ELI Nuclear Physics

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

101° Congresso Nazionale della Società Italiana di Fisica

The RF system of the ELI-NP gamma source linac

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ELI - Nuclear Physics overview

WHO:

One of the 3 pillars of the ELI (Extreme Light Infrastructure) project, hosted in Magurele site (Bucharest, Romania);

Advanced source of ɣ-rays delivered by the "EuroGammaS" consortium (**INFN - Università di Roma "Sapienza" - IN2P3/CNRS - Amplitude - Alsyom - ScandiNova - COMEB**).

HOW:

ɣ-rays generated by Compton back-scattering in the collision between a high quality **e^-** beam and a high power laser (10 PW);

Advantages wrt Bremmstrahlung ɣ-rays: **monocromaticity**, **tunability**, **higher collimation**, full control of **polarization**;

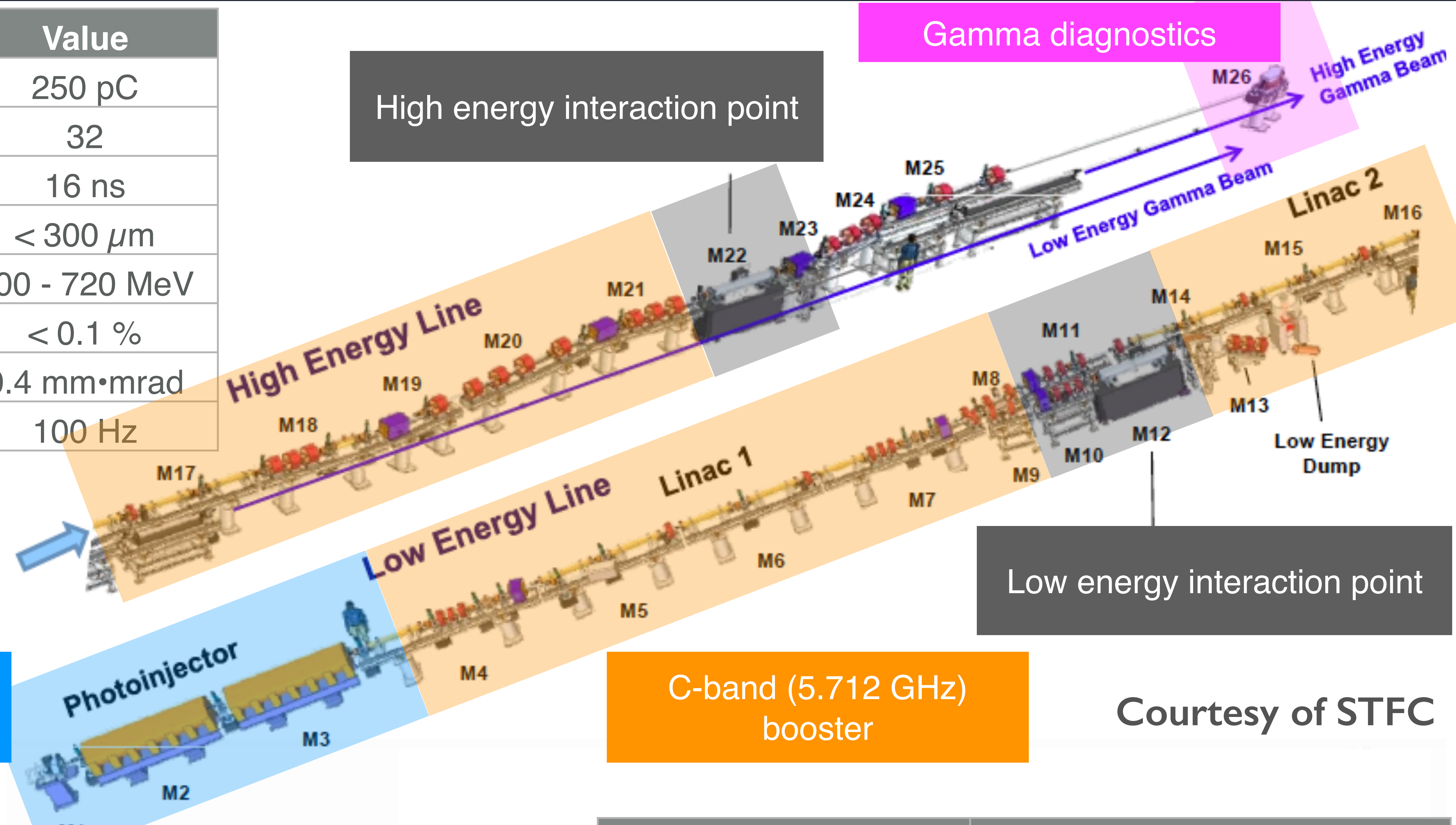
Challenges: alignment, synchronization, phase-space density.

WHY:

Open the era of nuclear photonics and pursue advanced applications in the field of national security, nuclear waste treatment, nuclear medicine, fundamental studies in nuclear physics dealing with the nucleus structure and the role of giant dipole resonances also for astrophysics studies.

Machine layout

Electron beam params	Value
Bunch charge	250 pC
N. of bunches / pulse	32
Bunch distance	16 ns
Bunch length	< 300 μm
Electron energy	300 - 720 MeV
Energy spread (RMS)	< 0.1 %
Norm. emittance	0.4 mm•mrad
RF Rep. rate	100 Hz



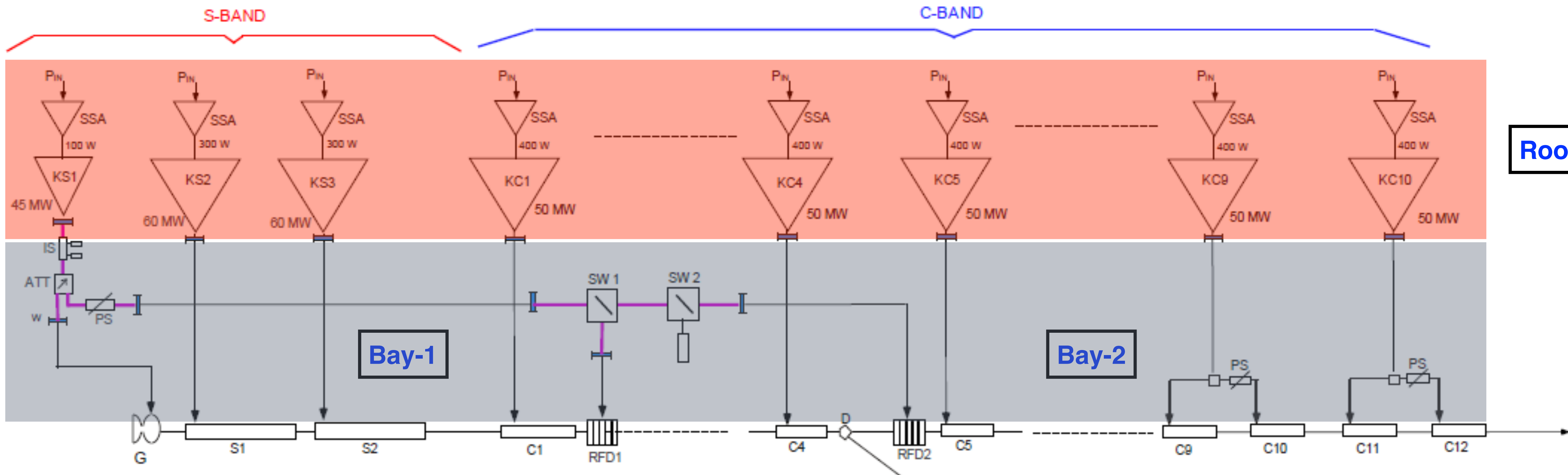
Courtesy of STFC

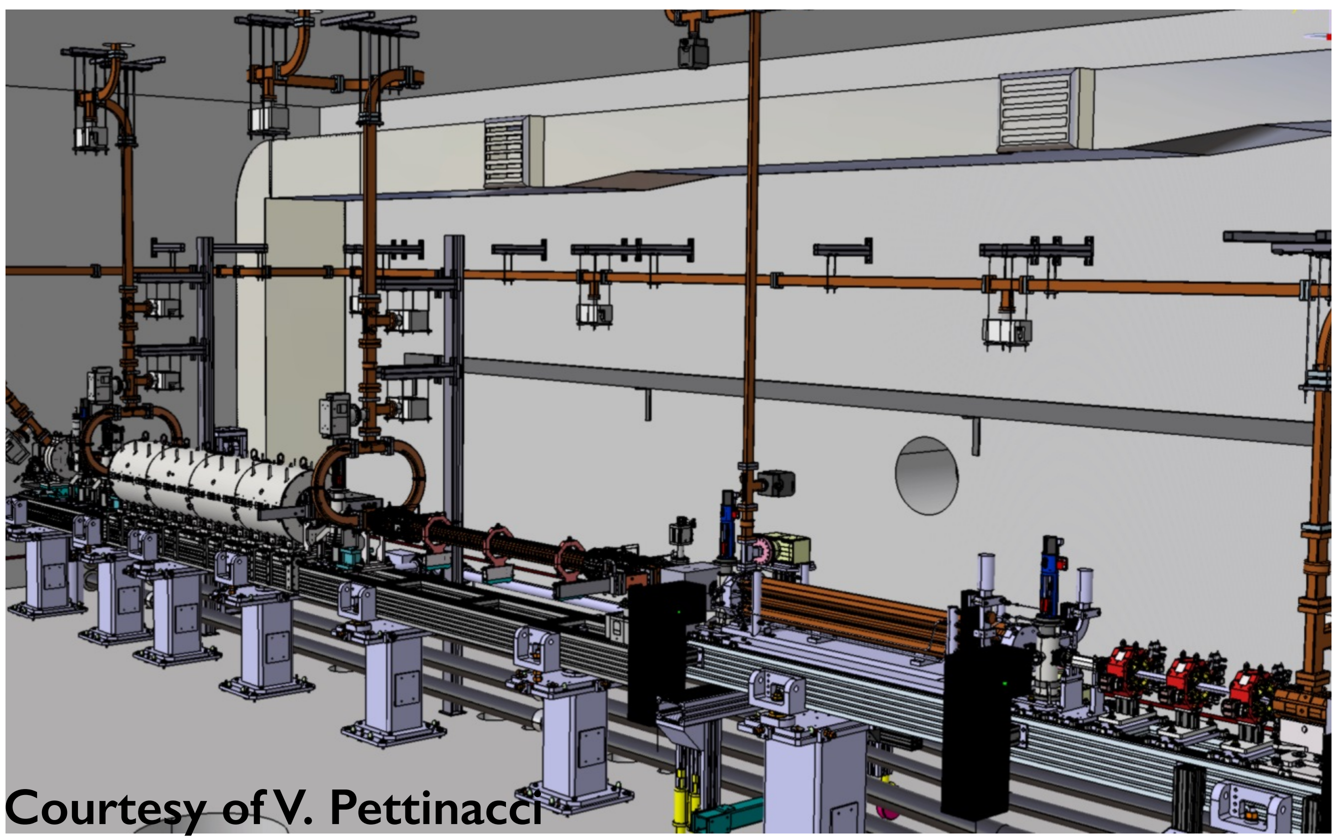
RF systems:

- 1 x SW S-band RF-gun (fabricated by COMEB, Rome);
- 2 x TW S-band SLAC-type sections (fabricated by RI, Koln);
- 2 x SW S-band RF deflectors (fabricated by RI, Koln);
- 12 x TW C-band sections (fabricated by COMEB, Rome).

Gamma beam params	Value
Energy	Tunable 1-20 MeV
RMS bandwidth	< 0.5%
Spectral density	> 10^4 ph/(s•eV)
Spot size	< 100 μm
Linear polarization	> 95%
Peak brilliance	> 10^{20} ph/(s•mm^2•mrad^2•0.1%)

RF power sources & distribution system





RF Power system:

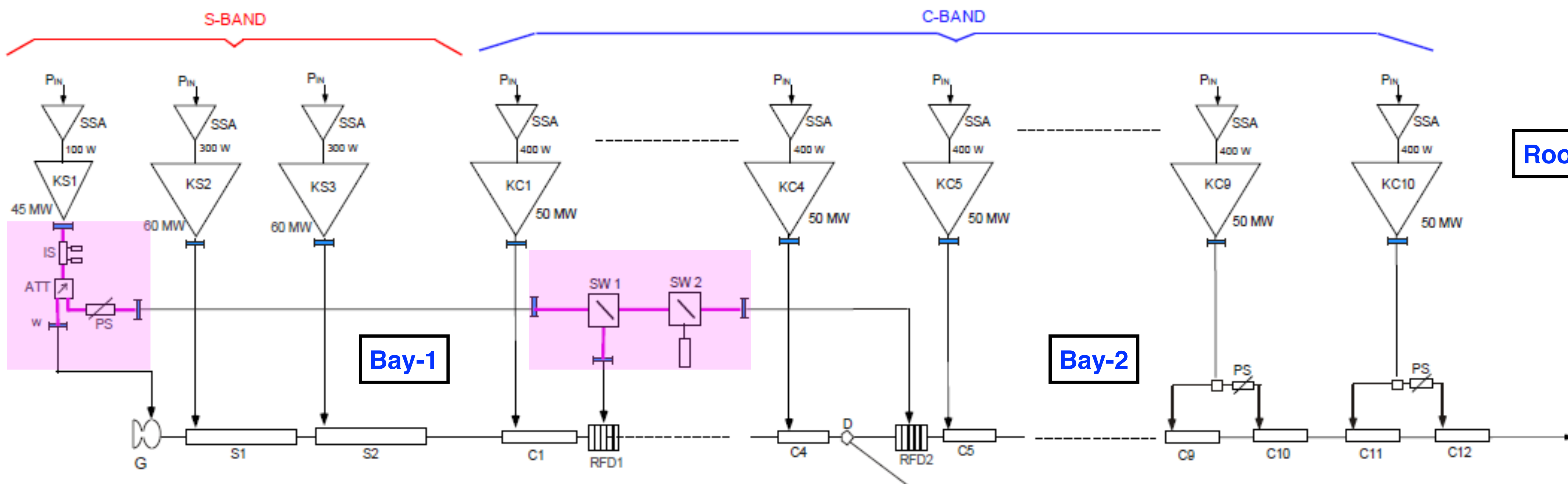
13 units: ScandiNova solid state modulators + Toshiba klystrons

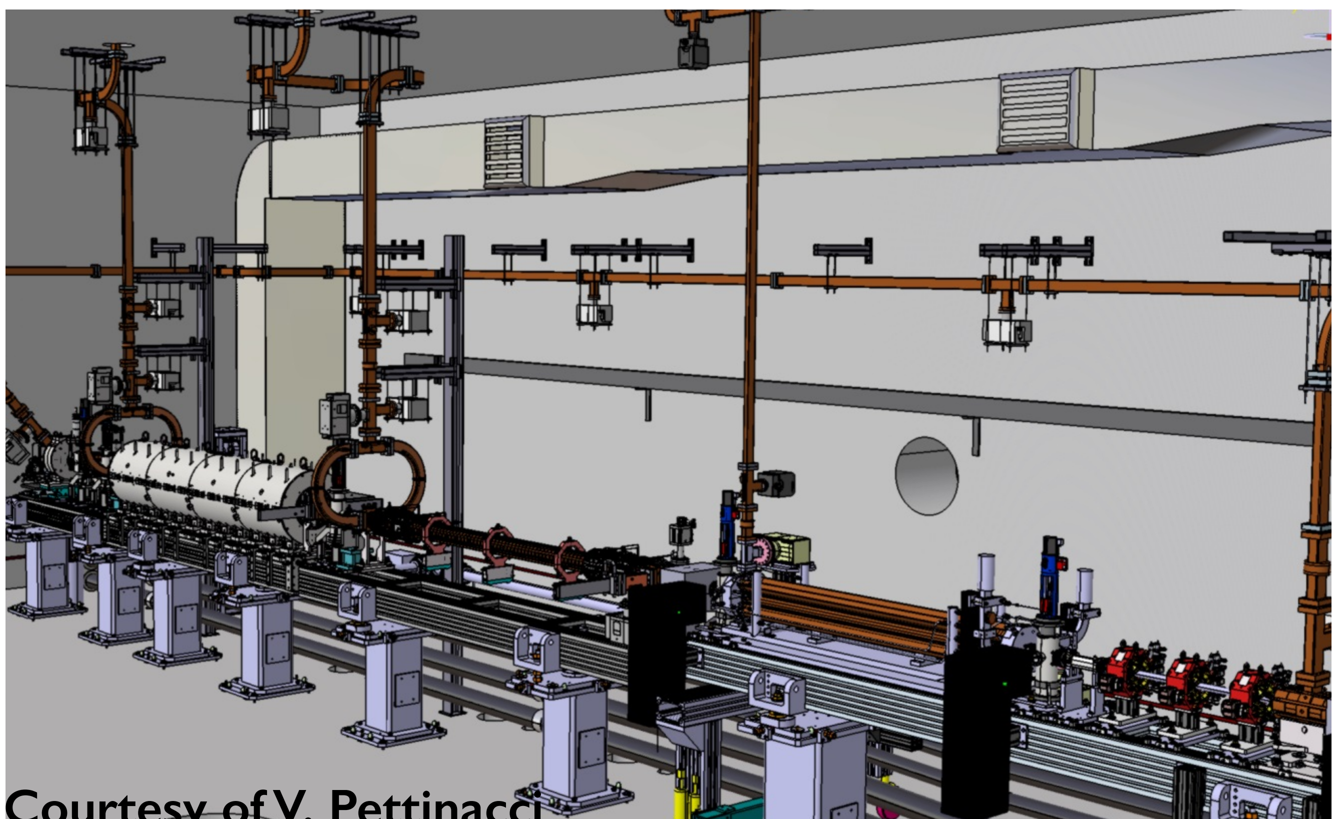
- 1 x 45 MW S-band RF unit;
- 2 x 60 MW S-band RF units;
- 10 x 50 MW C-band RF units.

Waveguides:

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

RF power sources & distribution system





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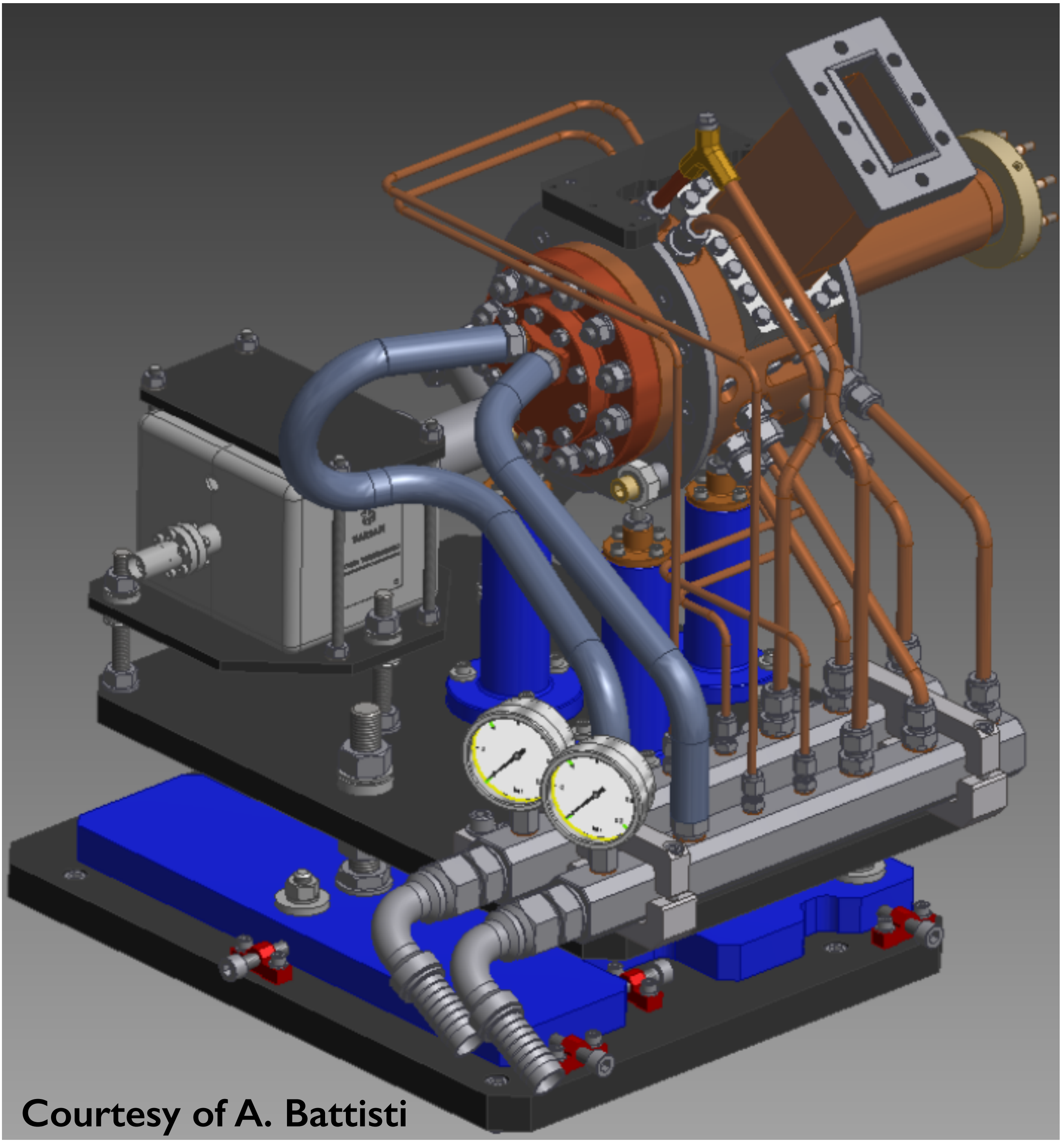
S-band network (SF6):

- Isolator, Attenuator (0-20 dB), Phase shifter, 2 x RF switch.

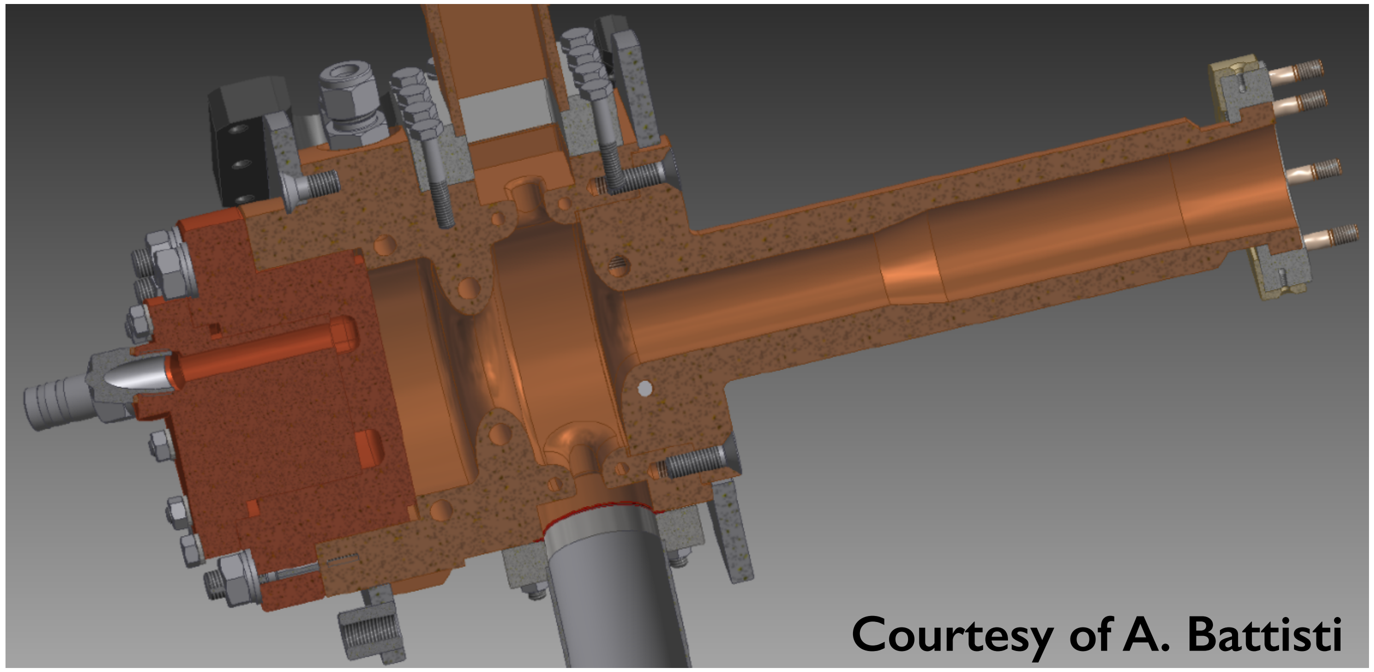
S-band RF gun - main features

<u>New design</u> of BNL/SLAC/UCLA 1.6 cell S-band RF-gun (2.856 GHz working frequency):



Courtesy of A. Battisti

- elliptical shaped irises w. larger aperture;
- tunability by deformation;
- coupling hole rounded to reduce pulsed heating;
- fabrication without brazing (w. special gaskets);
- cooled cathode;
- working mode π (SW)
- coupling coefficient ß=3;
- max RF peak power = 16 MW;
- peak field at cathode = 120 MV/m

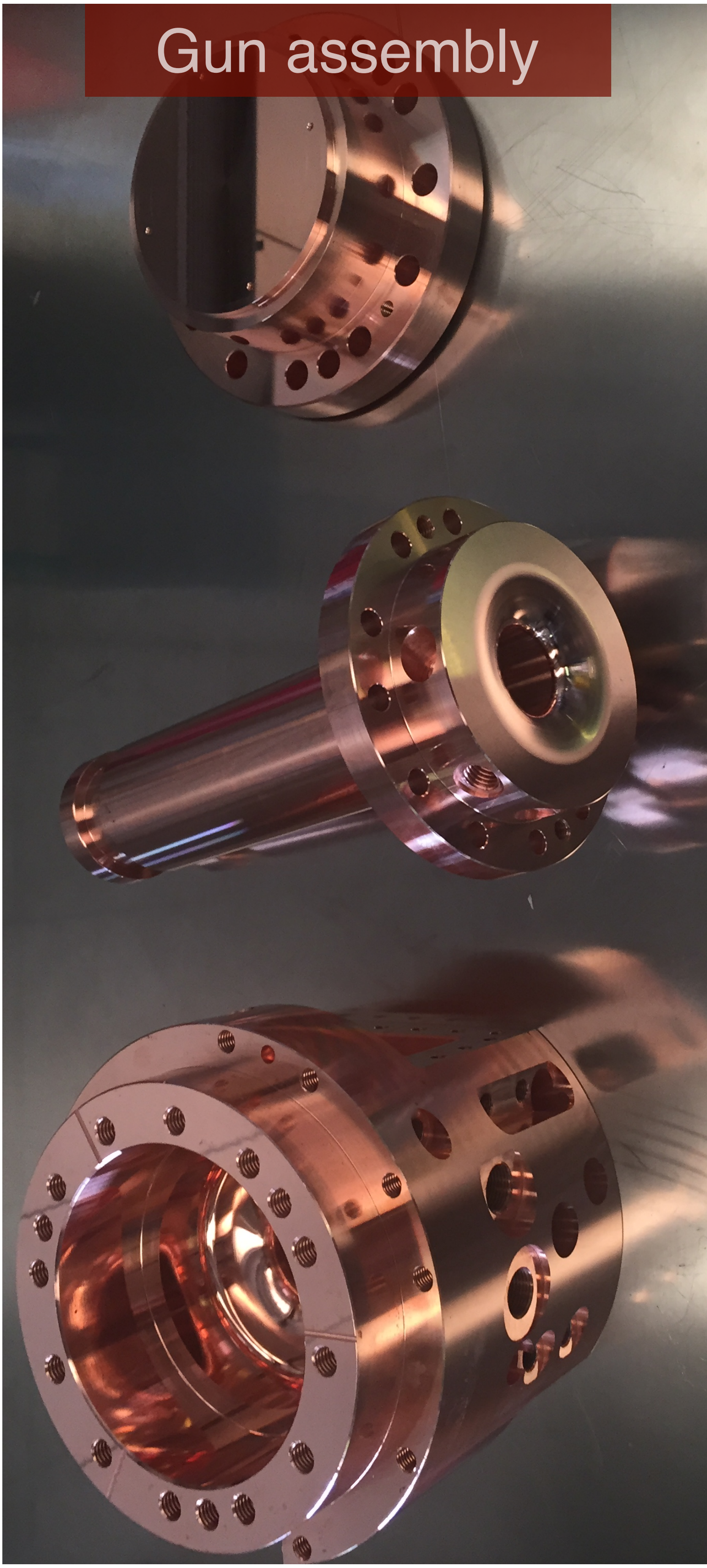


Courtesy of A. Battisti

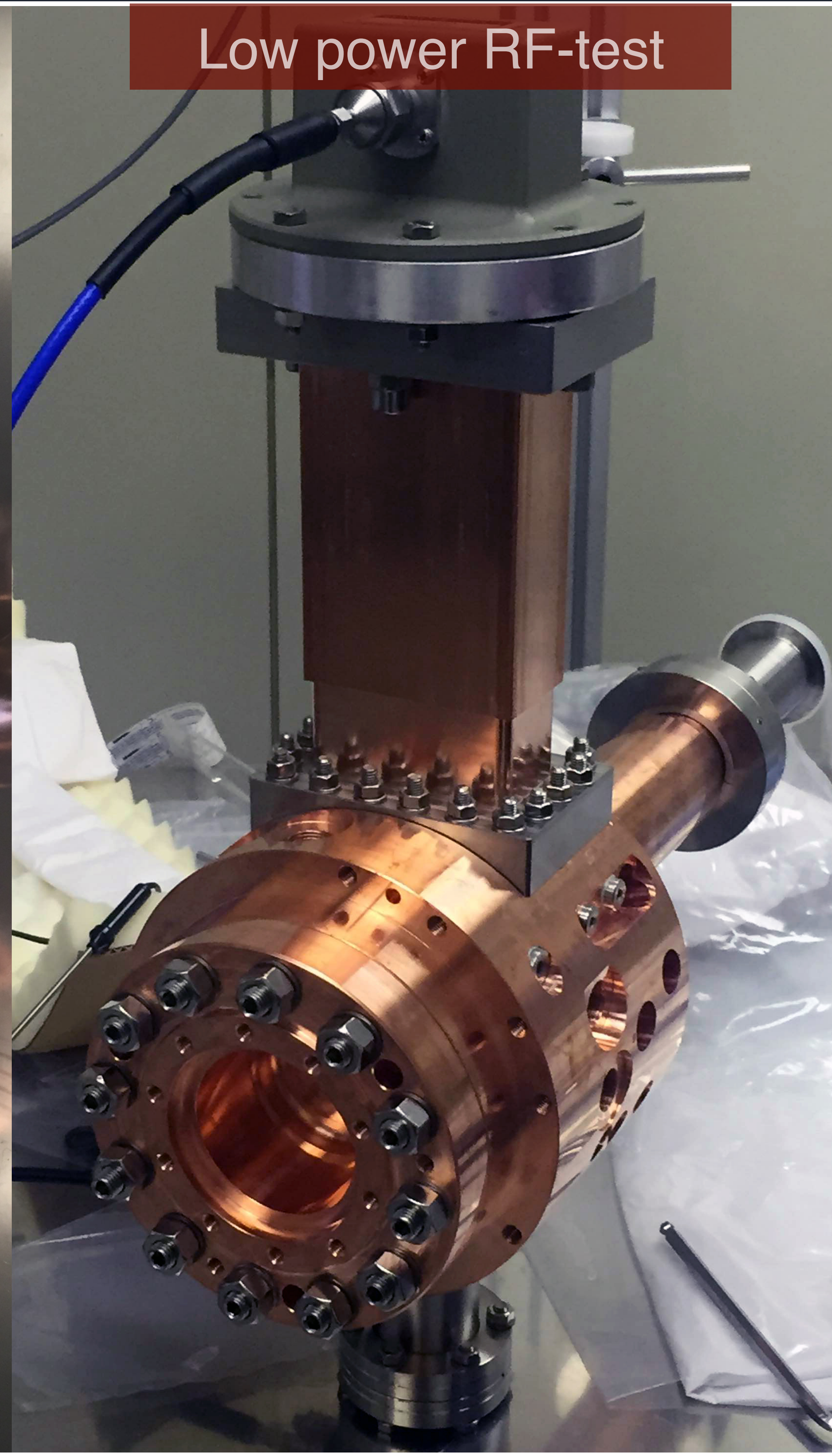
Design, tuning, vacuum test, low/high power RF test: INFN; Mechanical realization: COMEB (Italy)

RF Gun - mounting and RF testing @ LNF

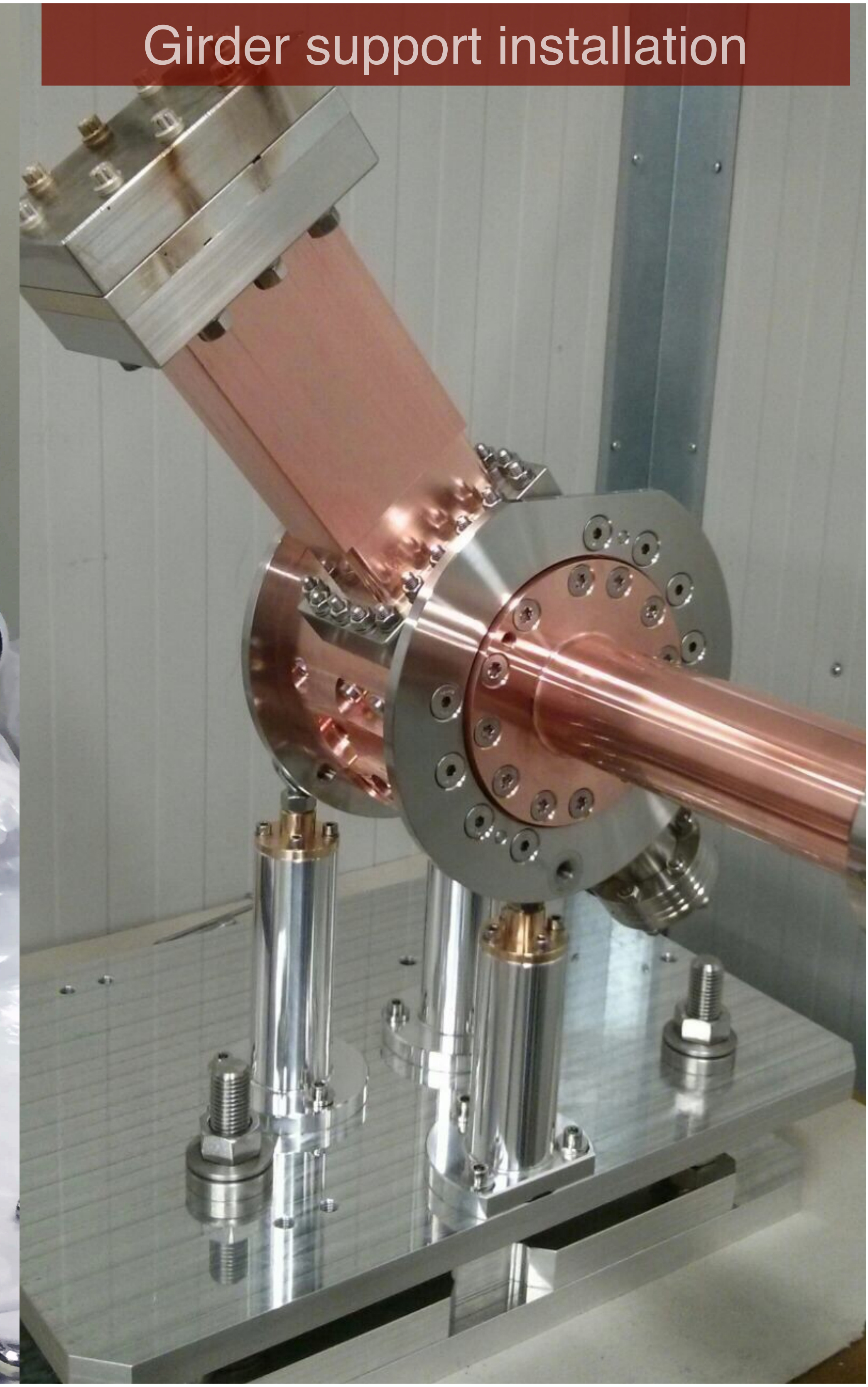
Gun assembly



Low power RF-test

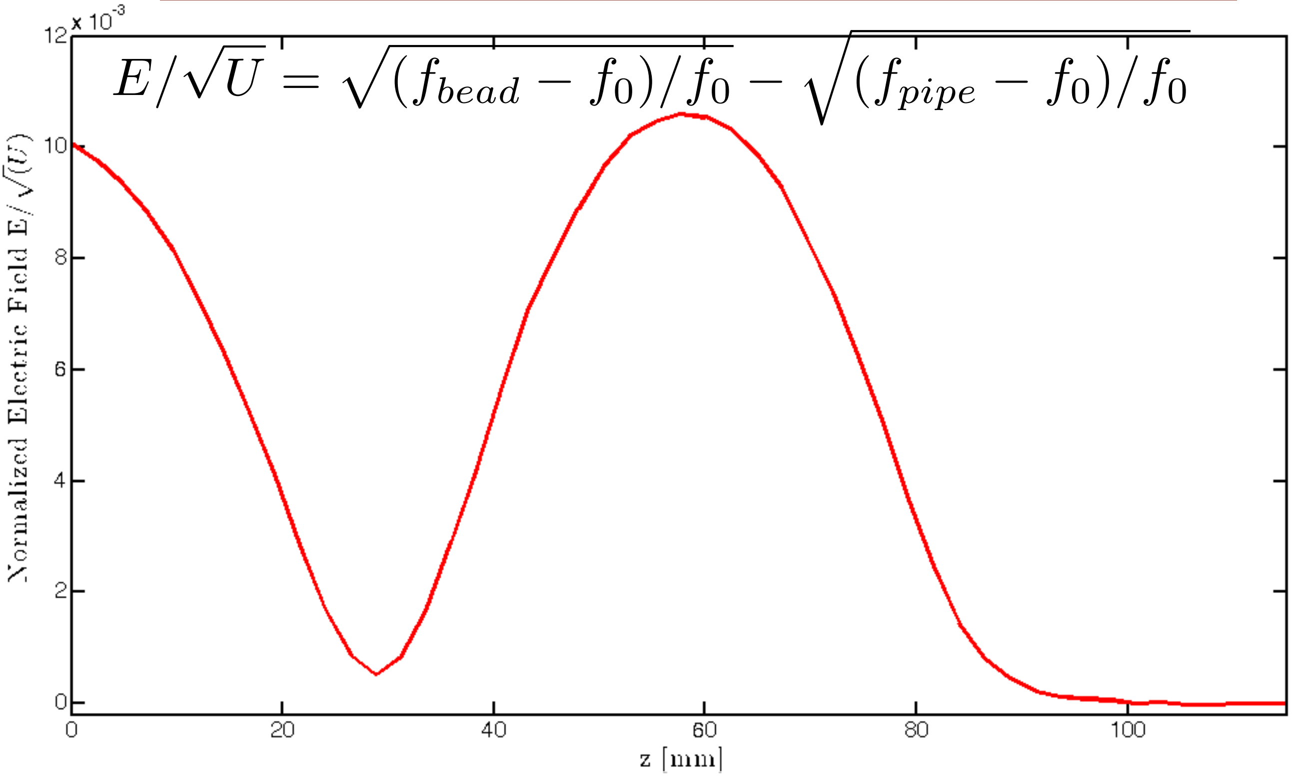


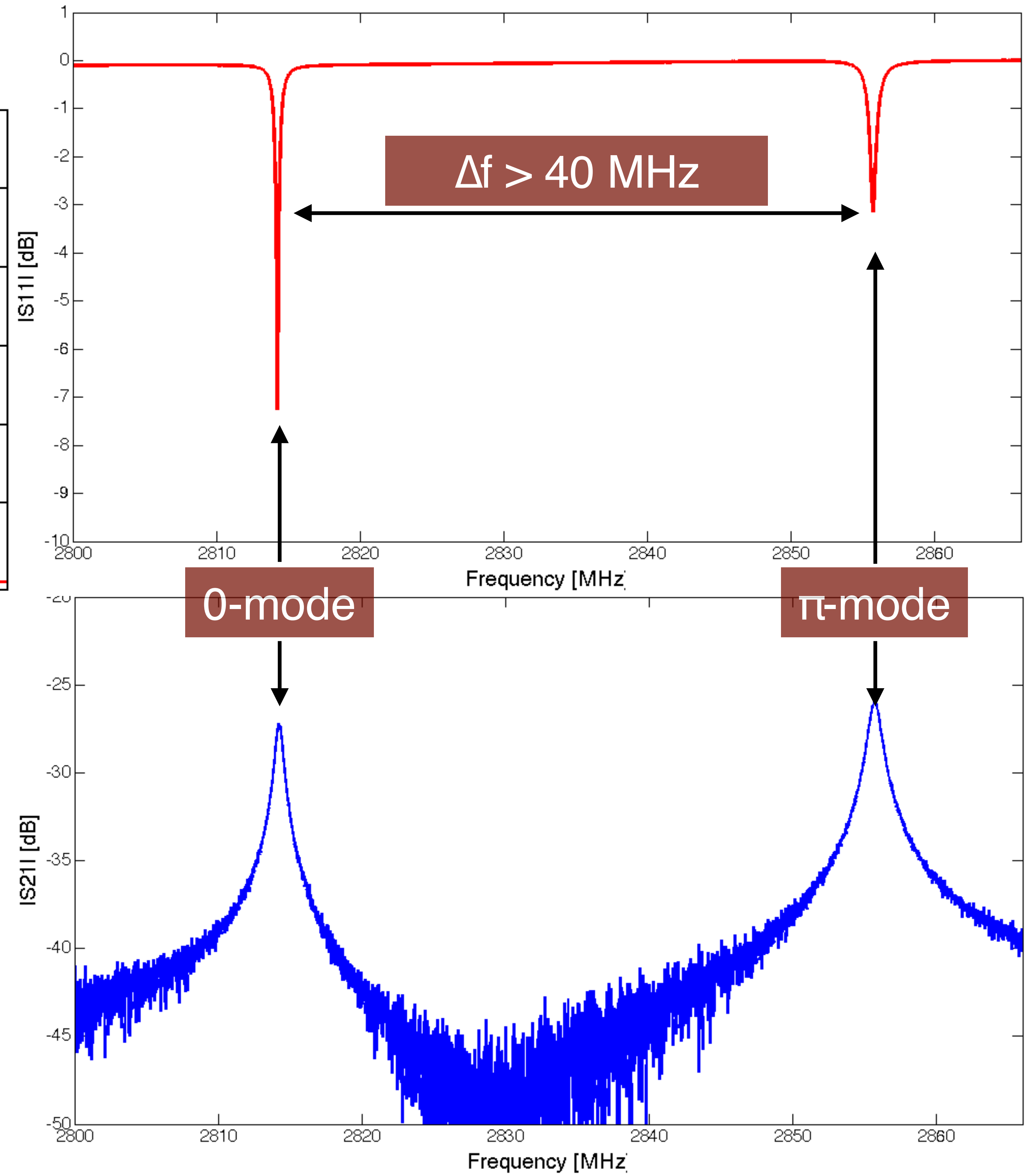
Girder support installation



RF Gun - low power RF test @ LNF

π-mode normalized electric field profile





Bead-drop & RF measurement results

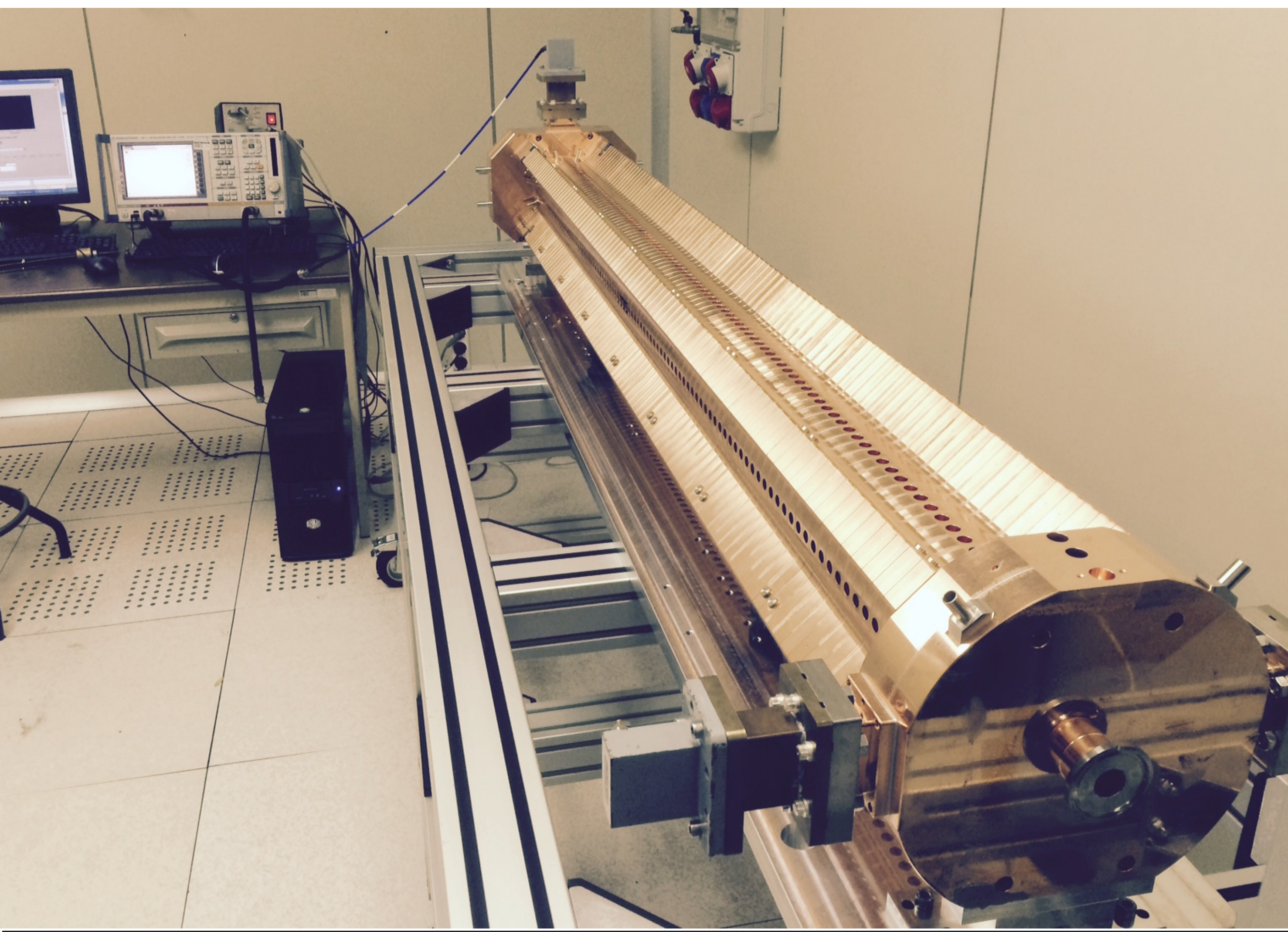
Design parameters π-mode:	Measured parameters π-mode:
f_π = 2.856 GHz	f_π = 2.8557 GHz
T_{cav} = 32 °C in vacuum	T_{cav} = 23 °C in air
field flatness < 3%	field flatness ~ 2%
β = 3	β = 2.87
Q_0 = 14500	Q_0 = 14200
Q_L = 3625	Q_L = 3670

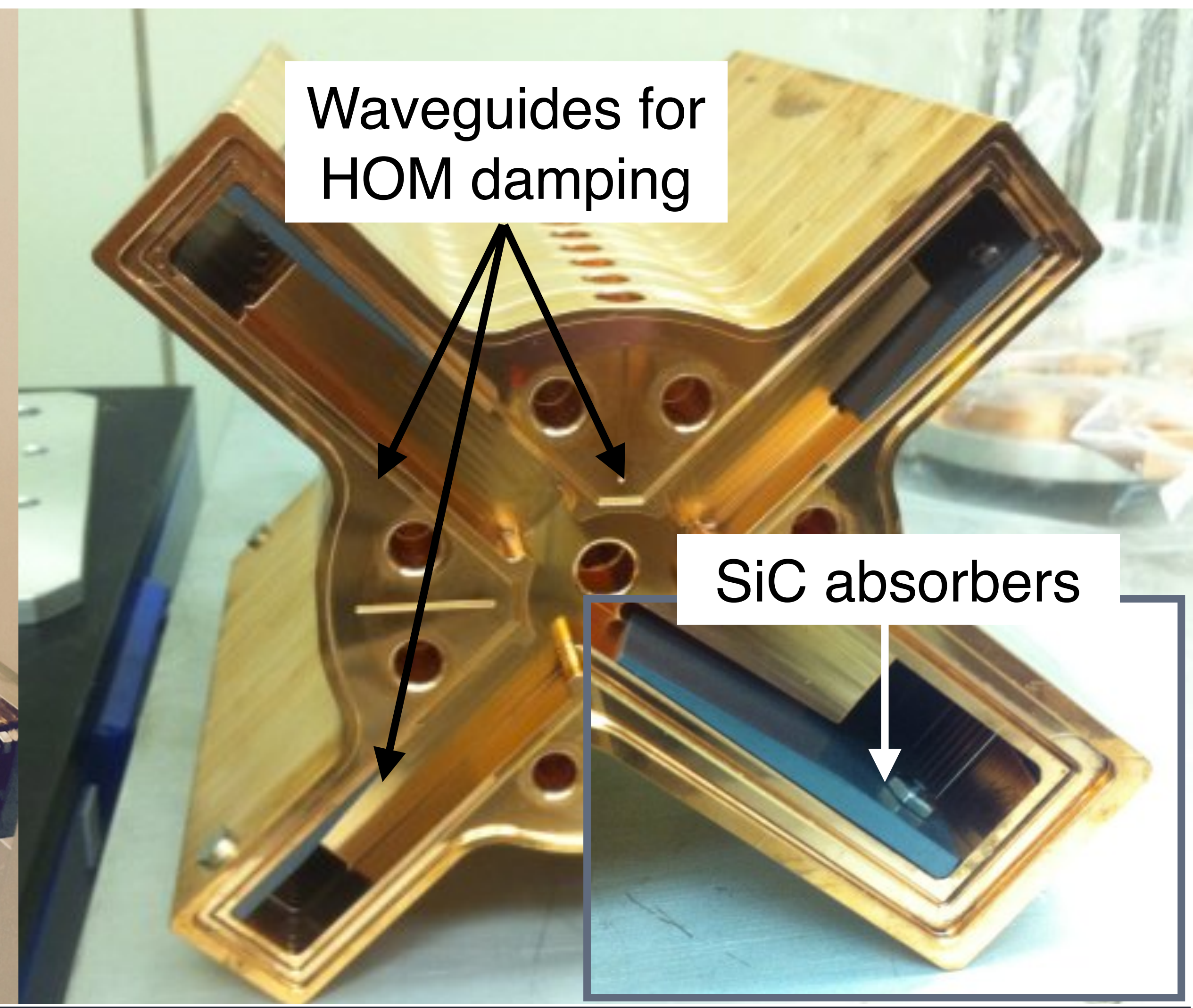
C-band accelerating sections

- 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.

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

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



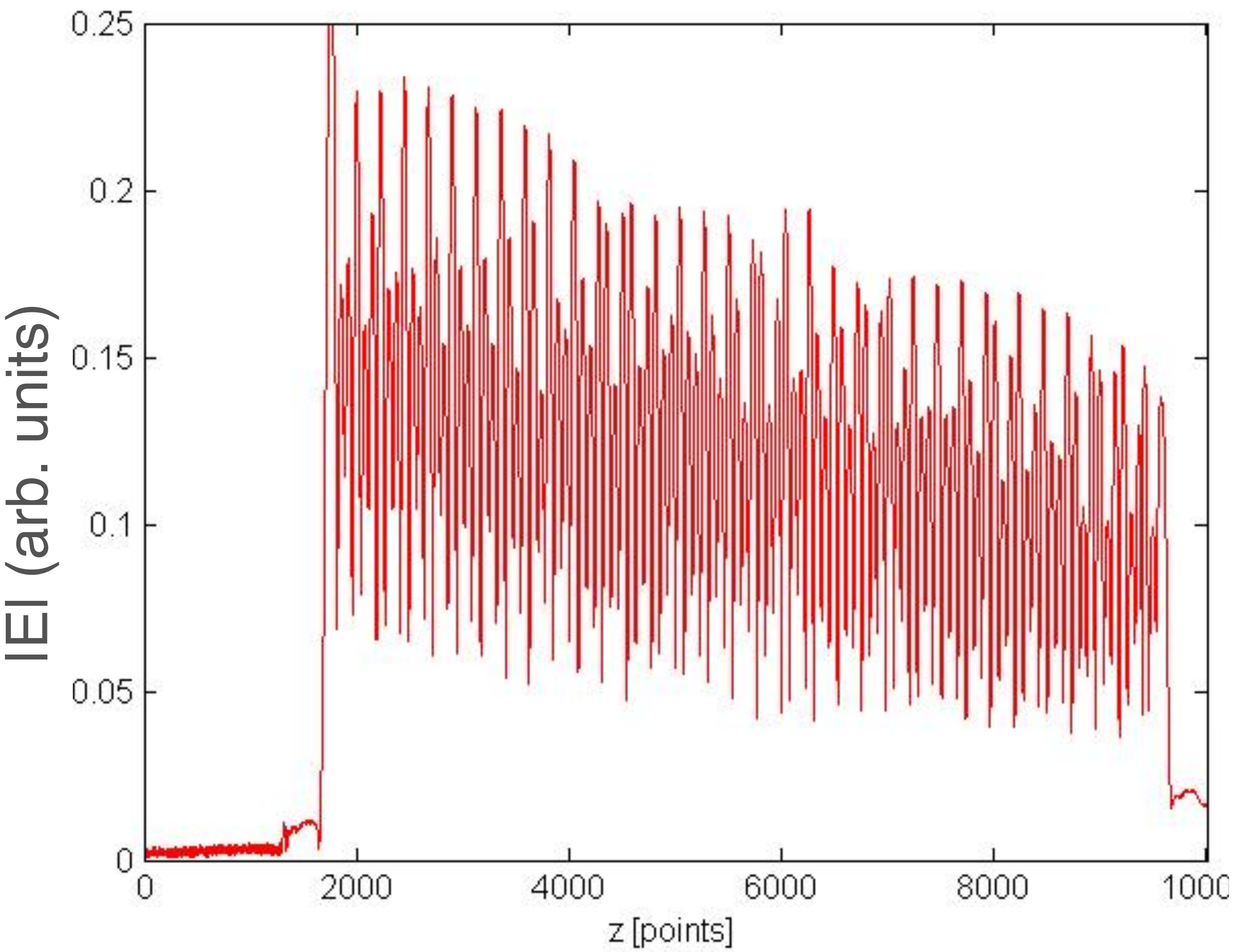


Tuning of the first C-band sections at LNF 1/2

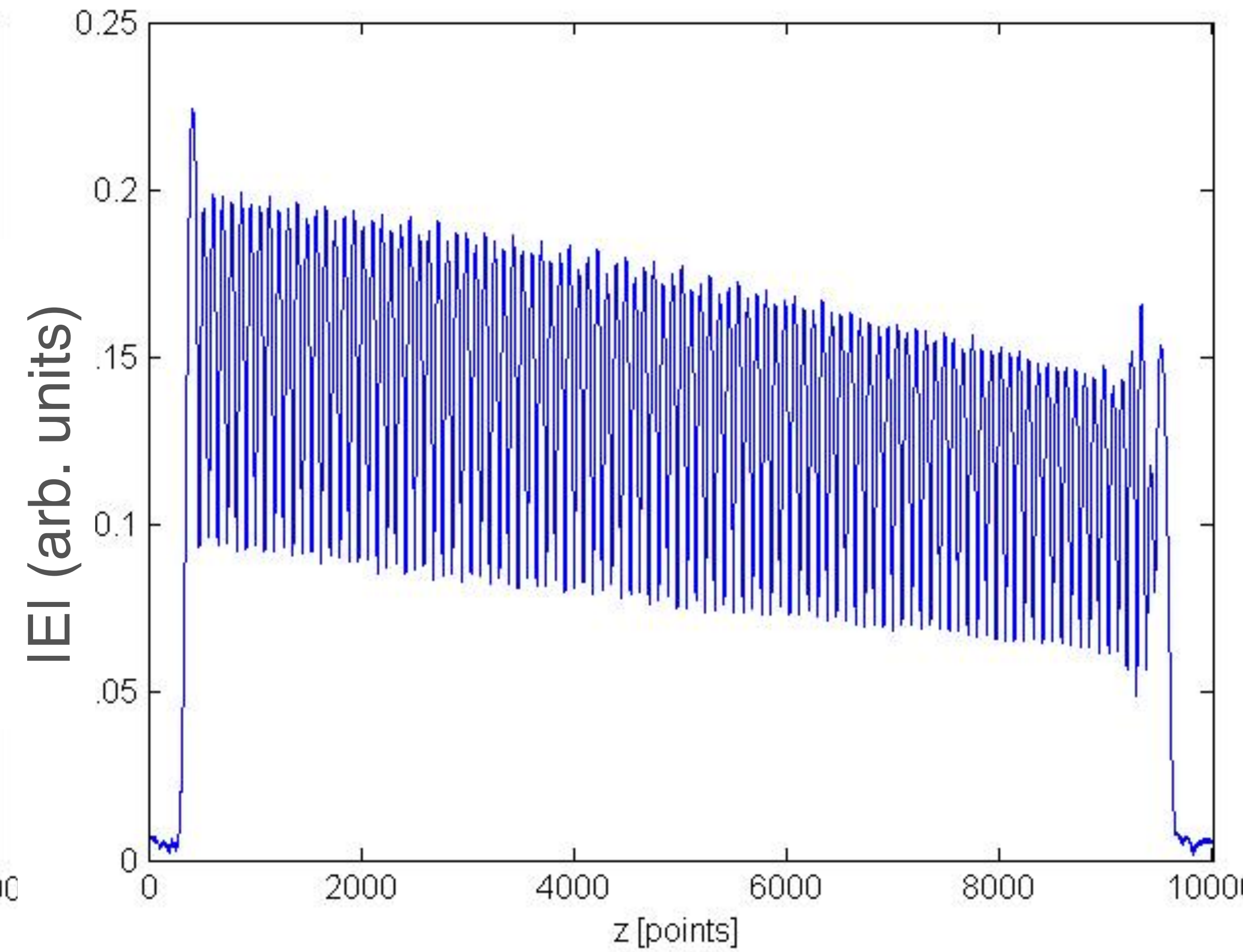
Bead pull perturbation technique (Steele [3]) + local reflection coefficient method [4]

Electric field profile

BEFORE tuning



AFTER tuning

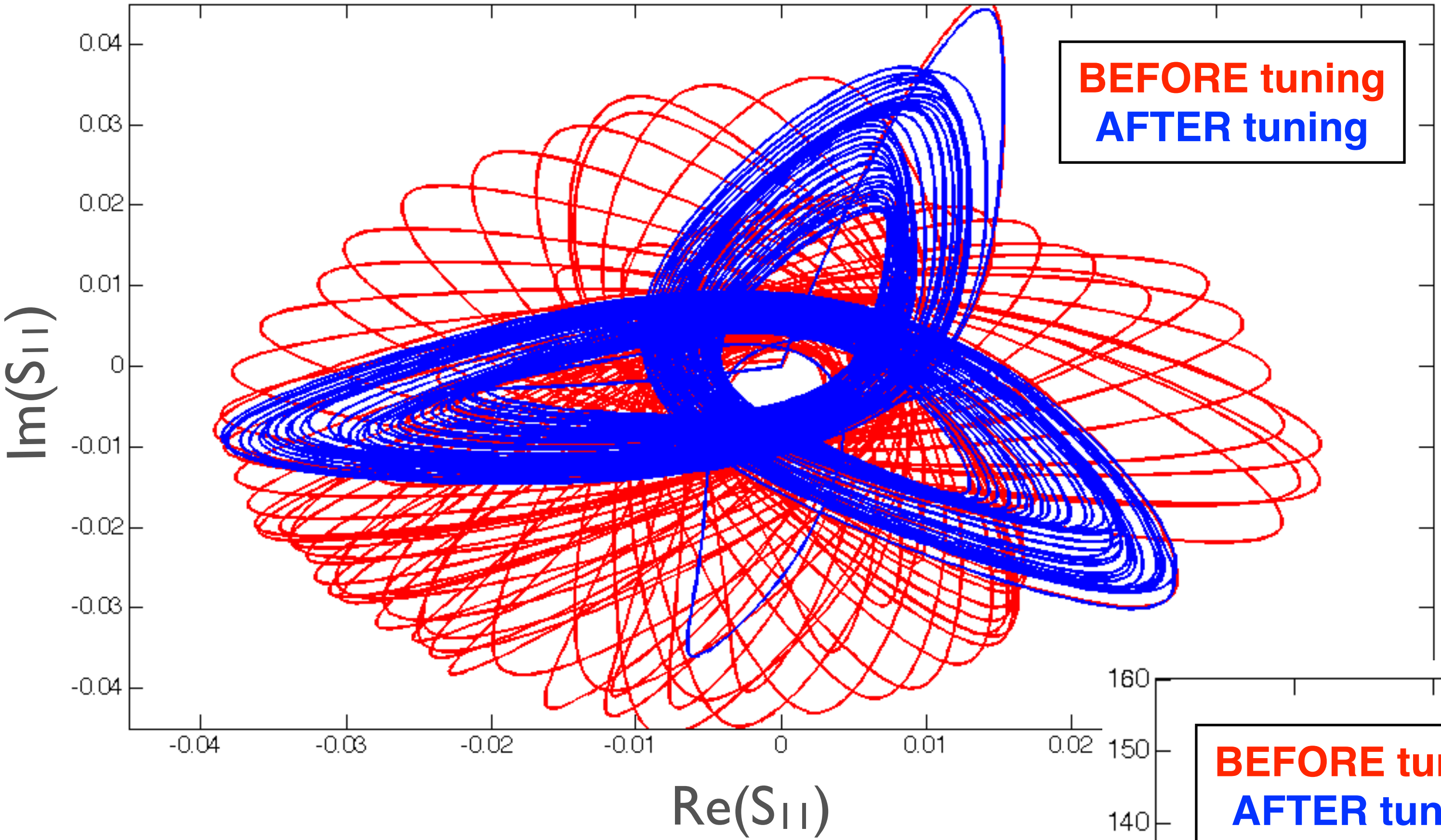


[3] C. Steele 1966 IEEE T. Microw. Theory 14 70

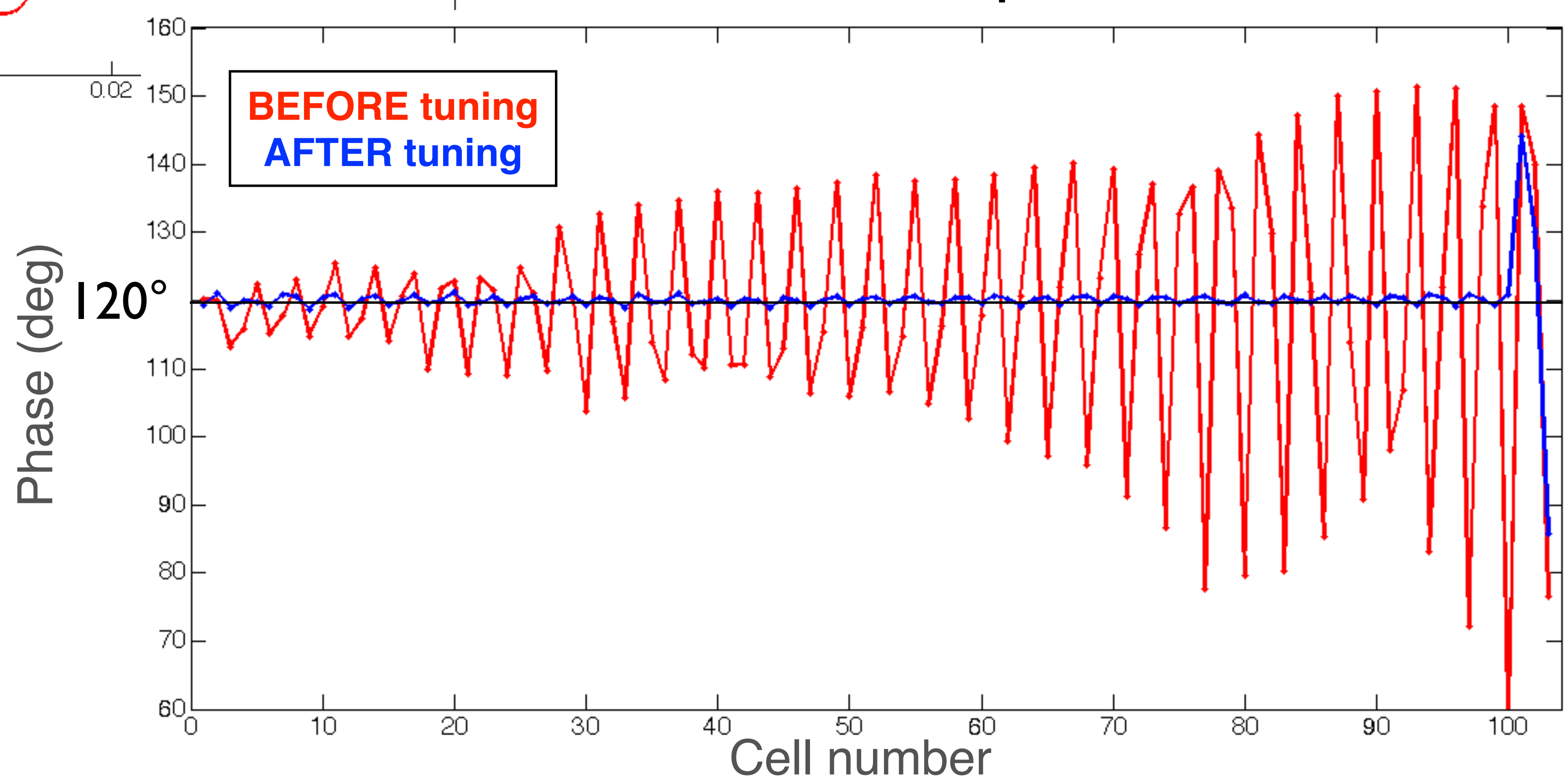
[4] D. Alesini *et al.* 2013 JINST 8 P10010

Tuning of the first C-band sections at LNF 2/2

S_{11} perturbed - S_{11} unperturbed



Phase advance per cell

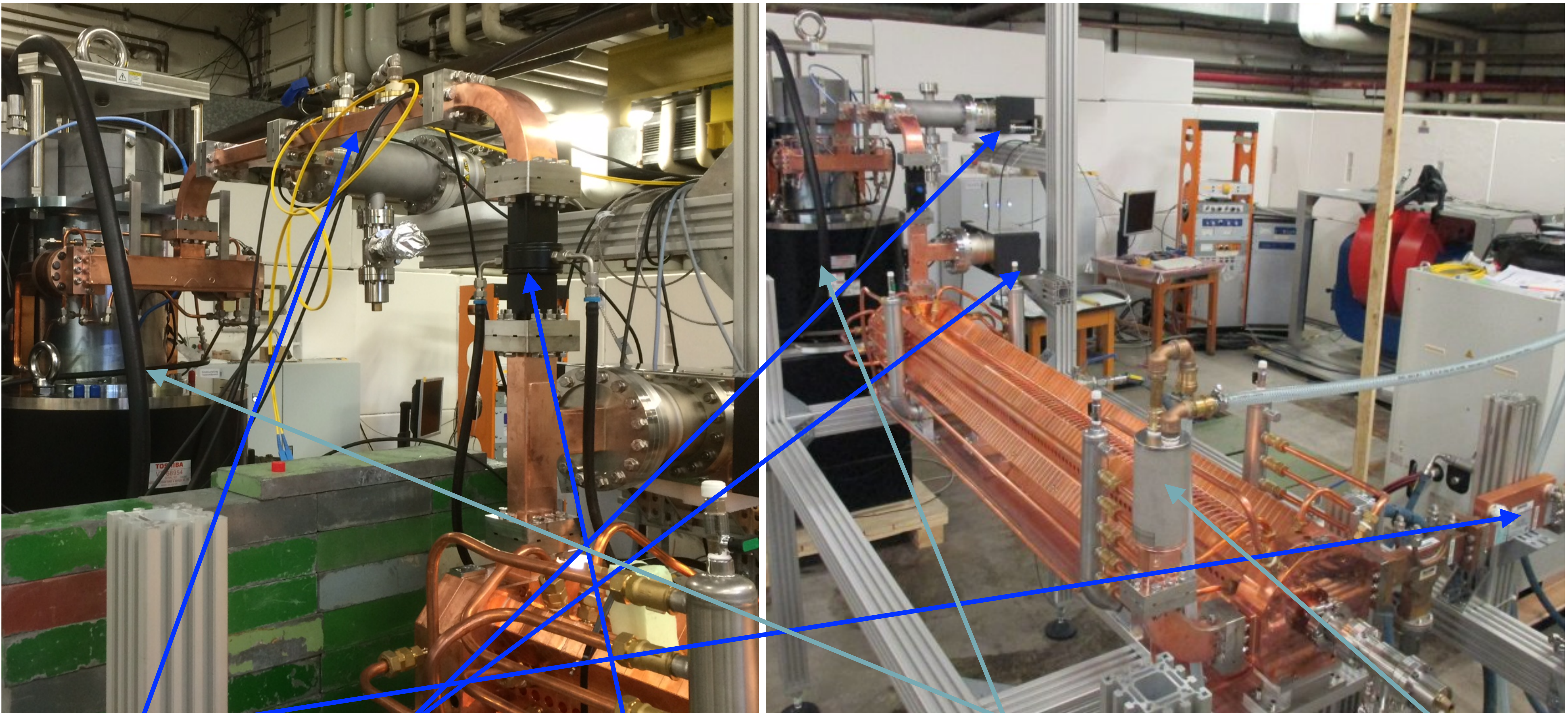


$S_{11} < -25$ dB AFTER tuning

RF Power test of C-band 1st prototype (@ Uni. Bonn)

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); t pulse = 820 ns
rep. rate = 100 Hz; BDR = $3 \div 8 \cdot 10^{-6}$ breakdown/s



Directional couplers | Ion pumps | Ceramic window | 50 MW power unit: ScandiNova solid state Modulator + Toshiba klystron | RF water load

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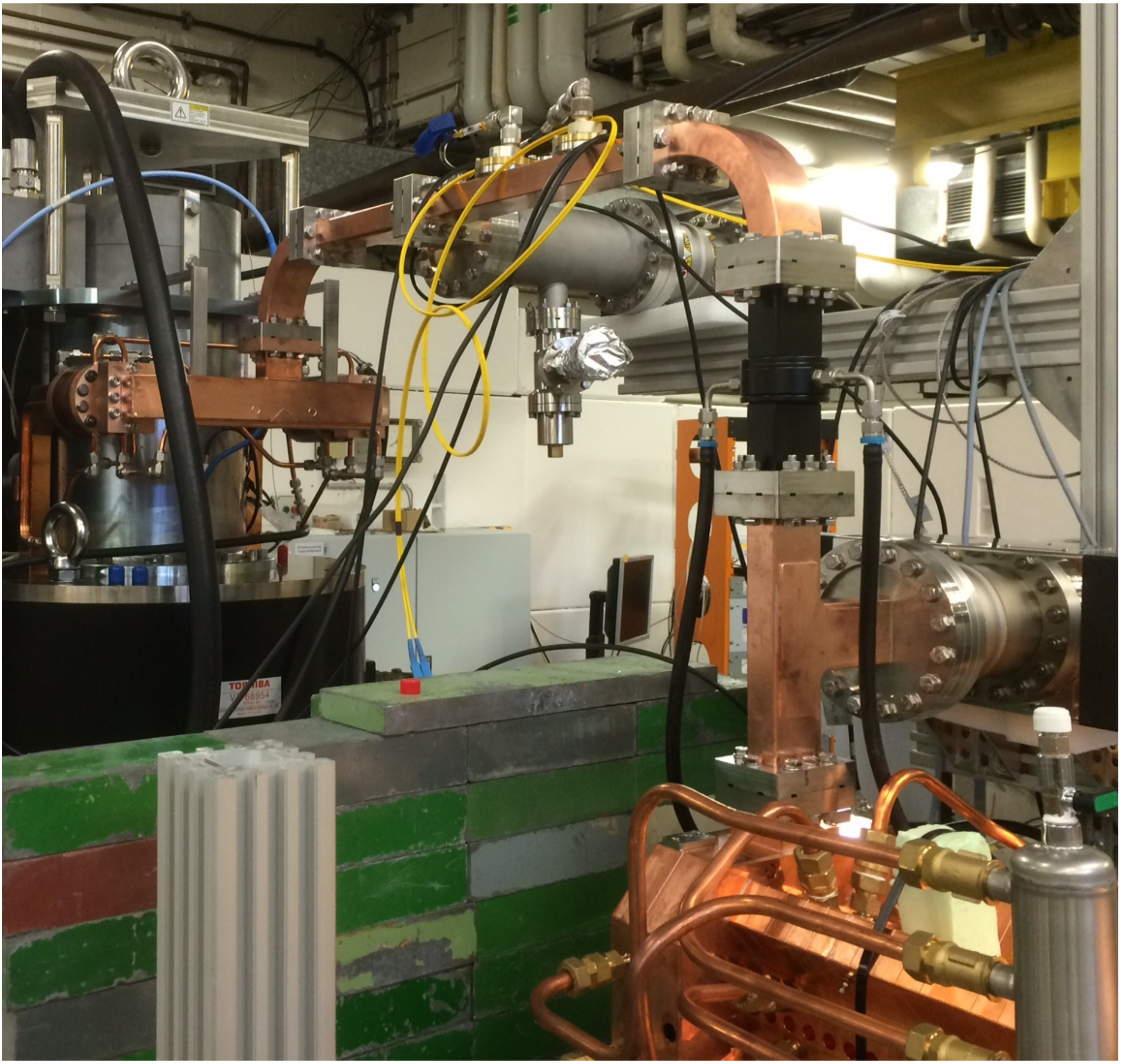
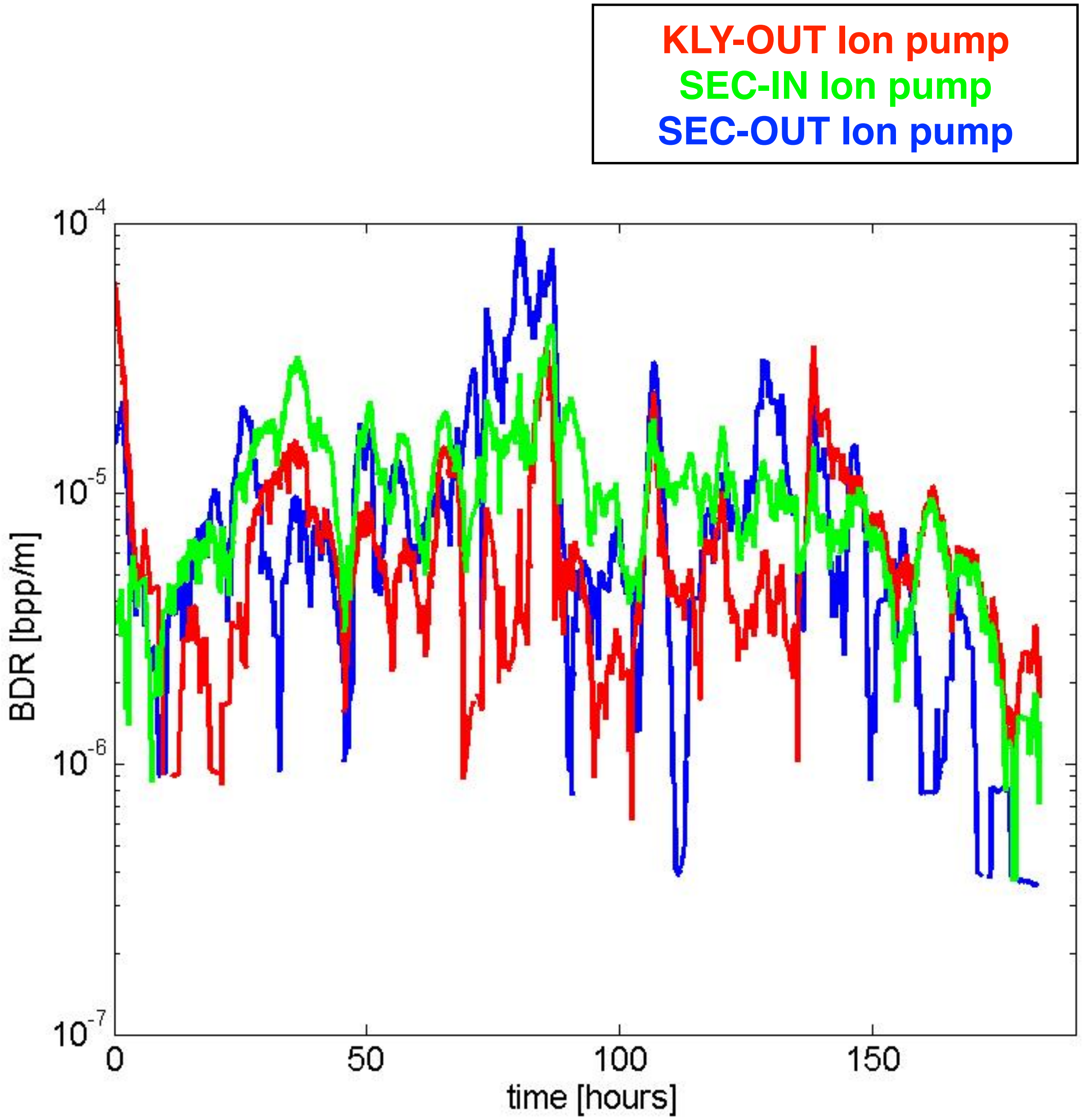
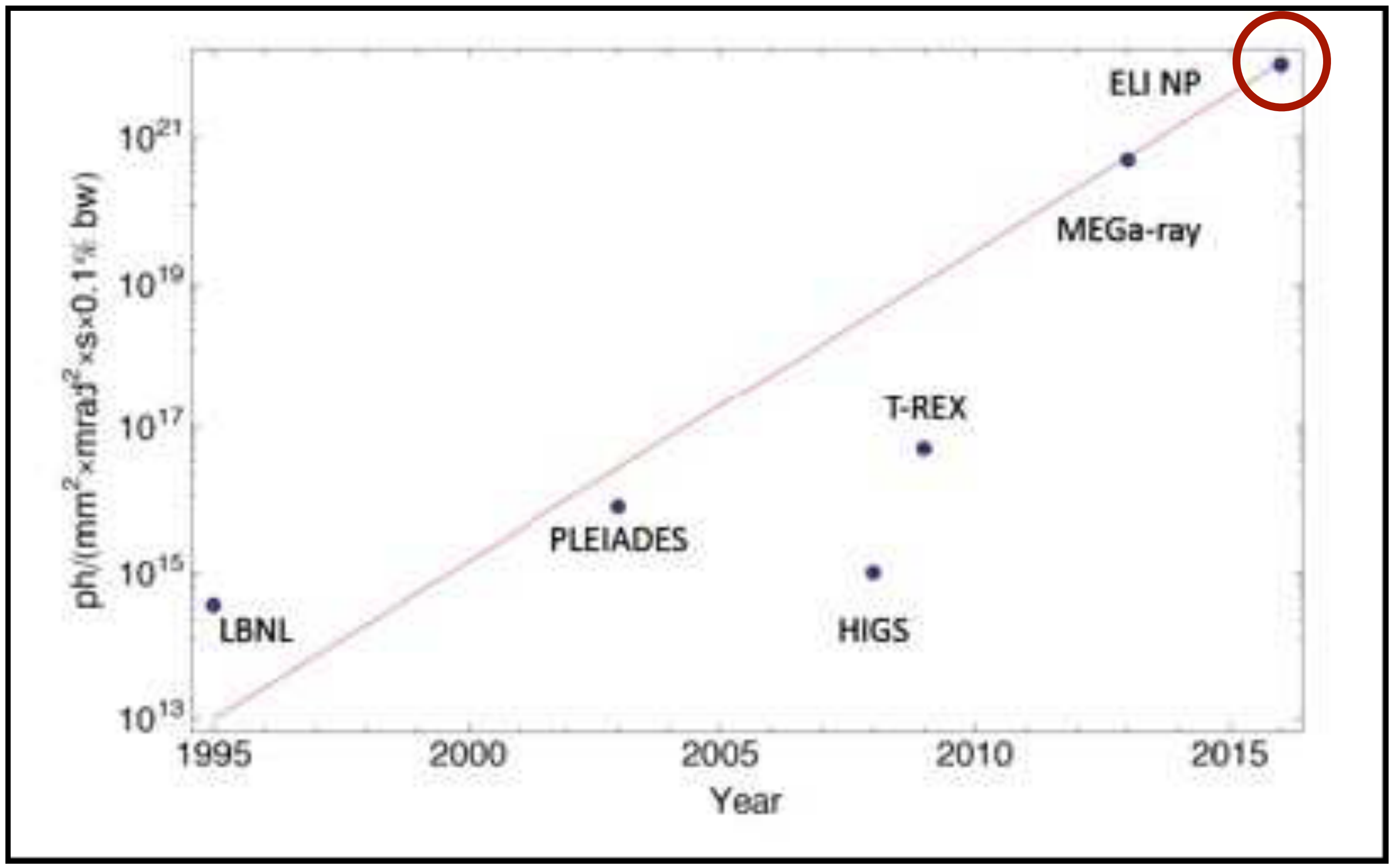


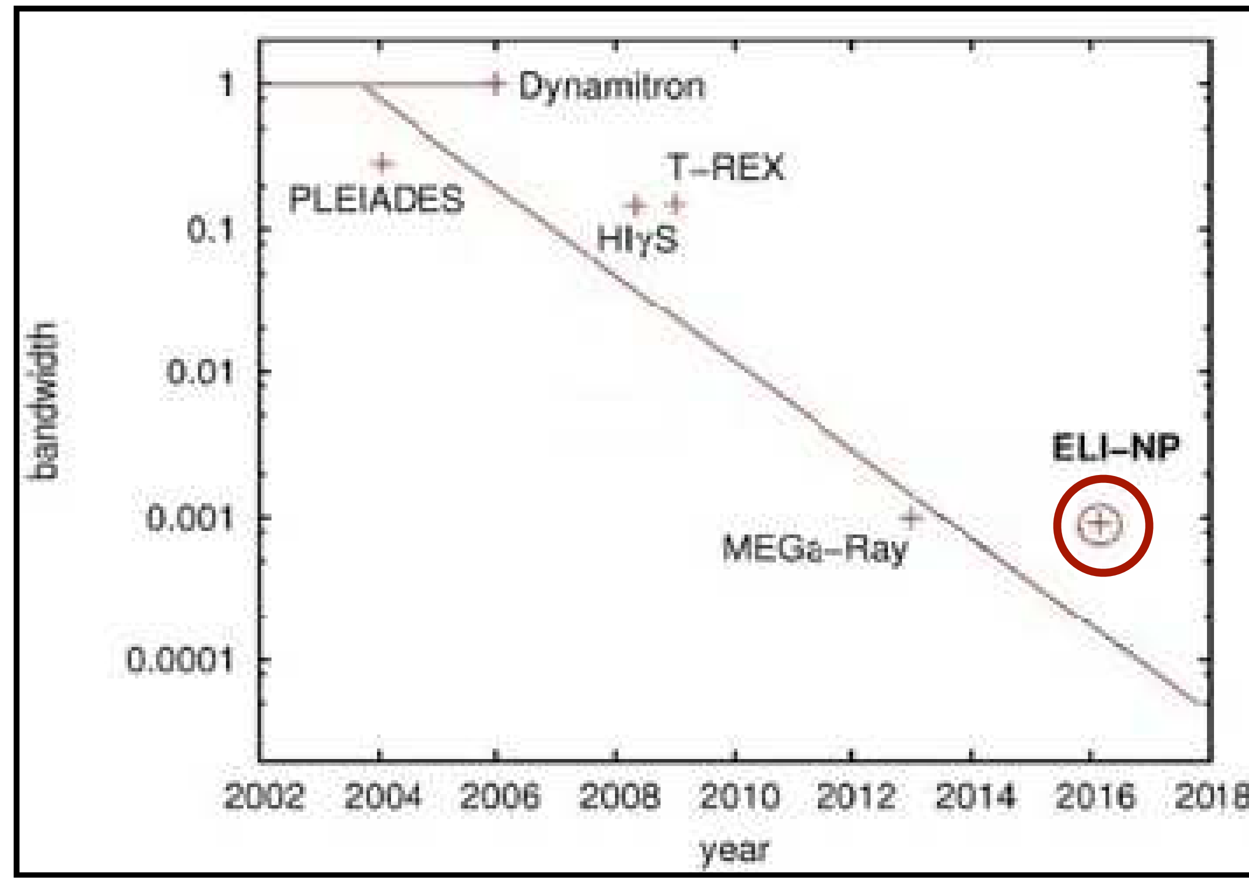


Thank you for your attention

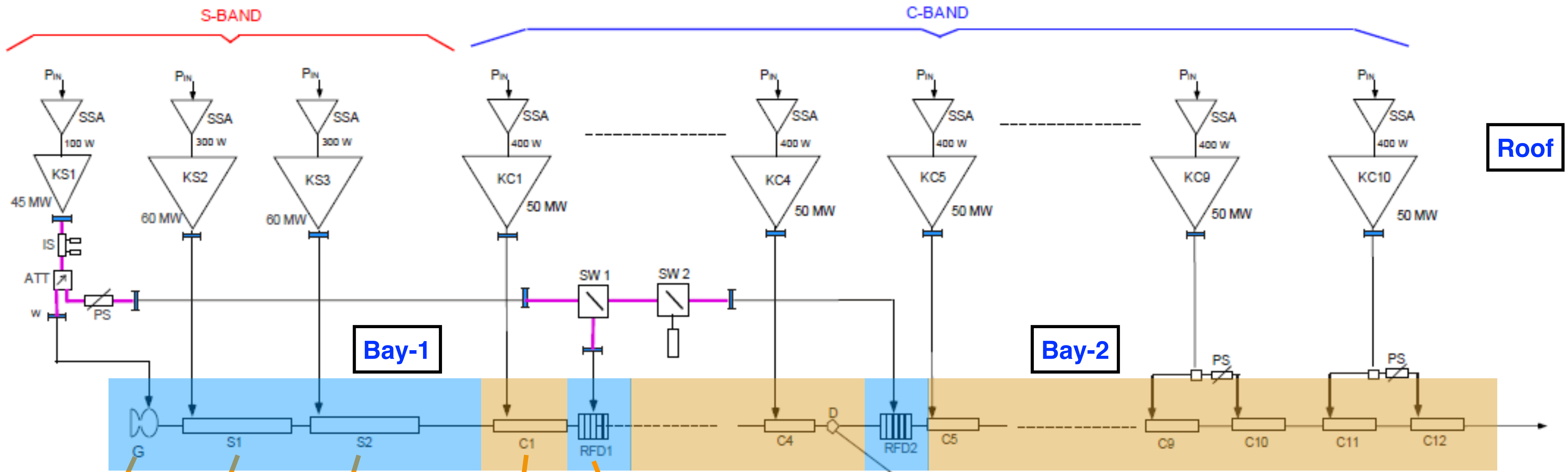
ELI performance

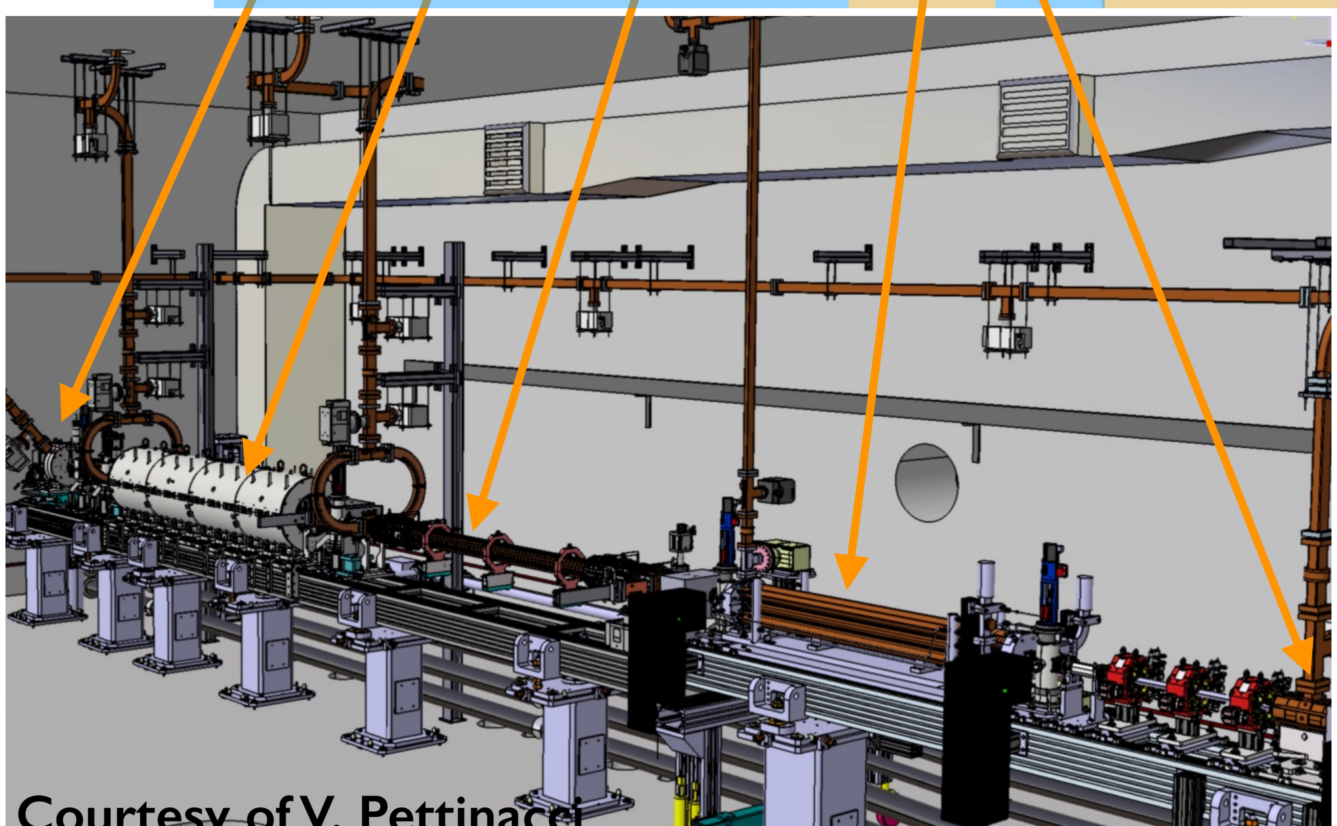
2 orders of magnitude higher fluxes than state of the art, short bandwidth (< 0.5%)





RF power sources & distribution system





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S-band injector

C-band booster

Waveguides:

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- C-band: WR-187 (0.03 dB/m)

S-band network (SF6):

- Isolator, Attenuator (0-20 dB), Phase shifter, 2 x RF switch.

Libera LLRF system - (Instrumentation Technology)

Parameter	Value
Number of input channels	8 per module
ADC resolution	16 bits
Max ADC sampl. freq.	130 MHz
Memory size per module	8 Gbits
Maximum RF input power	20 dBm
Maximum RF output power	13 dBm
RF station RMS jitter (long term)	100 fs
Phase resolution (added jitter)	< 10 fs
Amplitude resolution	0.1% RMS

Libera-LLRF features:

Signal monitoring
- values (voltage, phase, power, frequency…);
- fast ADC (up to 130 MHz);

Control loops for RF field:
- pulse to pulse feedback (with selectable input signal);
- klystron feedback loop (gain, phase);
- adjustable pulse shape (during operation) and beam loading compensation;

Operation mode:
- CW;
- pulsed;
- combined CW & pulsed;

HW configuration (single module):

1 receiver module (front-end) w. 8 RF inputs
1 trasmitter module (back-end) w. 1 RF output (I/Q)
1 timing module (clock for ADC, FPGA, DAC) + ILK
1 IF & LO generation module from reference signal
RF splitter for each Libera LLRF unit

ELI-NP Low Level RF system - transmitter/modulator

Generation and shaping of the RF pulse (Beam loading & energy spread compensation)

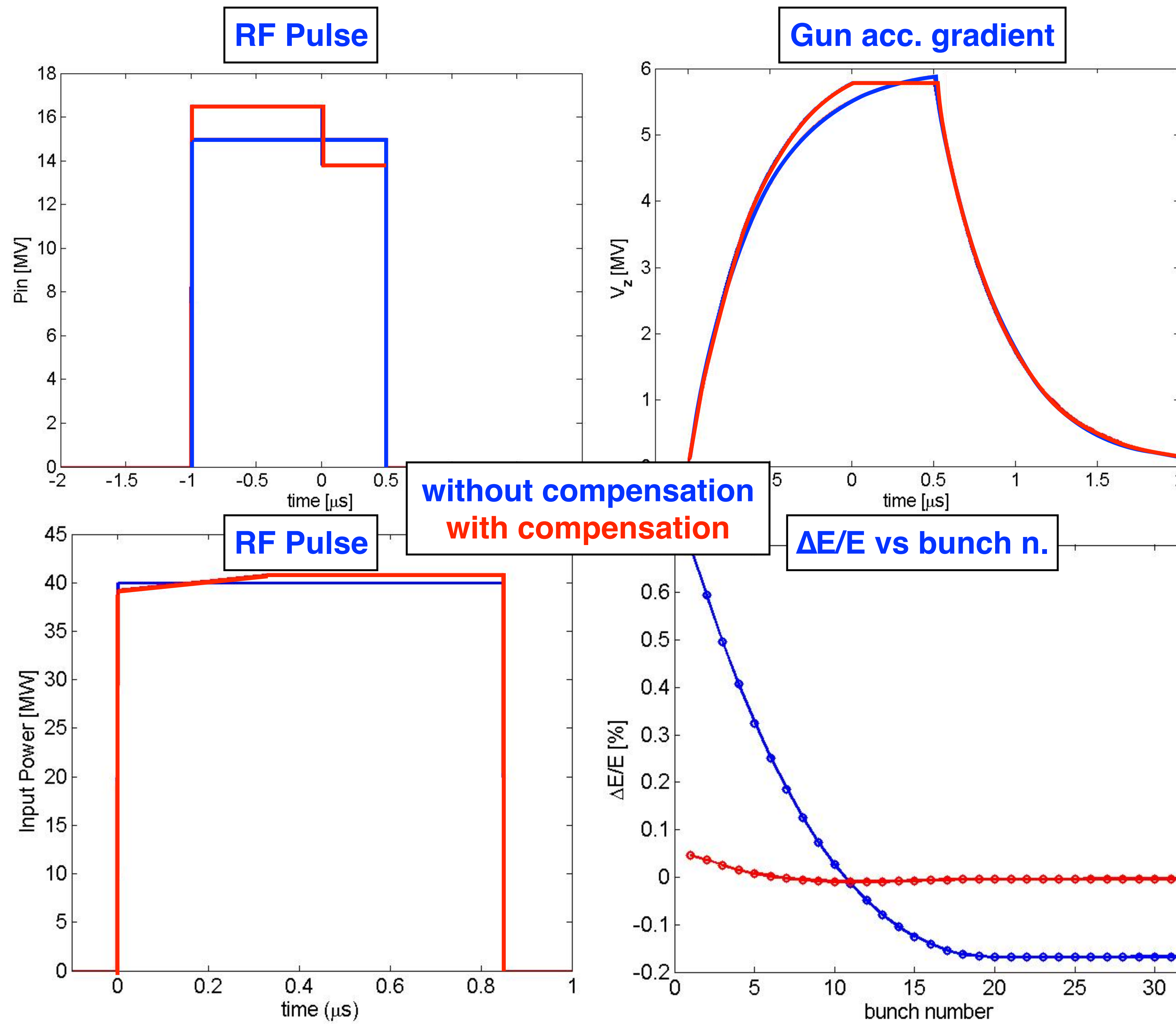
LLRF modules produced by Instrumentation Technologies (SL), according to INFN specifications

RF-Gun pulse shaping
energy spread compensation

The S-Band gun is a SW cavity and it has a finite filling time. In order to generate a **flat top in the accelerating field (**so to avoid energy spread in the bunch train) RF pulse shaping has to be performed. BL is negligible with respect to this “cavity filling time effect”.

C-band structures pulse shaping
beam loading compensation

The main effect of the BL is the **decrease of the accelerating field gradient** in the structure, since the effective field can be assumed as a superposition of the RF field and the induced wakefield. **The BL can be compensated with a proper shape of the input RF pulse**.



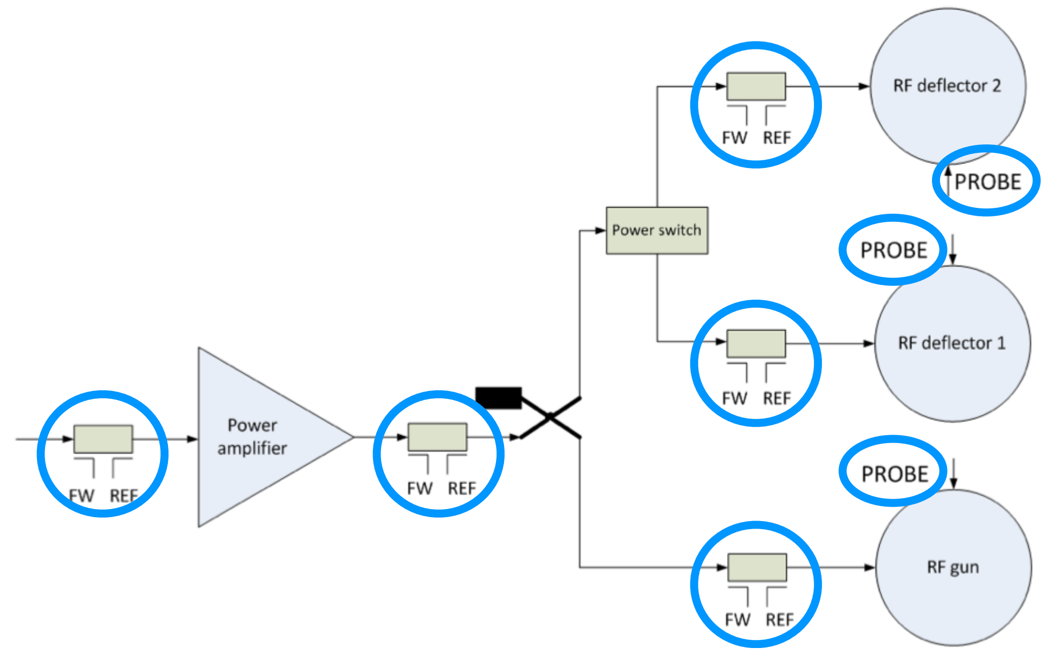
ELI-NP Low Level RF system - receiver/demodulator

- monitoring signals extracted from the accelerating sections (probes, directional couplers, etc…)
- amplitude and phase feedback to stabilize/control RF pulses

Total 13 modules (3 S-band + 10 C-band) Libera LLRF

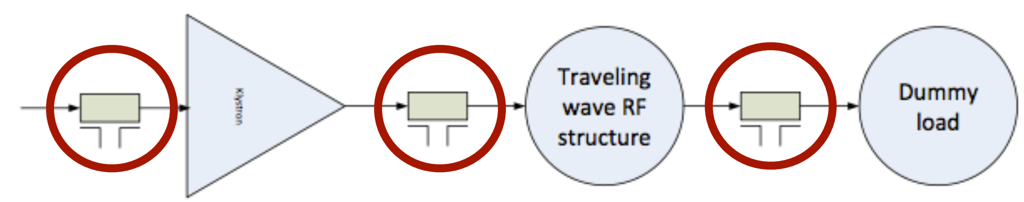
13 RF signals from SW structures (Gun + RFD)

- VM out (FWD-REF)
- KLY out (FWD-REF)
- RF-Gun in (FWD-REF) + Gun probe
- 2 x RFD in (FWD-REF) + 2 x RFD probe



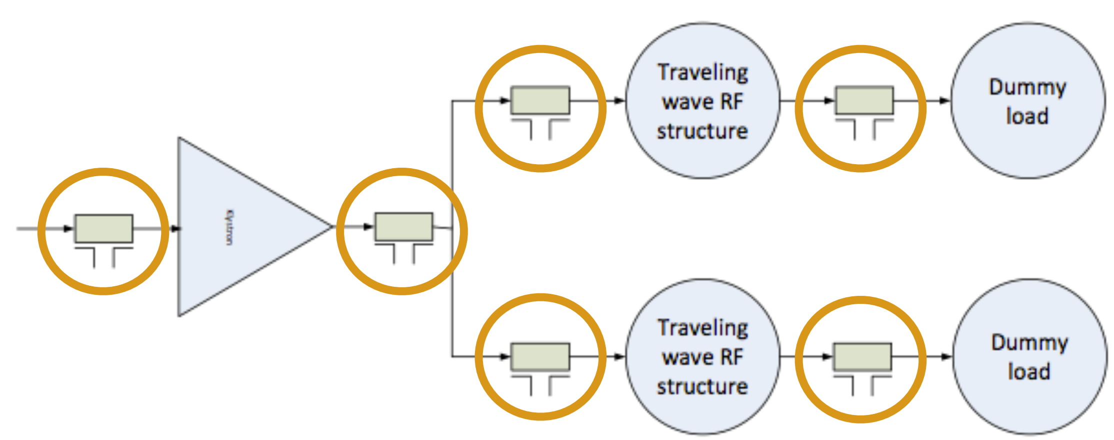
2 x 6 RF signals from S-band TW structures
8 x 6 RF signals from C-band TW structures

- VM out (FWD-REF)
- KLY out (FWD-REF)
- SEC out (FWD-REF)



2 x 12 RF signals from the last 4 TW structures

- VM out (FWD-REF)
- KLY out (FWD-REF)
- 2 x SEC in (FWD-REF)
- 2 x SEC out (FWD-REF)



RF Gun - main specifications

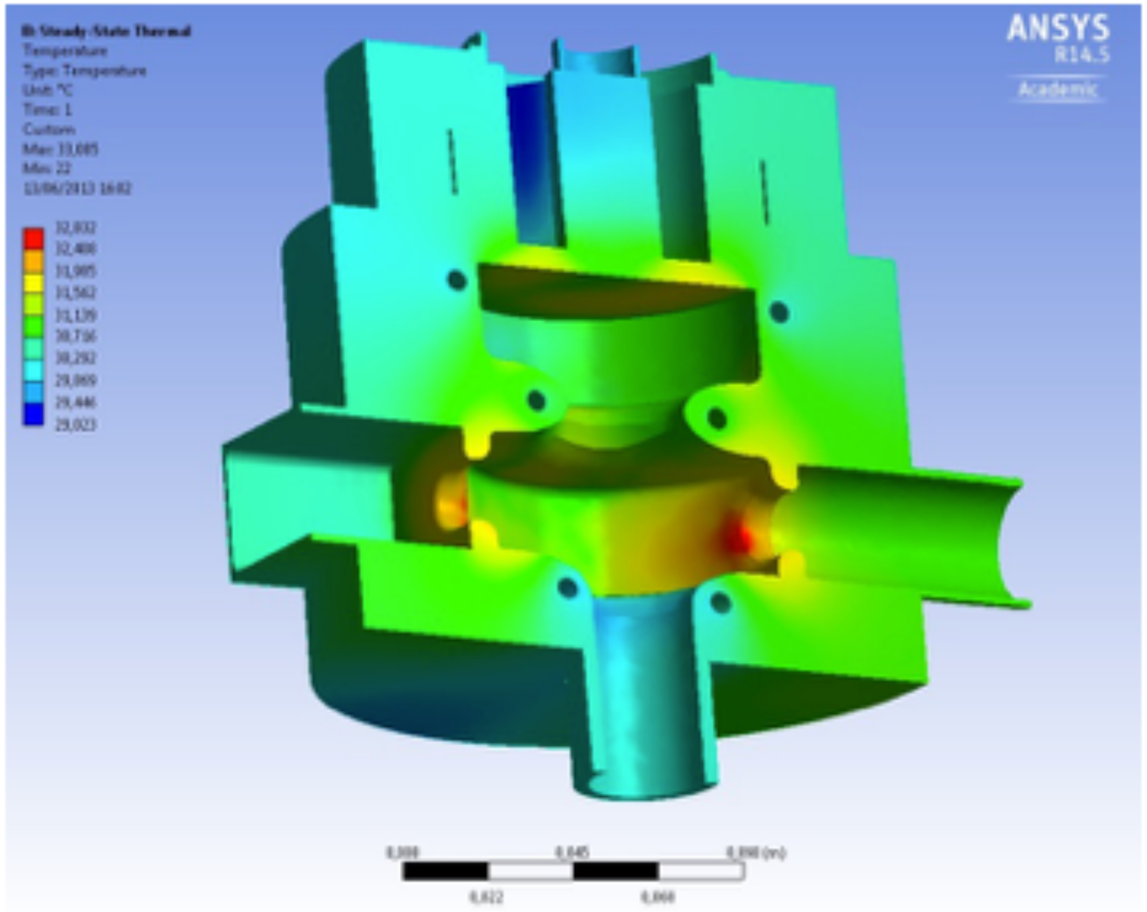
	Unit	Value
RF frequency	GHz	2.856
Repetition rate	Hz	100
Working mode		π SW
Max RF peak input power	MW	16
Peak field at cathode	MV/m	120
Max RF pulse duration	μs	2 (1.5 nominal)
Total beam duration	μs	0.5
Unloaded Q factor		14500
Average dissipated power	kW	1.3
Working temperature	°C	32
Coupling coefficient		3
Filling time	μs	0.42
Shunt impedance	MΩ	1.7
Operating vacuum pressure	mbar	$1 \div 5 \cdot 10^{-9}$
Type of cathode		copper
Cathode quantum efficiency @ 266 nm		$5 \cdot 10^{-5}$

S-band Gun thermal design

-A **detailed thermal analysis** has been performed to investigate the impact of the **100 Hz/long RF pulse** (for multi-bunch) operation.

-The **average dissipated power in the gun, is about 1.3 kW**. Thermal simulations has been performed using ANSYS and the same cooling pipes distribution of the new SPARC gun with a cooled cathode (the ELI-NP cooling system has been further improved and a final check on the thermal analysis has to be done).

-The **deformation due to the temperature increase gives a -400 kHz variation** of the resonance peak during operation at 100 Hz, full power and it's, therefore, necessary to **lower water temperature by -10 °C to keep the gun on resonance** during RF feeding (control of the chiller needed).



[V. Pettinacci, D. Alesini, L. Pellegrino and L. Palumbo, THPRI043, Proceedings of IPAC2014, p. 3860]
[V. Pettinacci, D. Alesini, L. Pellegrino and L. Ficcadenti, Thermal Analysis of a Radiofrequency Gun, ANSYS USER GROUP MEETING ITALIA , 2013]

S-band structures - main specifications - RI

	Unit	Value
RF frequency	GHz	2.856
Repetition rate	Hz	100
Number of cells	#	84+1 in+1 out coupler
Working mode		2π/3 TW
Phase velocity	/c	1
Group velocity	/c	2% - 0.6%
Max RF peak input power	MW	45
Average accelerating gradient	MV/m	23.5
Average dissipated power	kW	4.5
Unloaded Q factor		12300
Attenuation constant	neper	0.6
Working temperature	°C	30
Coupling coefficient		3
Filling time	μs	0.8
Shunt impedance	MΩ	53
Operating vacuum pressure	mbar	$5 \cdot 10^{-9} - 10^{-8}$
Max RF pulse duration	μs	1.3
Total beam duration	μs	0.5
Total length	m	3
Iris half-aperture	mm	13-9.5
Type		CG

C-band structures - main specifications

	Unit	Value
RF frequency	GHz	5.712
Repetition rate	Hz	100
Number of cells	#	102+1 in+1 out coupler
Working mode		2π/3 TW
Phase velocity	/c	1
Group velocity	/c	2.5%-1.4%
Max RF peak input power	MW	40
Average accelerating gradient	MV/m	33 (38-28)
Average dissipated power	kW	2.3
Unloaded Q factor		8800
Attenuation constant	neper	0.7
Working temperature	°C	30
Coupling coefficient		3
Filling time	μs	0.31
Shunt impedance	MΩ	67 - 73
Operating vacuum pressure	mbar	$5 \cdot 10^{-9}$ - 10^{-8}
Max RF pulse duration	μs	0.82
Total beam duration	μs	0.5
Total length	m	1.8
Iris half-aperture	mm	6.8-5.78

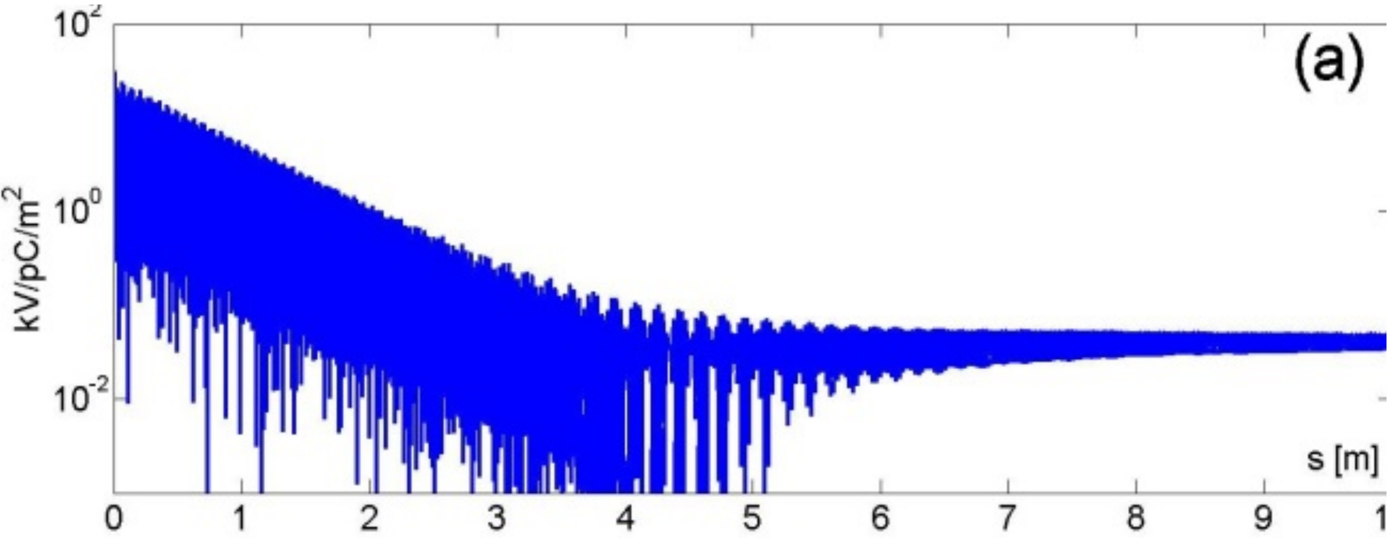
High Order Modes (HOM) damping

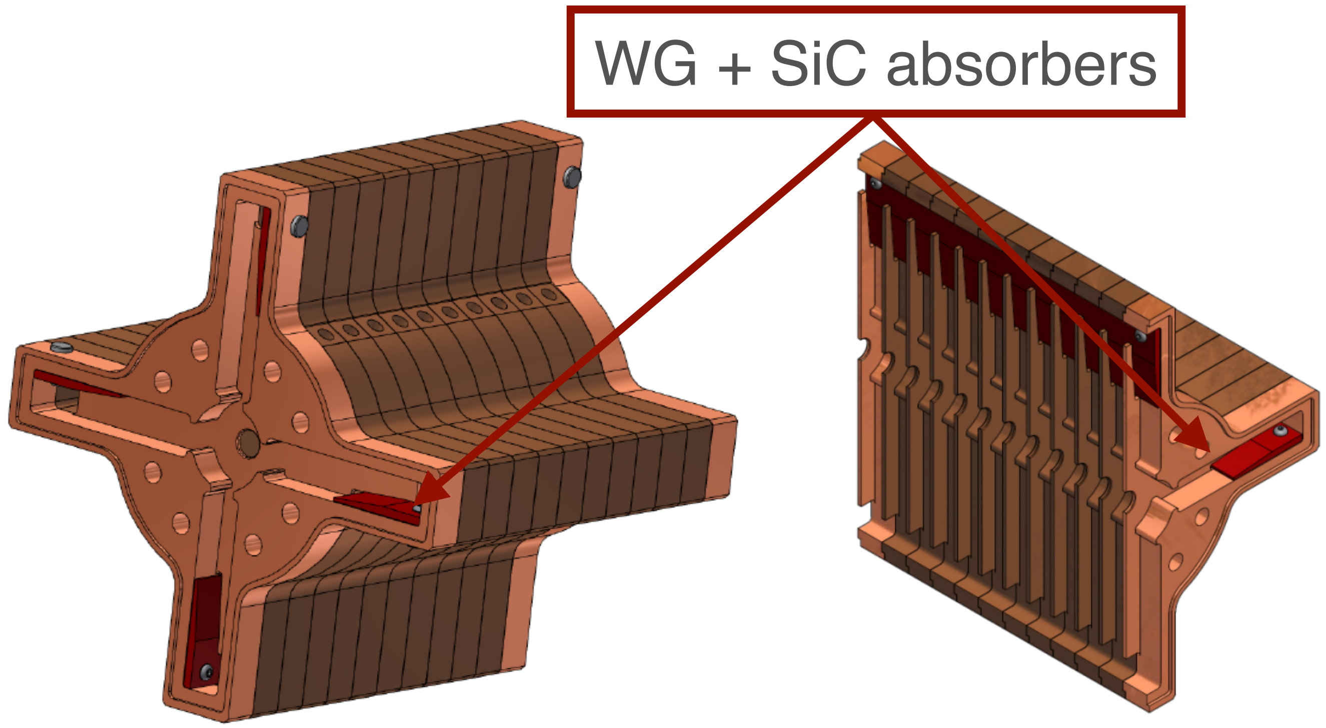
PROBLEM:
Multi bunch mode operation (32 bunches per pulse - rep. rate 100 Hz)
EM wakefields excited in the structure as a consequence of electron bunches passage
Wakefields can have longitudinal and transverse components - affect beam dynamics beam loading, instability, Beam Break Up (BBU) respectively

ADOPTED SOLUTION [2]:
Each cell has 4 waveguides that propagate and dissipate the excited HOMs into SiC RF loads
Each cell has 4 tuners and hosts 8 cooling pipes => thorough optimization of the mechanical layout
SiC absorbers geometry has been simplified keeping constant the damping performance

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

Transverse wake potential per unit length





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