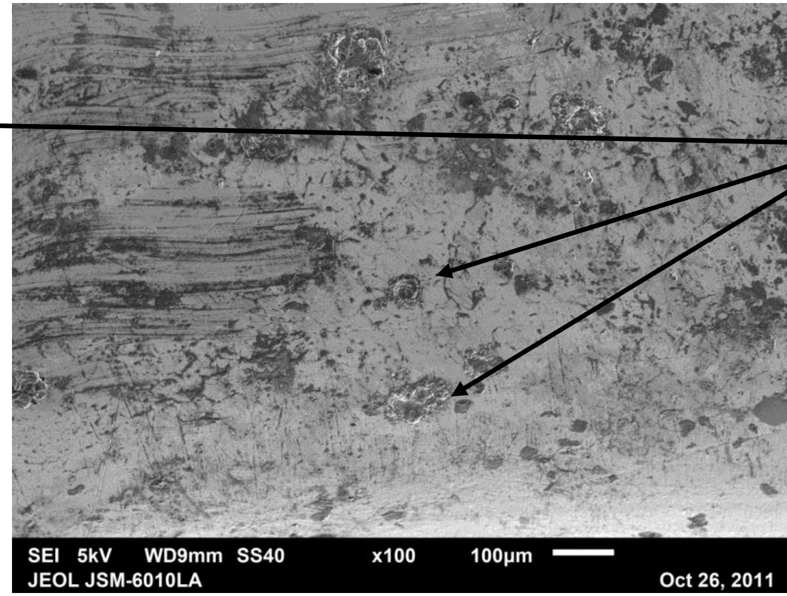




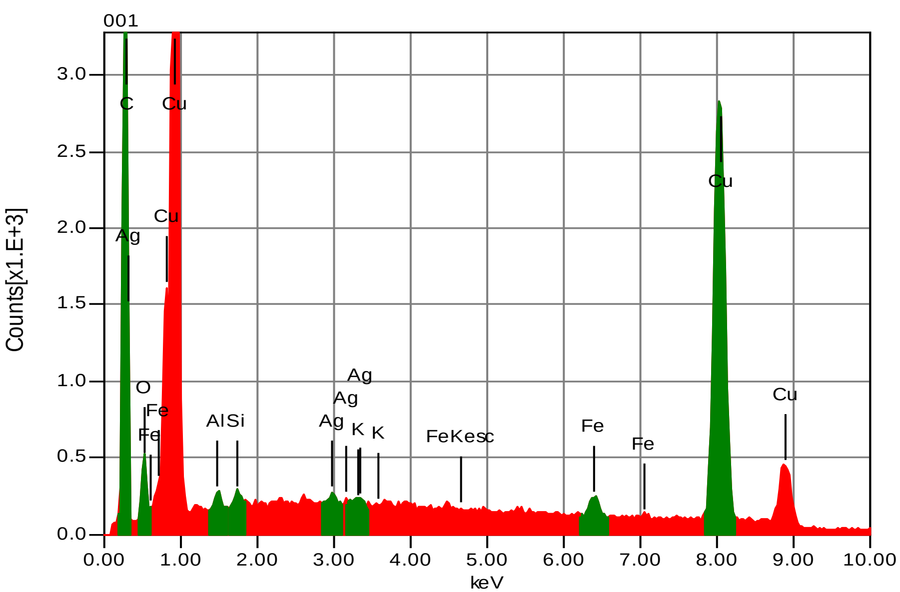


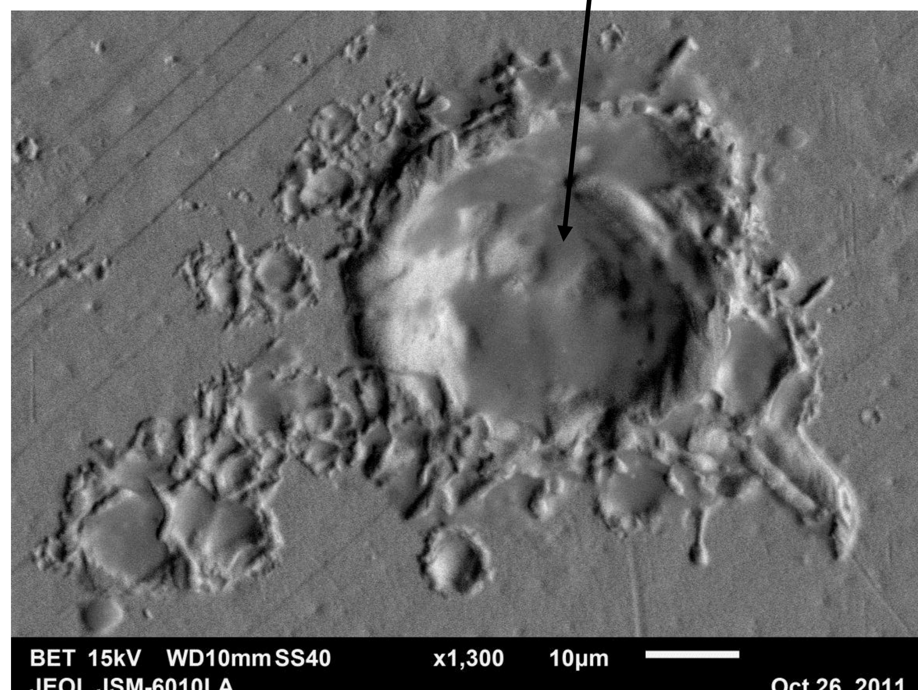
SEM IMAGES OF PITS IN 1st ACCELERATING CELL



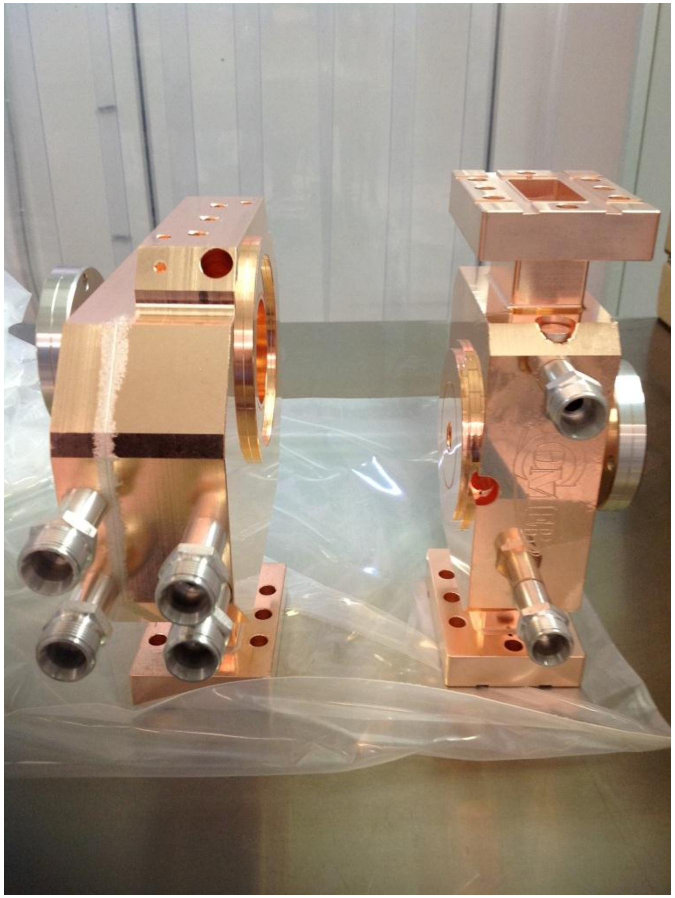


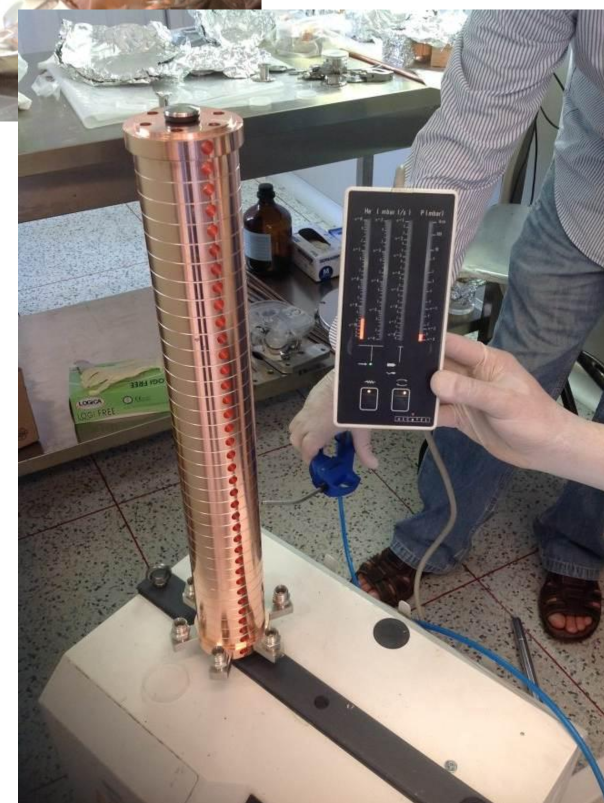
S. Bini, V. Lollo





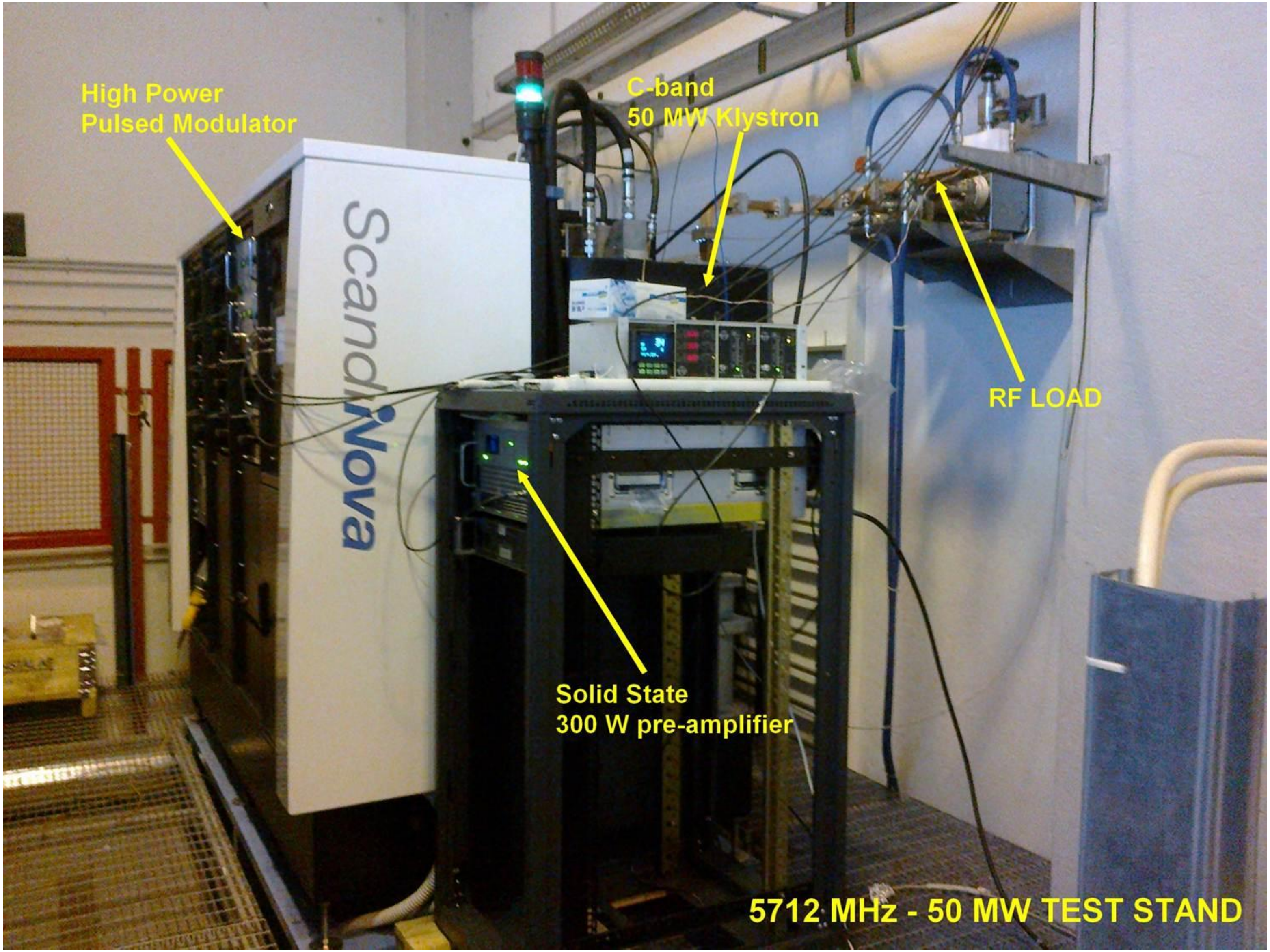
STATUS OF FINAL C-BAND ACCELERATING STRUCTURES





See M. Biagini presentation

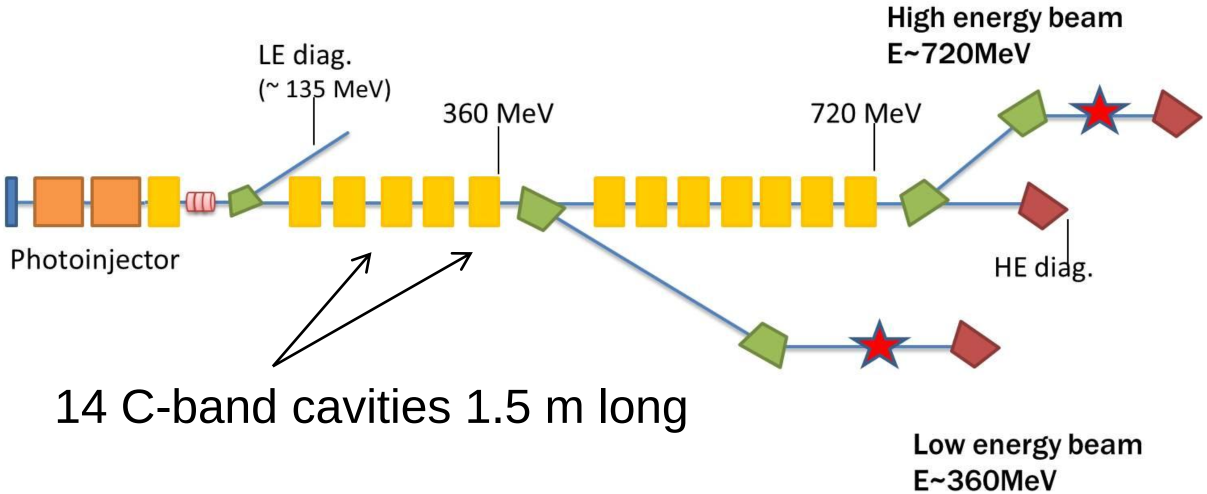
C-BAND POWER SOURCE AT LNF



C-BAND STRUCTURES FOR MULTI-BUNCH RF LINACS: ELI_NP PROPOSAL

In the **context of the ELI-NP Research Infrastructure**, to be built at Magurele (Bucharest, Romania), an advanced Source of Gamma-ray photons is planned, capable to produce beams of mono-chromatic and high spectral density gamma photons. The **Gamma Beam System is based on a Compton back-scattering** source. Its main specifications are: photon energy tunable in the range 1-20 MeV, rms bandwidth smaller than 0.3% and spectral density lager than 10^4 photons/sec.eV, with source spot sizes smaller than 100 microns and linear polarization of the gamma-ray beam larger than 95%.

European Collaboration for the proposal of a Gamma-Beam System to the ELI-NP Project



Bunch charge	250 pC
Number of bunches	25
Bunch distance	15 ns
C-band average accelerating gradient	35 MV/m
RF rep Rate	100

MULTI-BUNCH EFFECT ANALISYS

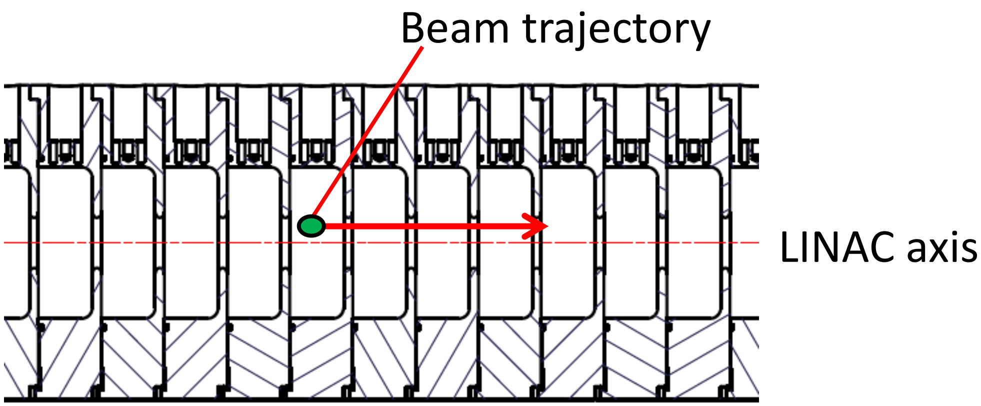
TRANSVERSE EFFECTS

1. Cumulative beam break-up in LINACS: general considerations
2. Cumulative beam break-up in the ELI-NP C-Band LINAC
3. C-Band Damped structures

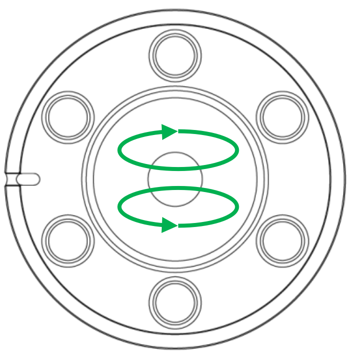
LONGITUDINAL EFFECTS

1. Multi-bunch effects in energy modulation along the train: Beam loading and its compensation

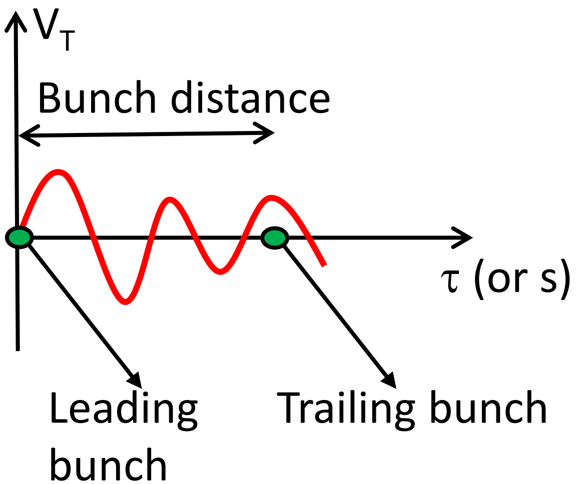
BEAM BREAKUP IN LINACS: GENERAL DESCRIPTION



Any beam offset or structure misalignment can **excite transverse long range wakefield** which will then cause **subsequent bunches to be deflected**. The dipole mode TM_{11}-like gives, generally the dominant effect in LINACS.



B field of the TM_{11}-like mode



Off-axis beam trajectories arise due to a variety of errors:

-***Offset at injection***

-***Misalignment of focusing magnets***

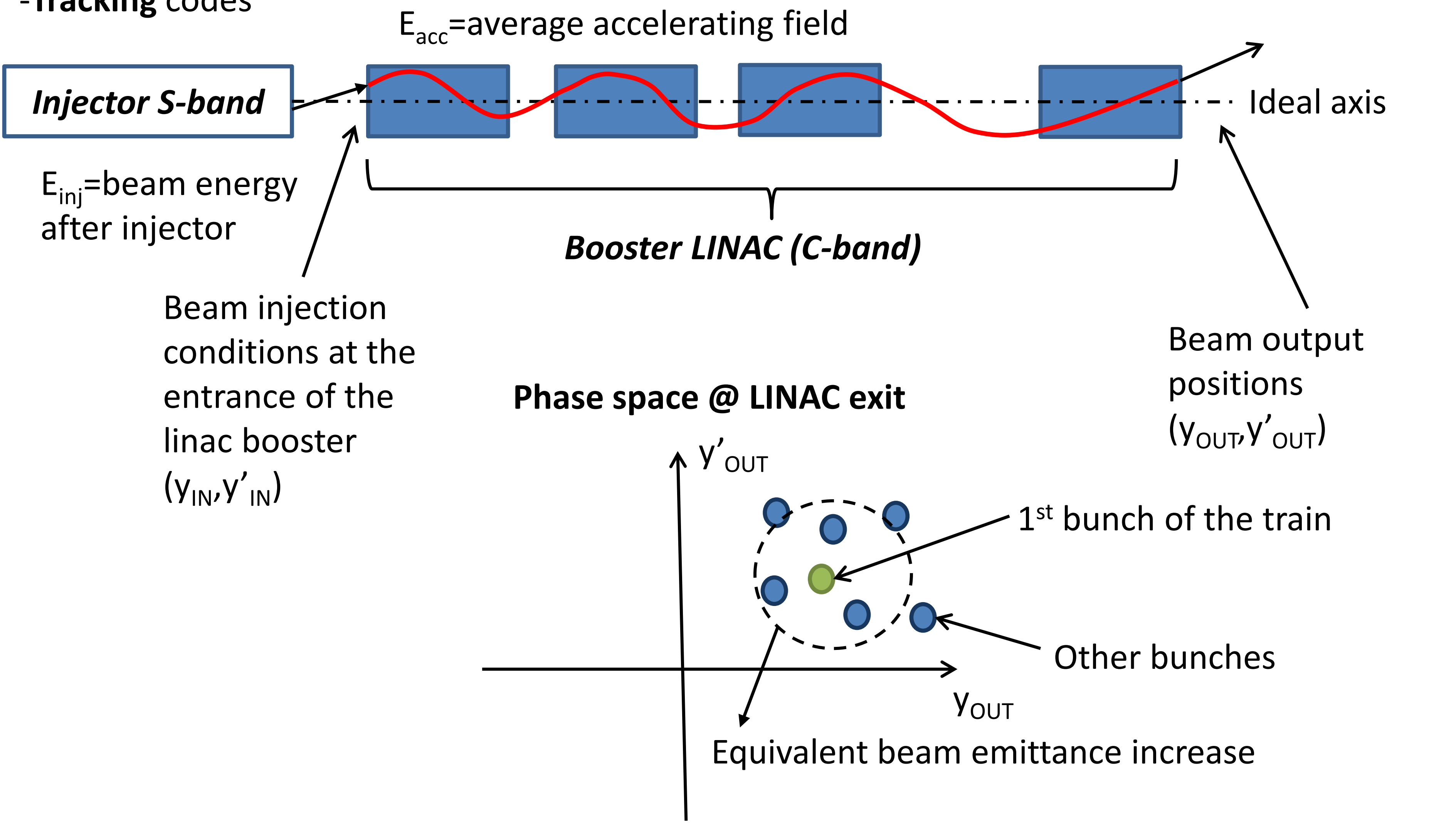
-***Misalignment of accelerating sections***

$$v_y(\tau) = \frac{V_y(\tau)}{L} \cong q\Delta y \underbrace{w_T e^{-\frac{\omega_{res}}{2Q}\tau} \sin(\omega_{res}\tau)}_{w_T(\tau)\ \left[V/(Cm^2)\right]} \quad [V/m]$$

Beam breakup analysis: tracking code

-**Analytical** approaches can be used to evaluate the beam breakup effects (for example Mosnier theory).

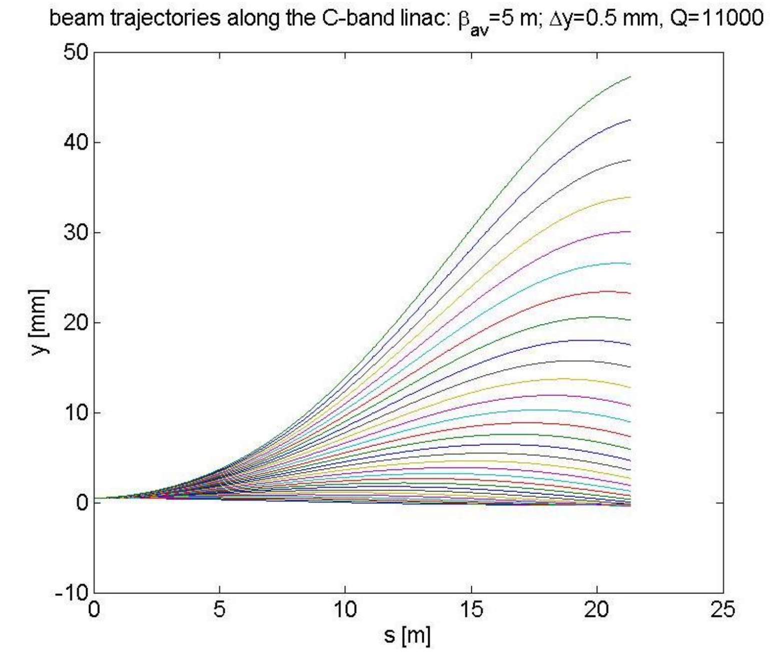
-**Tracking** codes

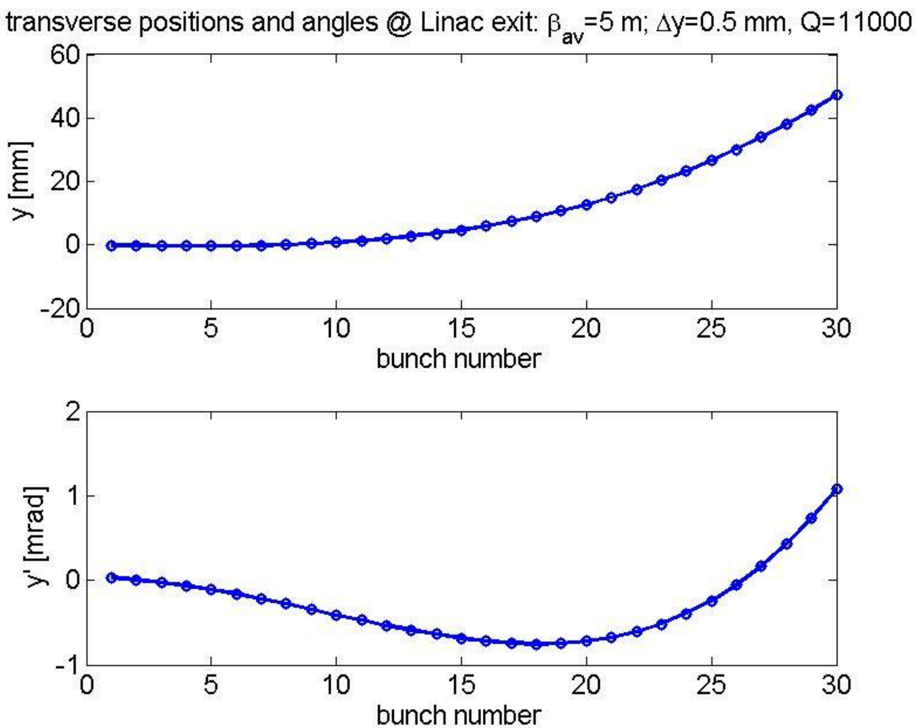


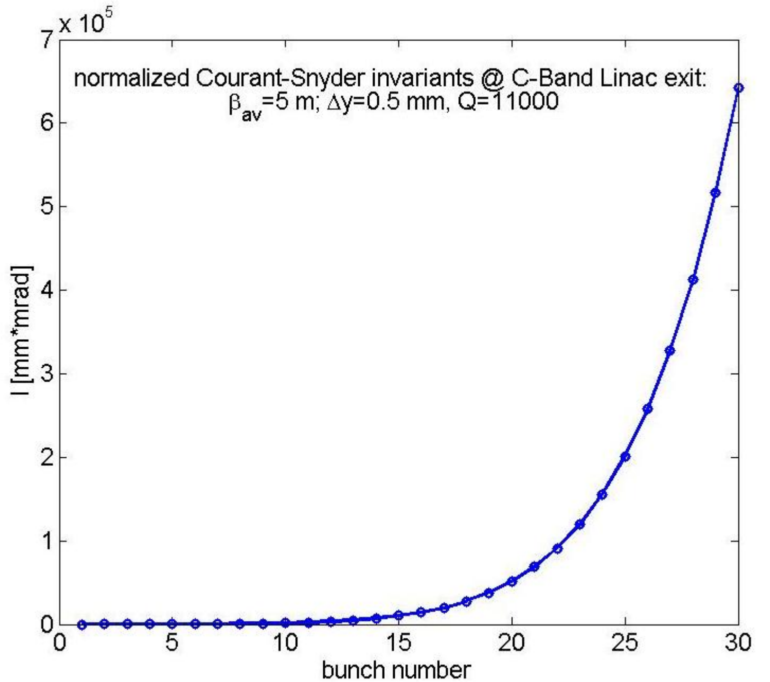
Tracking results

Hypothesis:

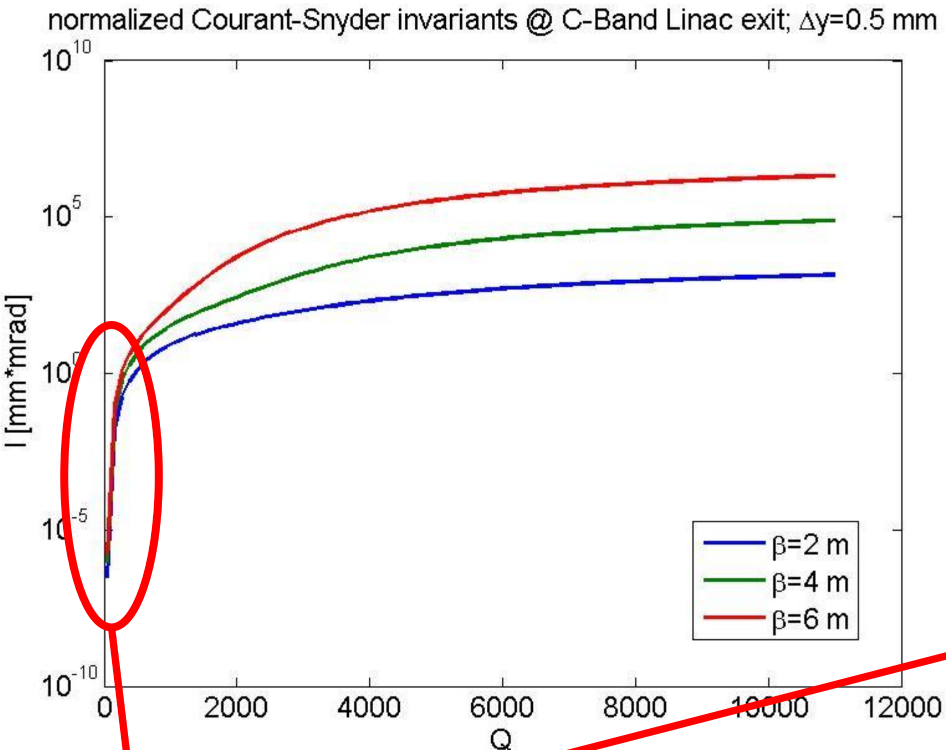
1. **Initial condition** at linac injection equal for all bunches
2. **Constant β-function**
3. **Perfect build-up** mechanism of all transverse wakes that decays with the quality factor of the mode
4. One **single mode** trapped in each cell
5. Maximum transverse kick sampled by each bunch

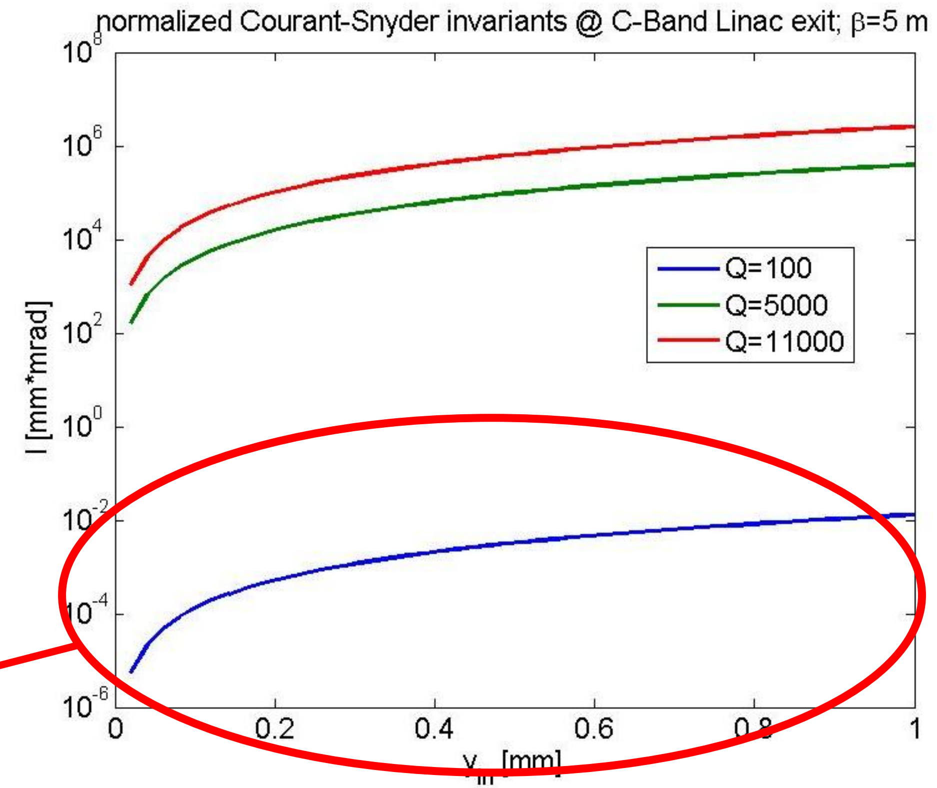


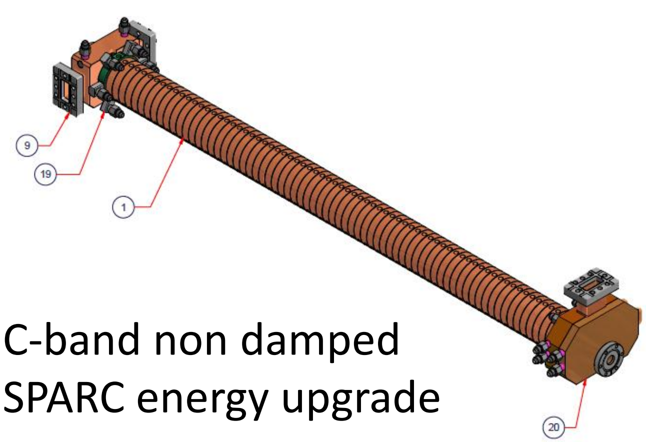




Mitigation of multi-bunch effect with damped structures



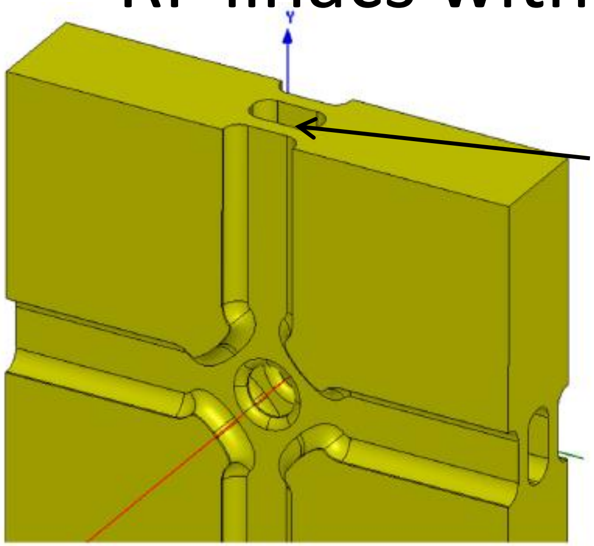




C-band non damped
SPARC energy upgrade

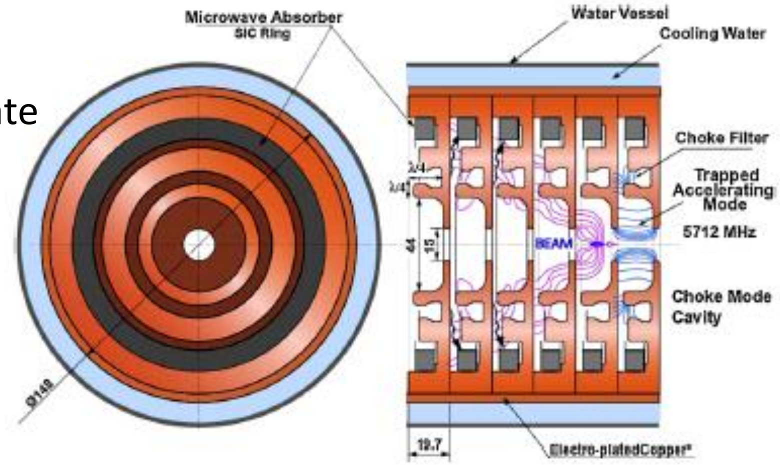
DAMPED STRUCTURES

RF linacs with damping of dipole modes



Dipoles modes propagate in the waveguide and dissipate into a load

CLIC structures X-band, high gradient



C-Band structures Spring-8

Advantages

1. Strong damping of all modes above waveguide cut-off
2. Possibility of tuning the cells
3. Good cooling possibility

Disadvantages

1. Machining: need a 3D milling machine
2. Multipole field components (octupole) but not critical at least for CLIC

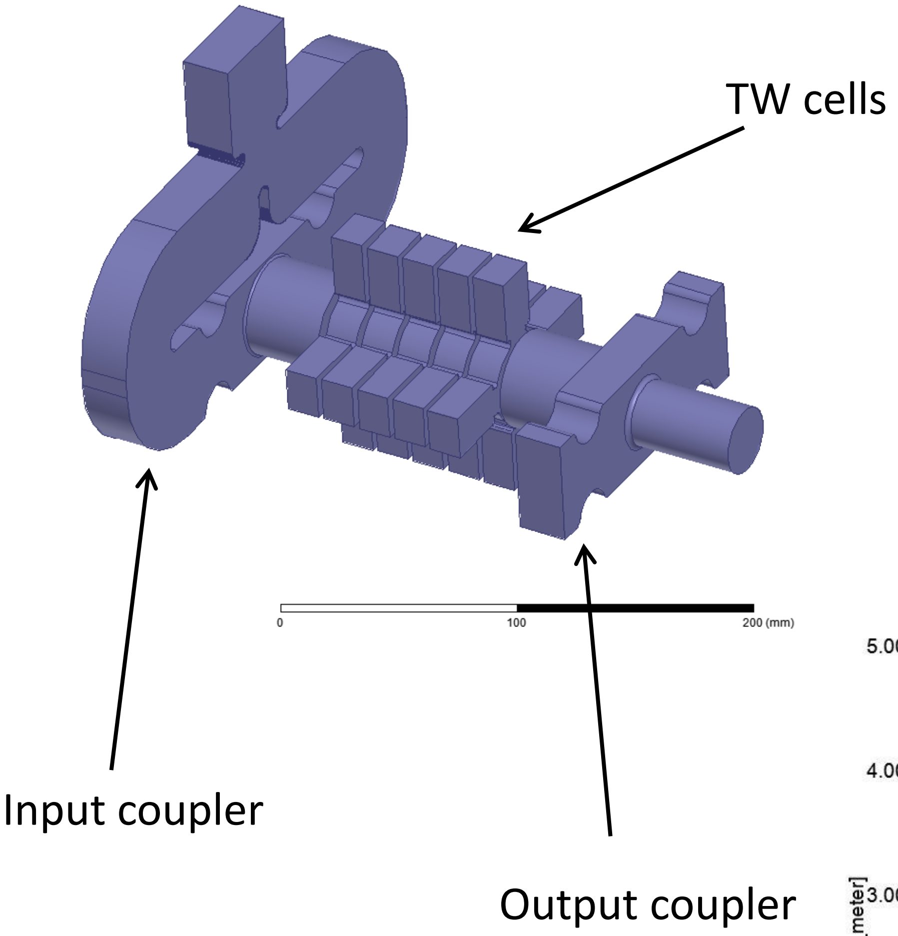
Advantages

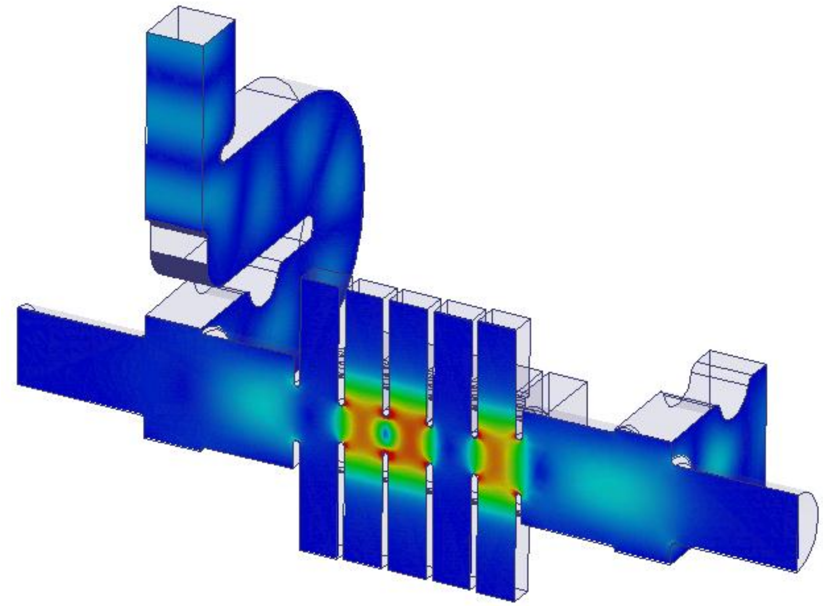
1. Easy machining of cells (turning)
2. 2D geometry: no multipole field components

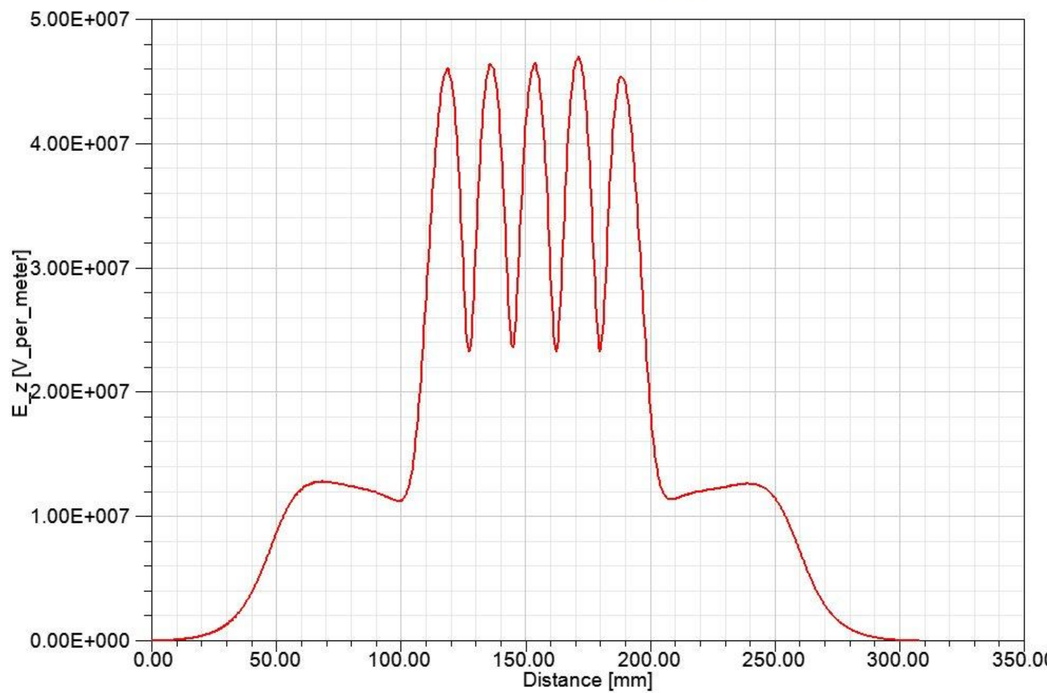
Disadvantages

1. Critical e.m. design: notch filter can reflect also other modes.
2. Not possible to tune the structure
4. Cooling at 100 Hz, long pulse length (?)

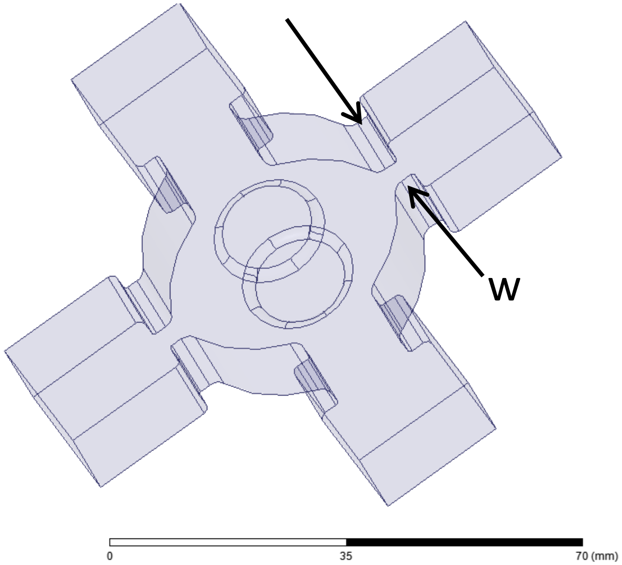
ELI Damped structure

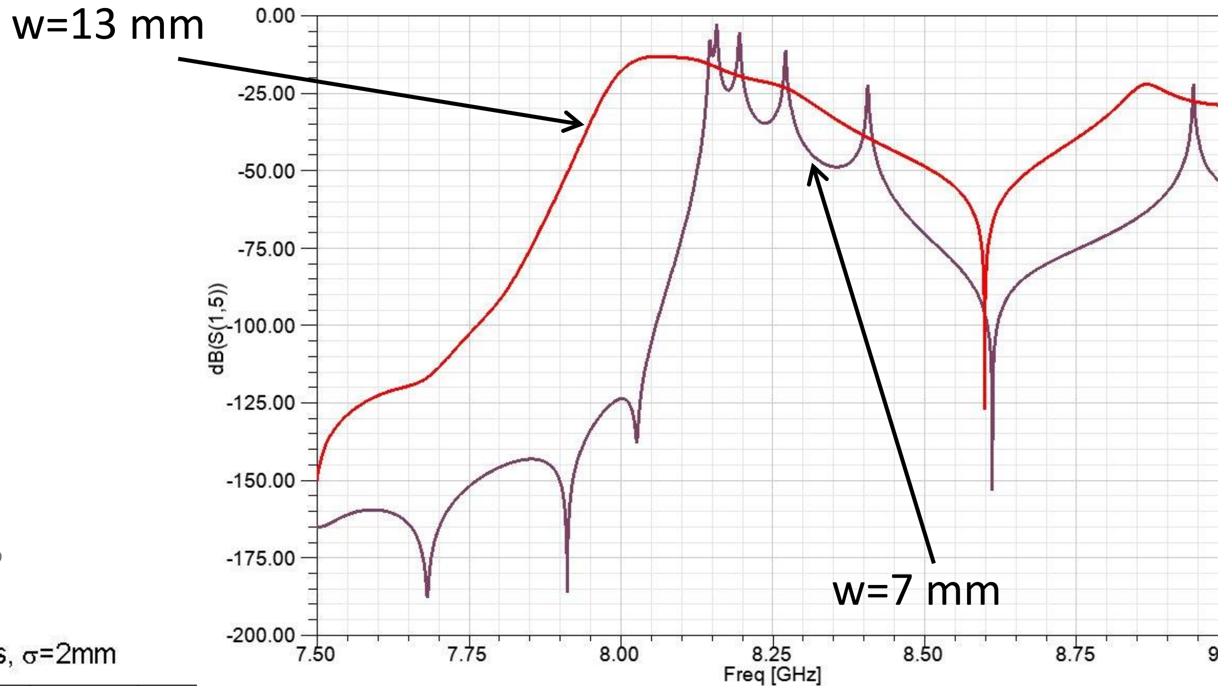


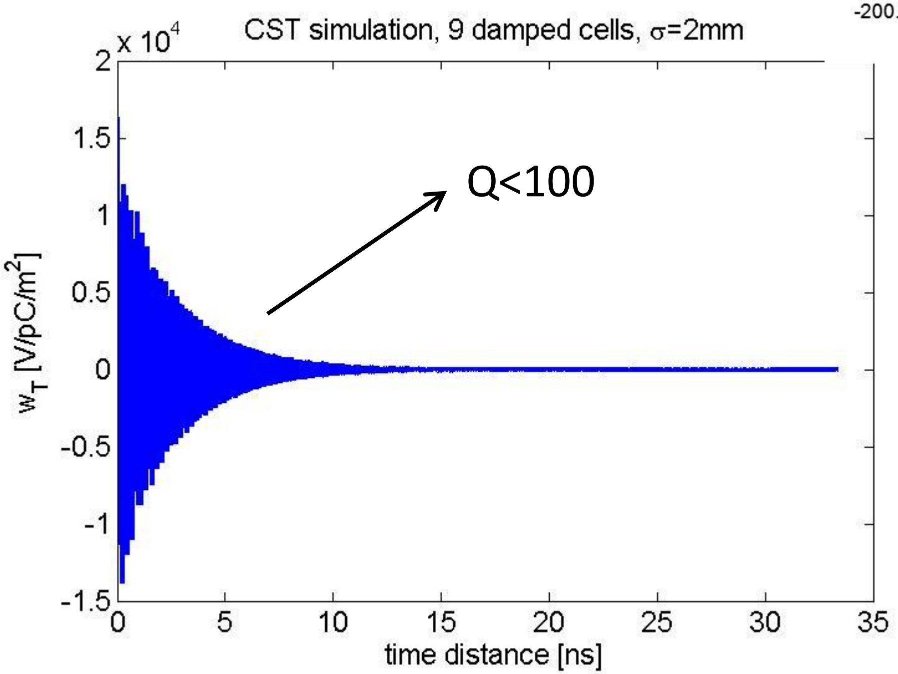




ELI Damped structure: effect of waveguide damping



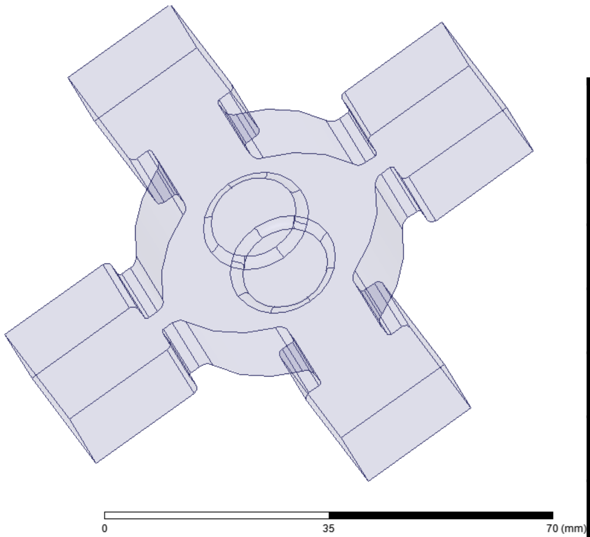


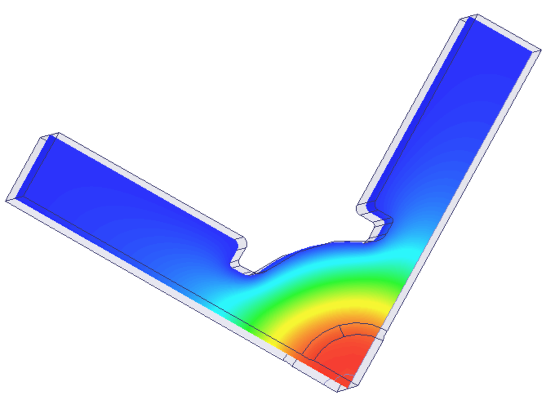


First dipole mode (TM_{11}-like) passband

HFSS

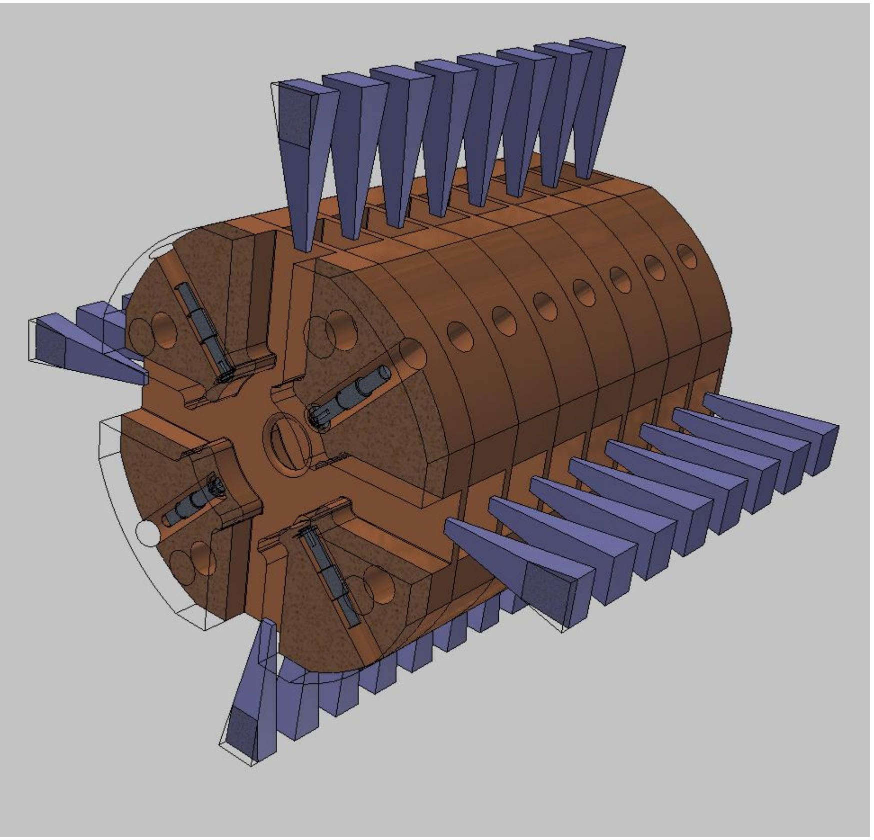
ELI Damped structure: parameters

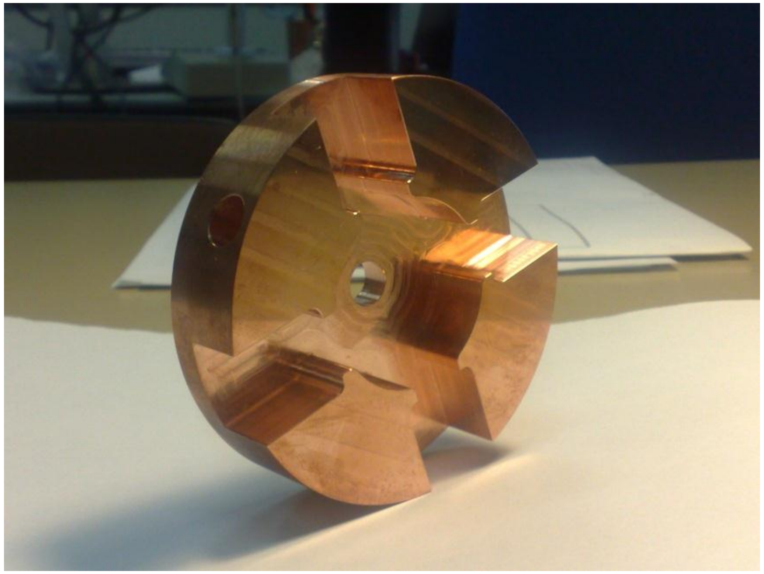




PARAMETER	VALUE
Type	TW-constant impedance
Frequency (f_{RF})	5.712 [GHz]
Phase advance per cell	$2\pi/3$
Structure Length (L)	1.5 m
Iris aperture (a)	6.5 mm
group velocity (v_g/c):	0.022
Field attenuation (α)	0.31 [1/m]
series impedance (Z)	45 [$M\Omega/m^2$]
Filling time (τ)	230 [ns]
Power flow @ E_{acc}=35 MV/m	27 [MW]
$E_{s\ peak}/E_{acc}$	2.1
$H_{s\ peak}/E_{acc}$	$4.3 \cdot 10^{-3}$ [A/V]
Minimum RF pulse length (τ_{IMP})	0.5 [μs]
Output power	$0.39 \cdot P_{in}$
$E_{ACC\_average}$@ P_{IN}=40 MW	34 MV/m
Pulsed heating @ P_{IN}=40 MW	7 ^{o}C
Accelerating field unbalance (E_{IN}, E_{OUT})	42.4MV/m, 26.65 MV/m
Average dissipated power @ 100 Hz, P_{IN}=40 MW	1.2 [kW]

ELI Damped structure: Mechanical drawings, realization and prototype





The fabrication of a prototype with a reduced number of cells is necessary to:

A. Test the effectiveness of the dipole mode damping including the test the absorbing material performances
B. Test the vacuum properties of the structure with absorbing material
C. Perform the low power tests and the tuning of the structure
D. Test the high gradient performances of the structure

OUTLINE: MULTI-BUNCH EFFECTS

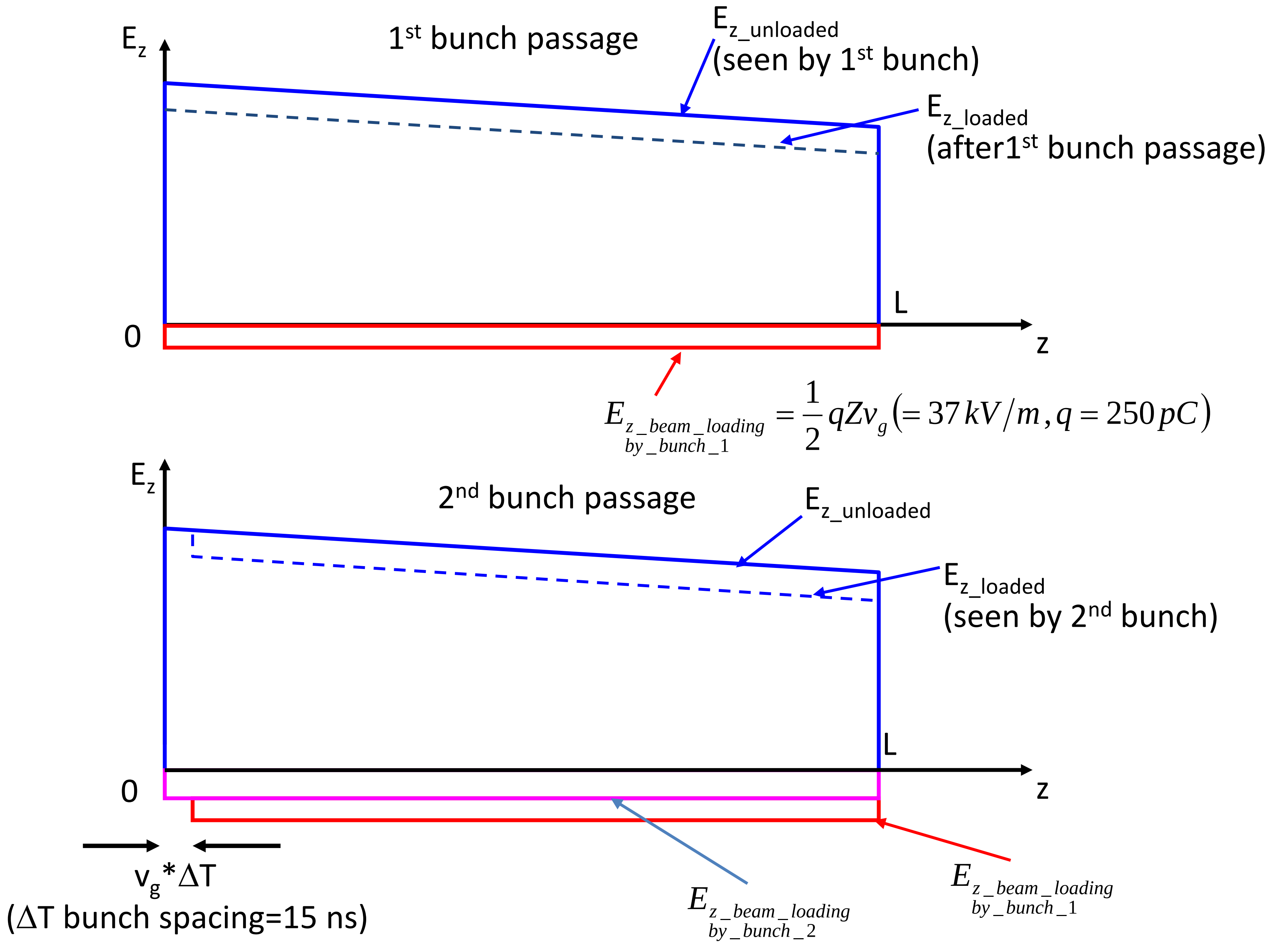
TRANSVERSE EFFECTS

1. Cumulative beam break-up in LINACS: general considerations
2. Cumulative beam break-up in the ELI-NP C-Band LINAC
3. C-Band Damped structures
4. S-Band Injector beam break-up

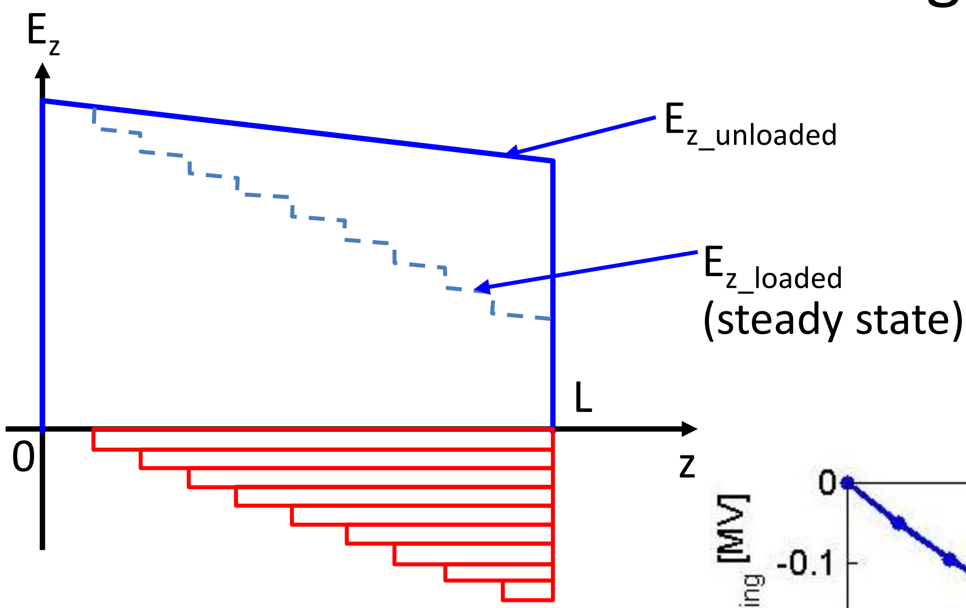
LONGITUDINAL EFFECTS

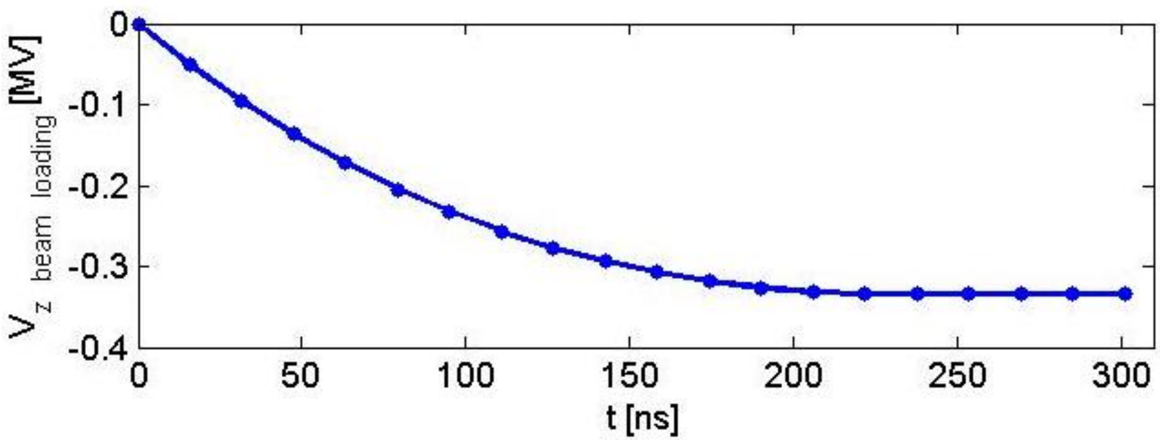
5. Multi-bunch effects in energy modulation along the train: Beam loading and its compensation

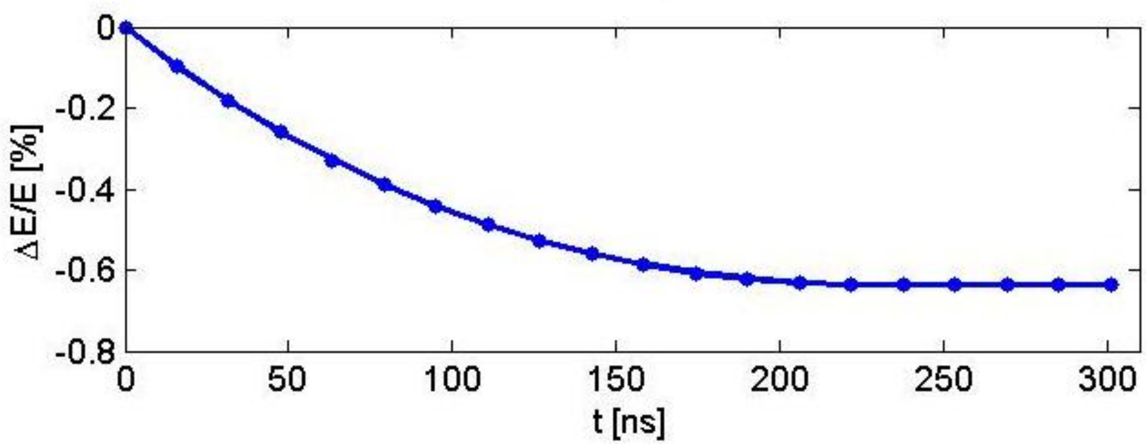
Beam loading: loaded accelerating field



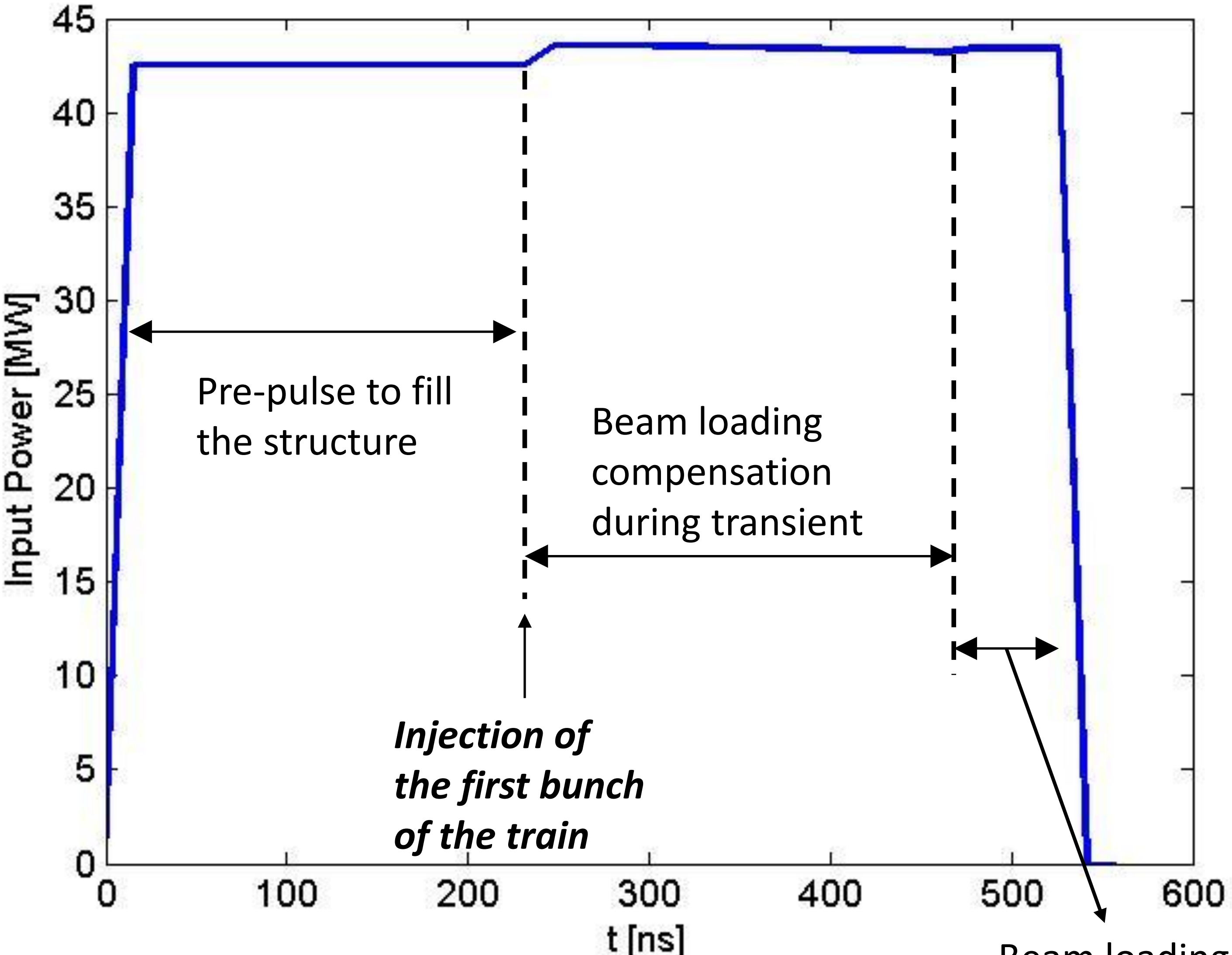
Beam loading: build-up







Beam loading: possible compensation



Beam loading compensation after one filling time of the structure

C-BAND structures for Handron therapy

Courtesy from Silvia Verdú-Andrés

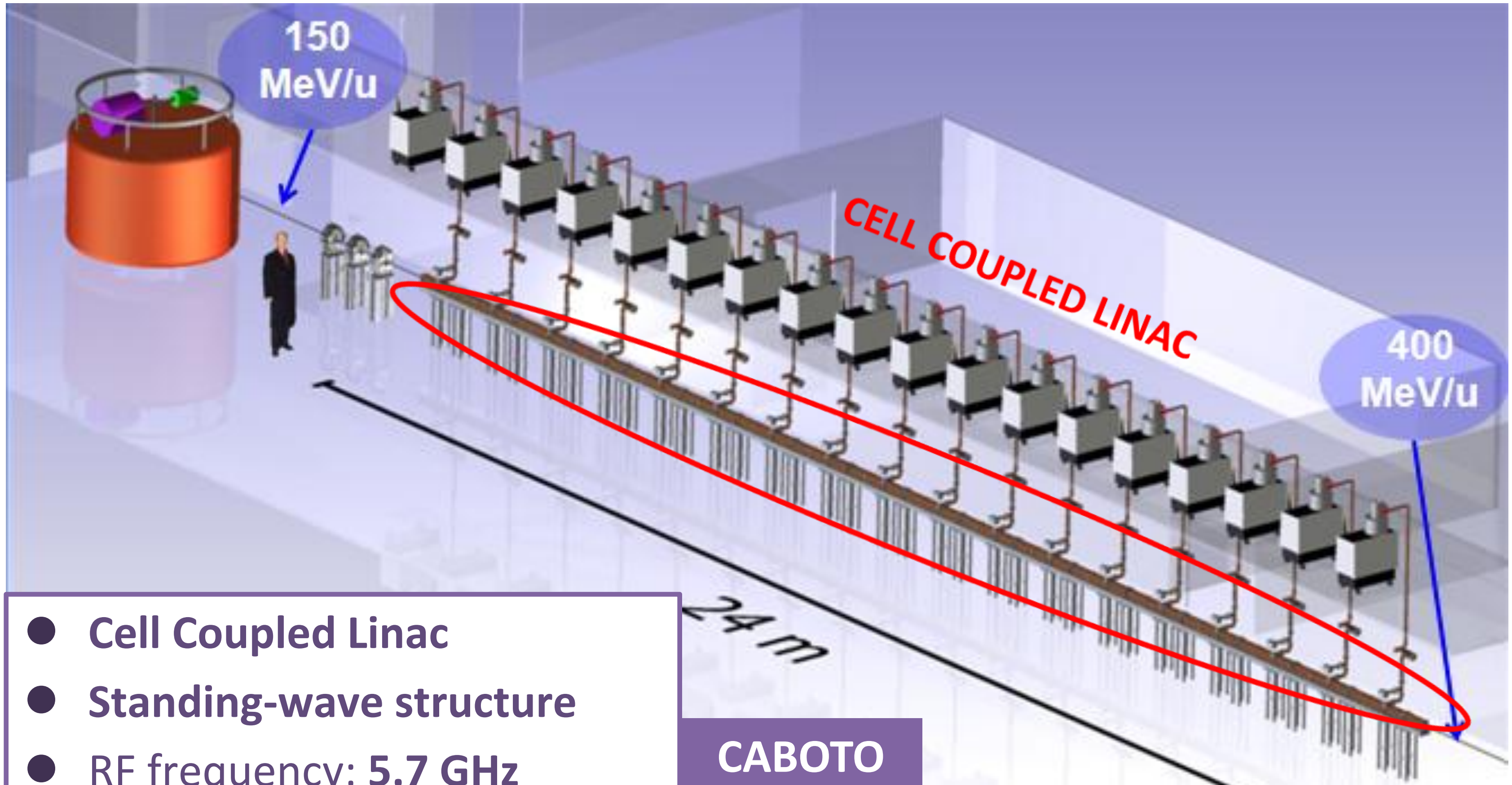
TERA Foundation, Novara, Italy

and

Instituto de Física Corpuscular IFIC (CSIC-UV), Paterna (Valencia), Spain

Accelerators for Hadrontherapy: Cyclinac

The Italian research foundation TERA proposes a new type of accelerator, the cyclinac, made of a high-frequency linac which boosts the energy of the hadrons accelerated by a cyclotron.



- **Cell Coupled Linac**
- **Standing-wave structure**
- RF frequency: **5.7 GHz**
- **2.5 μs**-long pulse at **300 Hz**

CABOTO

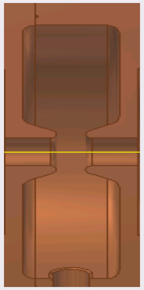
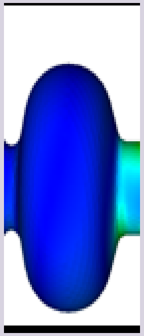
(CArbon BOoster for Therapy in Oncology)

Main cyclinac features

- **Active energy modulation:** No absorbers are needed to degrade the beam energy. The linac is divided in different sections, called units, each one fed by its own klystron. Beam energy modulation is done by switching on and off the different units in which the linac is divided and "fine" energy modulation is obtained by acting on the power (amplitude and phase) used to feed the last active unit. .

CABOTO (*Carbon BOoster for Therapy in Oncology*) is the newest proposal of TERA and will accelerate C^{6+} and H_2^{+} from 150 up to 400 MeV/u. It works at **5,7 GHz**. The CCL (Cell Coupled Linac) is made of **eighteen** 1,3 m long units .

Common goals for TERA and CLIC

	Cell shape	E_S/E_0	E_0 [MV/m]	E_s^{max} [MV/m]	$BDR_{required}$ [bpp/m]
TERA linacs		4—5	35—40	**200**	**10^{-6}**
CLIC structures		2	100	**200**	**10^{-6}**

CONCLUSIONS

1) C-Band accelerating structures have been proposed for the SPARC photoinjector energy upgrade;

2) A prototype with a reduced number of cells has designed, fabricated and tested at high power (KEK) giving excellent results in term of BDR @ 50 MV/m

3) The final accelerating structures are in fabrication in parallel with the test and installation of the high power system

4) The multi-bunch operation with C-band cavities has been carefully studied in the framework of the ELI_NP proposal and damped C-band structures are under development

5) One of the possible applications of C-band cavities for proton/carbon acceleration has been illustrated