Elettra Sincrotrone Trieste

Elettra
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Trieste

Status of FERMI upgrade, RF system development & test

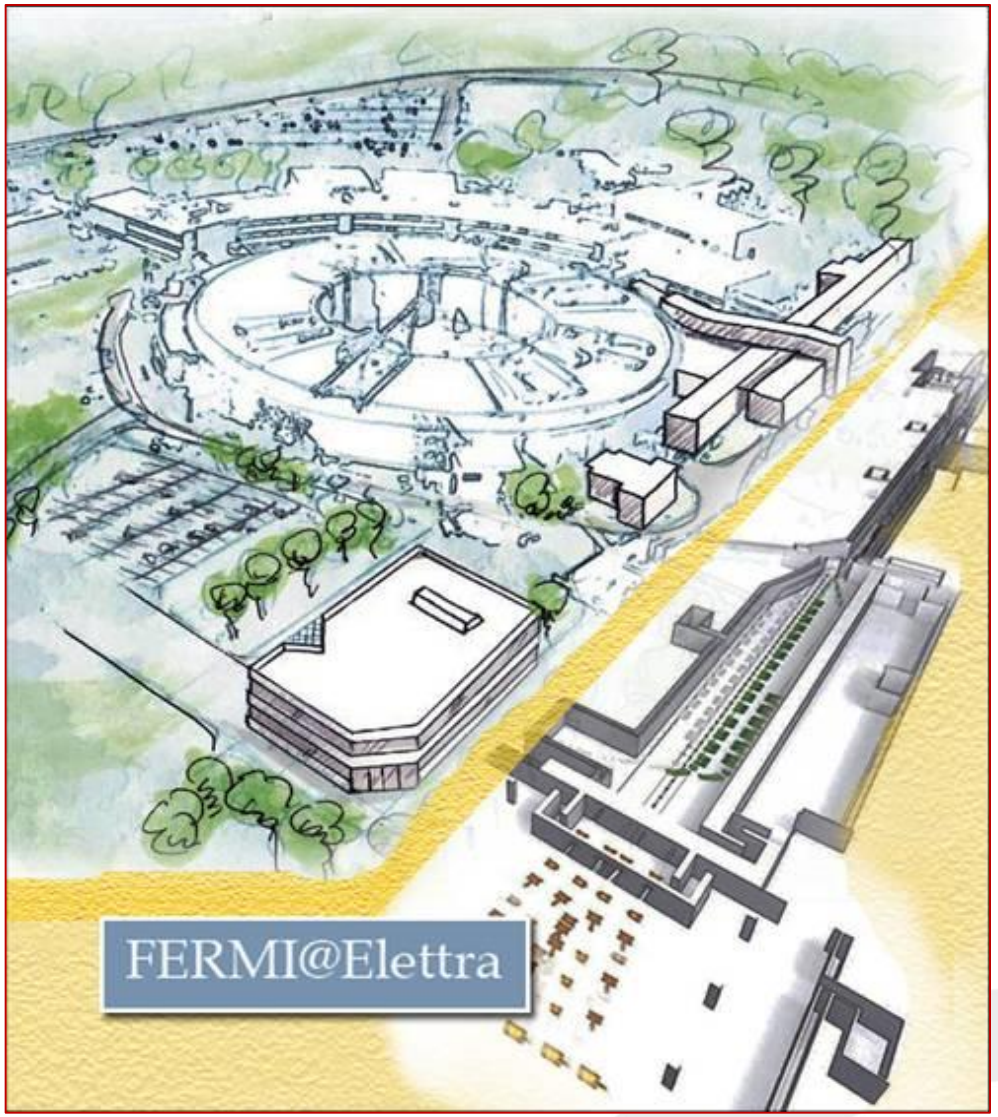
Nuaman Shafqat

on behalf of

S-Band RF Systems Team

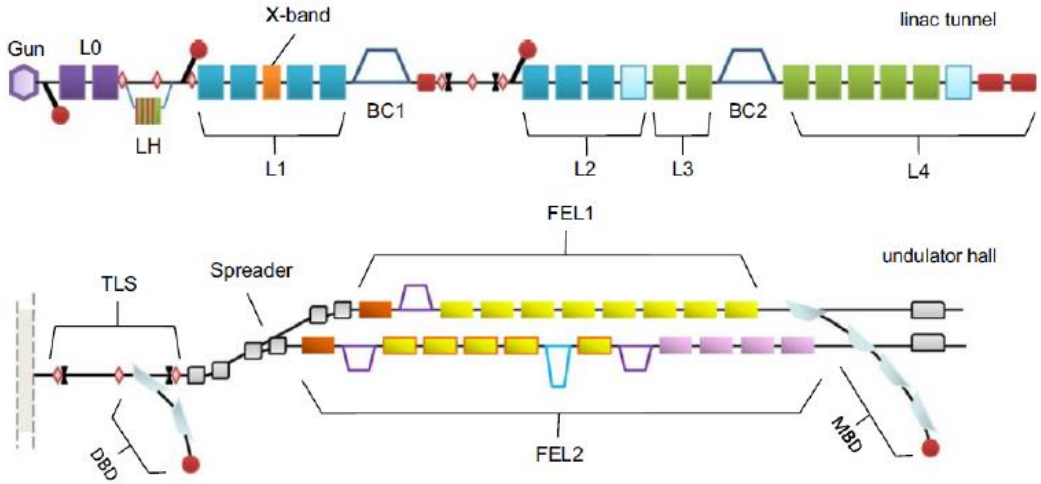
LAYOUT

- What is FERMI
- FERMI Upgrade
  - Beam energy upgrade
  - Beam quality upgrade
- FERMI linac
- High Gradient module
  - RF design
  - Fabrication & testing of short prototype
  - Fabrication & testing of full HG module
- High power S-band waveguide components
  - In-vacuum phase shifter
  - Spherical pulse compressor
- Summary and conclusions



THE FERMI FEL

The **FERMI** linac-based FEL at the Elettra Laboratory (Trieste, IT) is an international user facility for scientific investigations in material science.
The electron bunches are produced in a laser-driven photo-injector and accelerated, with a **3-GHz, normal conducting Linac**, to energies up to **1.5 GeV**,



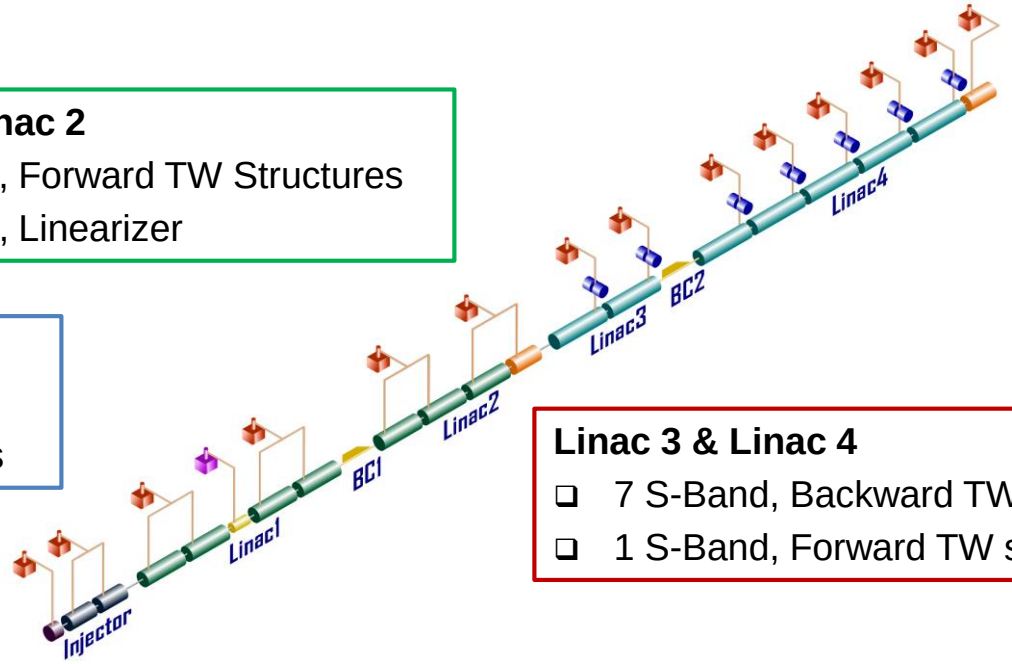
The FERMI facility comprises two separate coherent radiation sources, **FEL-1** and **FEL-2**.
FEL-1 operates in the wavelength range between **100 and 20 nm** via a single cascade harmonic generation, while the **FEL-2** is designed to operate at shorter wavelengths (**20-4 nm**) via a double cascade mechanism.

THE FERMI LINEAR ACCELERATOR

The **FERMI Linac** is a S-Band (3 GHz), **1.5 GeV** normal conducting, linear accelerator.

Linac 1 & Linac 2
- 8 S-Band, Forward TW Structures
- 1 X-Band, Linearizer

Injector:
- 1 S-Band, RF Gun
- 2 S-Band, Forward TW structures



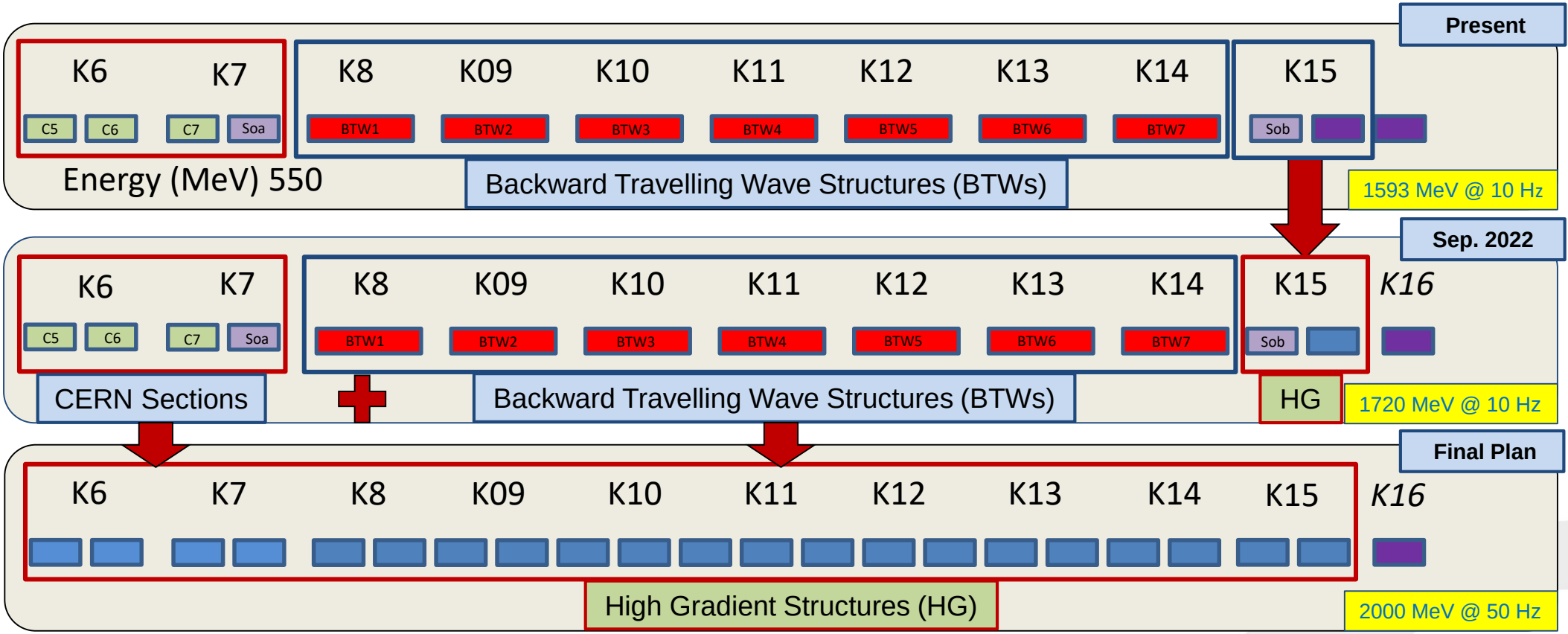
Linac 3 & Linac 4
- 7 S-Band, Backward TW Structures
- 1 S-Band, Forward TW structure

- **Power Sources**: 45 MW peak power, 4.5 μs pulse width, Klystron
- **Linac 1 & Linac 2**: one klystron feeds two FTW accelerating structures
- **Linac 3 & Linac 4**: one klystron feed one BTW accelerating structure

In order to reach a beam energy of **2.0 GeV**, all the BTW structures will be replaced & all the CERN sections will be pushed to higher gradient operation

THE FERMI FEL UPGRADE PLAN
BEAM ENERGY UPGRADE

- **To reduce pulse duration to the sub-10 fs** range to resolve charge transfer processes, bond dynamics, vibrational dynamics
- **To extend photon energy range to N (410 eV), O (543 eV)** which translates to the extension of operating of FERMI to **~2 nm**.

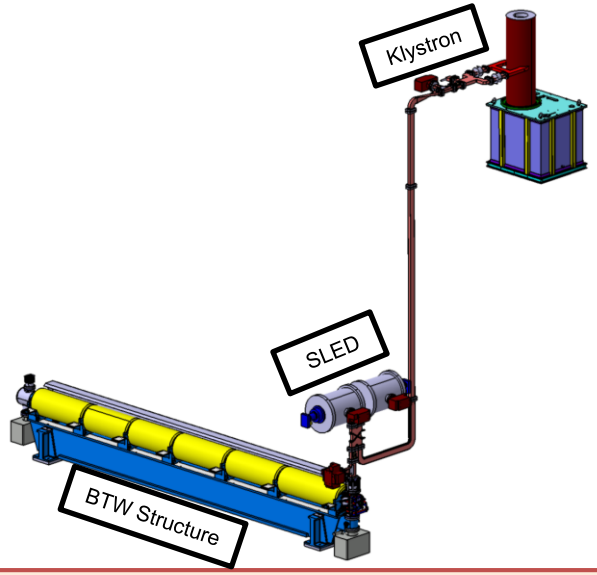


L. Giannessi., "FERMI Upgrade Perspectives" , *in FUture of Seeded free Electron lasers. (FUSEE)*, Trieste, Italy, 10 Nov. 2019

FERMI LINAC UPGRADE PALN
ACC. SECTIONS TO BE REPLACED

CERN Sections

- Developed as injector of LEP Injector Linac (LIL) in **1984**
- One **45 MW** klystron feeds two 4,5 m CERN sections.
- Accelerating gradient is **12,6 MV/m.**
- **Three** out of seven CERN sections would be replaced by HG structures



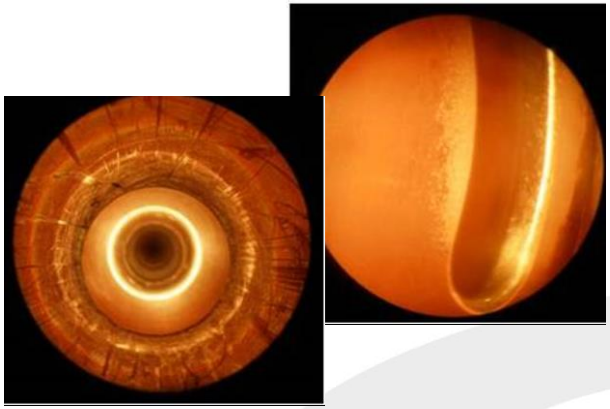
Backward Travelling Wave Sections

- Designed specifically for FERMI
- Each BTW section is fed by **45 MW** klystron followed by **SLED**.
- Suffer from frequent breakdowns and are limited to **18,0 MV/m at 50 Hz**
- **All seven** would be replaced by HG structures

Parameter	S0A-S0B	C1-C7	S1-S7
Mode	TW2/3π	TW 2/3π	BTW3/4π
Frequency (MHz)	2998.01	2998.01	2998.01
Total length (m)	3.2	4.5	6.15
Filling time (μs)	0.903	1.5	0.757
Attenuation (Np)	0.603	0.7	0.611
Acc. gradient (MV/m)	15.8	13.1	23.6
Energy gain (MeV)	50	60	145

S0a and S0b Sections

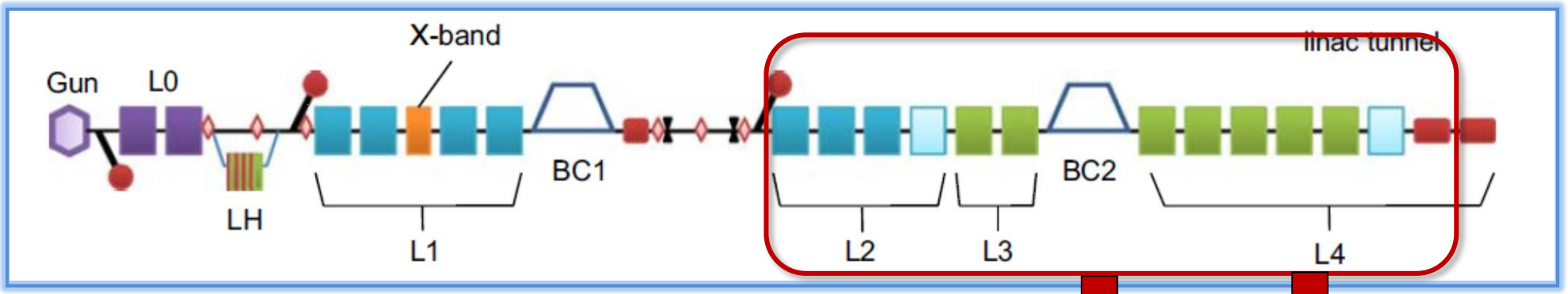
- Came from the old Elettra injector.
- One **45 MW** klystron feeds two 3,2 m S sections.
- Accelerating gradient is **15,0 MV/m.**
- **Both S0a and S0b** would be replaced by HG structures



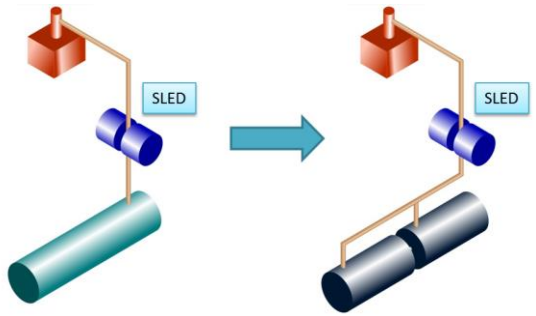
THE FERMI UPGRADE PROPOSAL

TO EXTEND THE RANGE TO SHORTHER WAVELENGTH UP TO 2 nm

Actual Linac Energy	→	Target Linac Energy	→	Solution
1.5 GeV @ 10Hz		**2.0 GeV @ 50Hz**		**High Gradient 30MV/m**



Replace 12 acc. sections + one deflector with 10 HG modules



Energy budget of upgraded linac

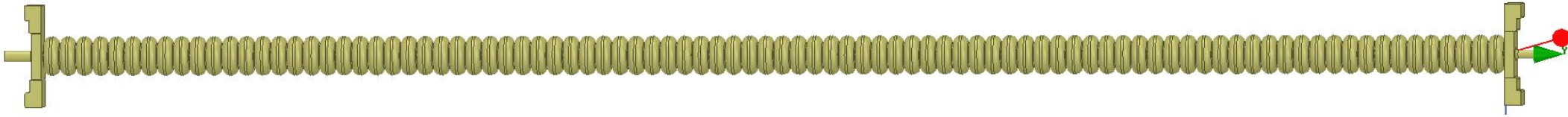
Total Energy (MeV) = 2xRI+4xCERN+20xHG

Total Energy (MeV) = 2x50MeV+4x57Mev+20x90MeV

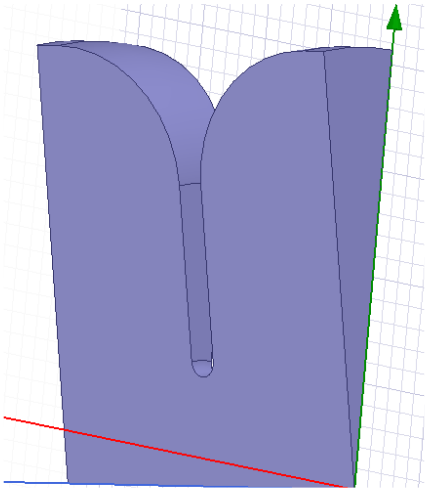
Total Energy (MeV) = 2128

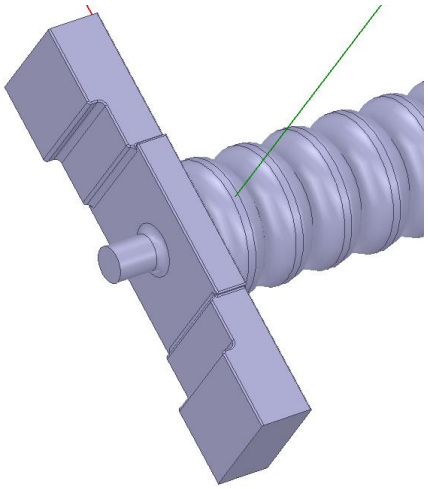
It means we can operate HG sections at 28 MV/m

NEW ACCELERATING MODULE



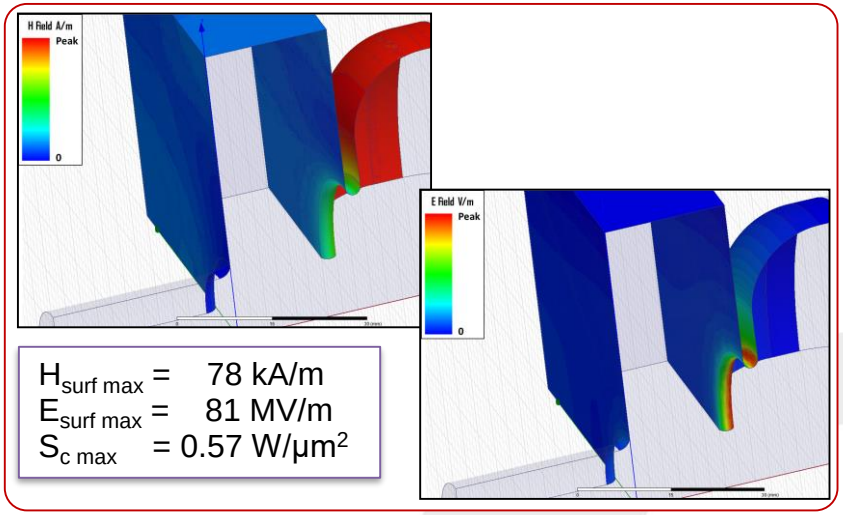
- The new accelerating module will be comprised of 3.0 m long, **constant gradient type** structures. **Double rounding** is introduced to reduce Ohmic losses and increase Q
- A customized version of **dual-fed-electric coupled (EC) coupler** is chosen for the new high gradient (HG) structures
  - Very low surface magnetic field
  - Easy to machine
  - Reduced cost of fabrication





Structure RF Parameters		
L	2988.3	mm
N_{cell}	84	
a	11.13 → 8.8	mm
R_{sh}	72.07 → 80.70	MΩ/m
Q_0	15850	
Filling Time	644.8	ns
Attenuation	0.383	Neper

Coupler RF Parameters		
	Input Coupler	Output Coupler
E_{surf} [MV/m]	78	82
H_{surf} [kA/m]	69	71
S_c [MW/mm^2]	0,47	0,39
k_q [V/ms]	1956	1319



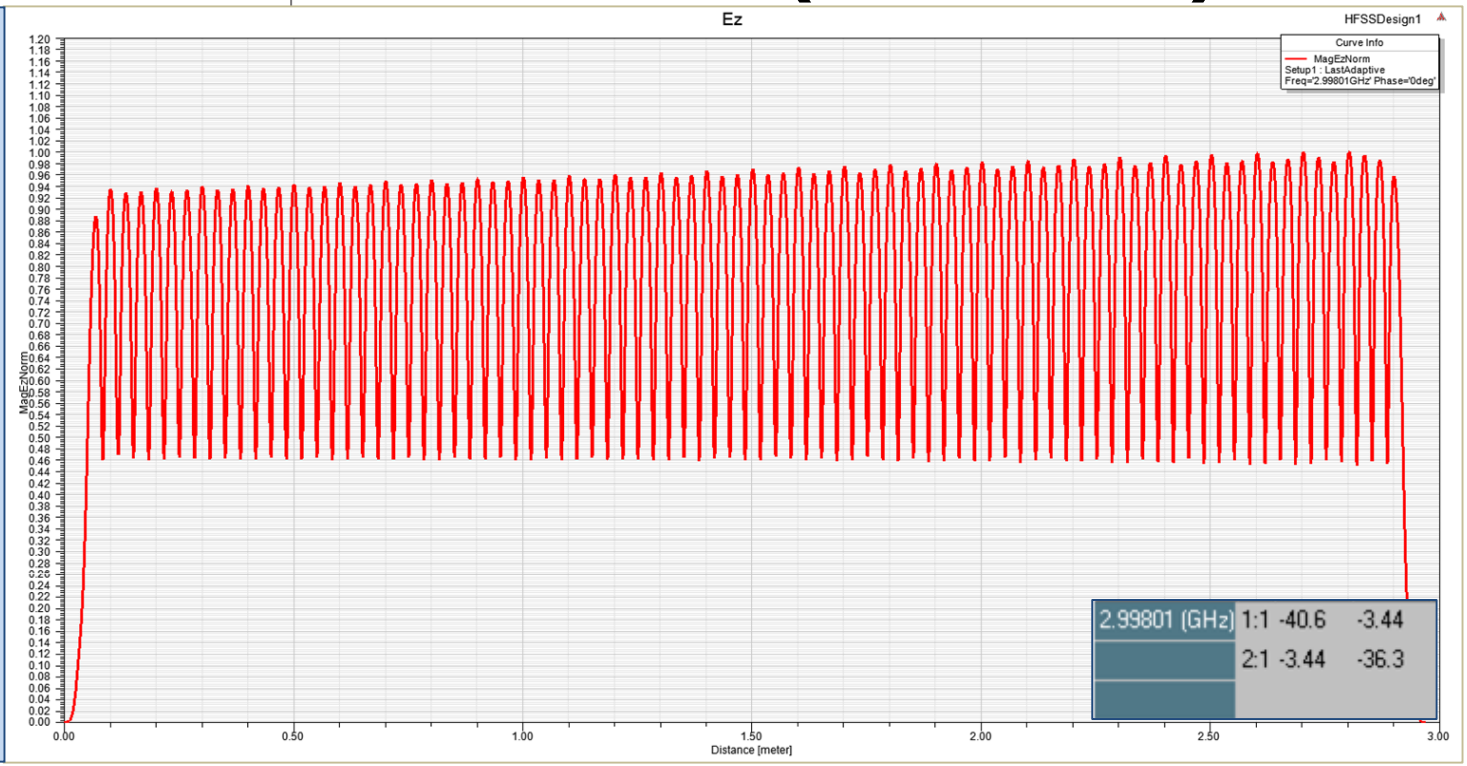
$H_{surf\ max}$ = 78 kA/m
$E_{surf\ max}$ = 81 MV/m
$S_{c\ max}$ = 0.57 W/μm^2

C. Serpico, N. Shafqat, A. Grudiev, and R. Vescovo, "High gradient high reliability, and low wakefields accelerating structures for the FERMI FEL", *Review of Scientific Instruments*, vol. 88, p. 073303, 2017

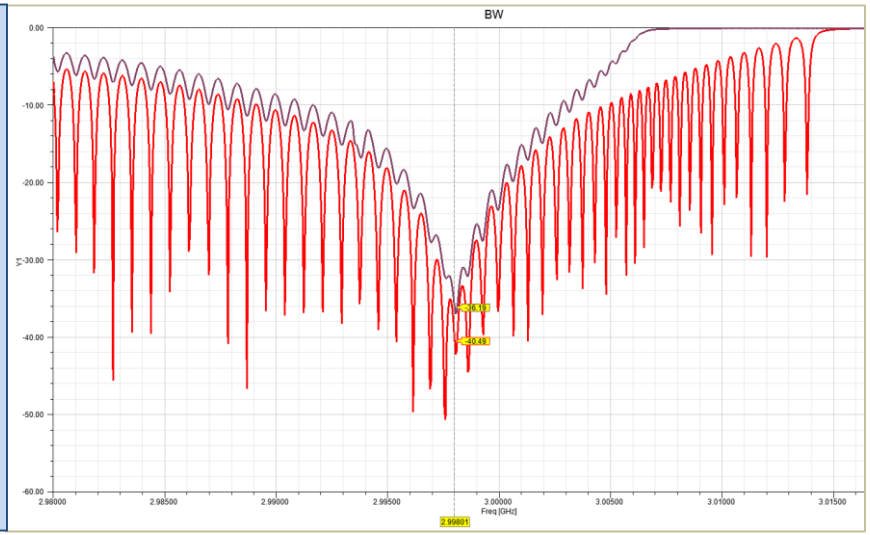
N. Shafqat, S. Di Mitri, C. Serpico, and S. Nicastro, "Design study of high gradient, low impedance accelerating structures for the FRRMI free electron laser upgrade", *Nuclear Instruments and Methods in Physics Research A*, vol. 867, pp. 78-87, 2017

RF Analysis of Full HG Structure (3.0 meter)

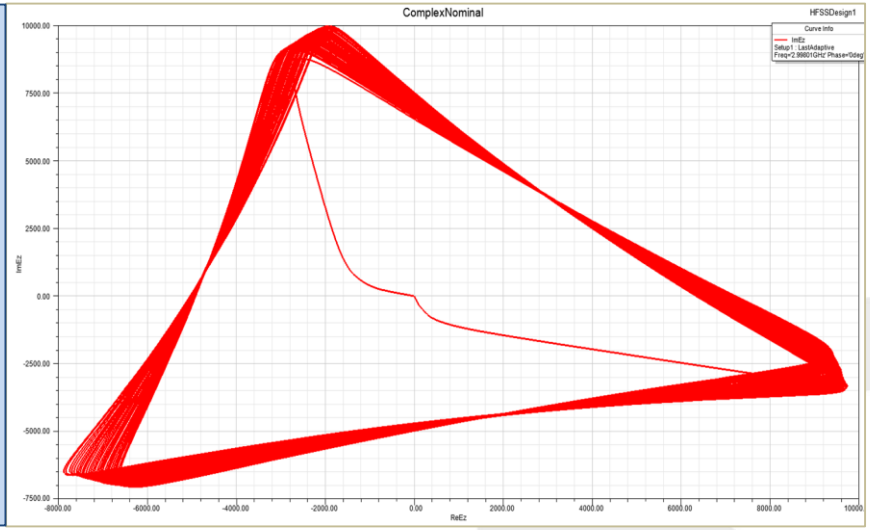
Normalized Magnitude of Ez



Bandwidth



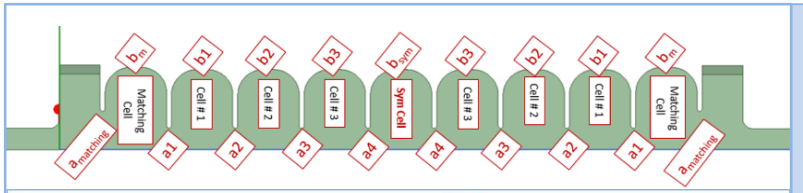
ImEz vs ReEz



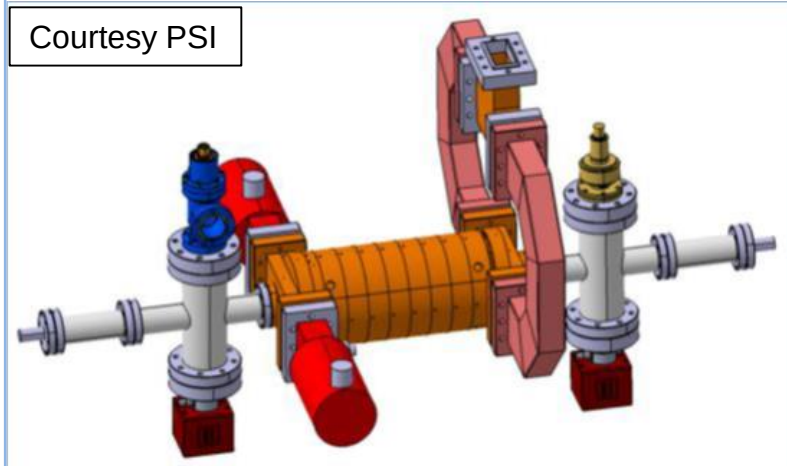
N. Shafqat et al., "Design and high-power test of a short prototype of high gradient S-band accelerating structure for the FERMI free electron laser linac upgrade")", *Nuclear Instruments and Methods in Physics Research A*, vol. 979, Nov. 2020

PSI Prototype Factory Acceptance Test

- To prove the reliability and the feasibility of the upgrade plan, a short prototype has been built in collaboration with Paul Scherrer Institute (PSI).
- The prototype is realized using the same structure technology as developed for SwissFEL
- The prototype is made by 7 regular cells & 2 EC-couplers.
- Cells & couplers are realized with ultra-high precision with tolerance of +/- 4µm.
- Prototype is machined on tune.



Courtesy PSI



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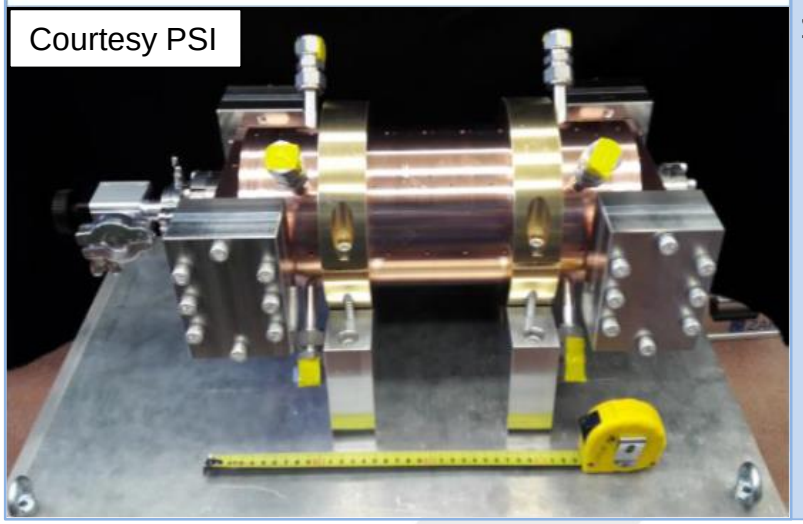
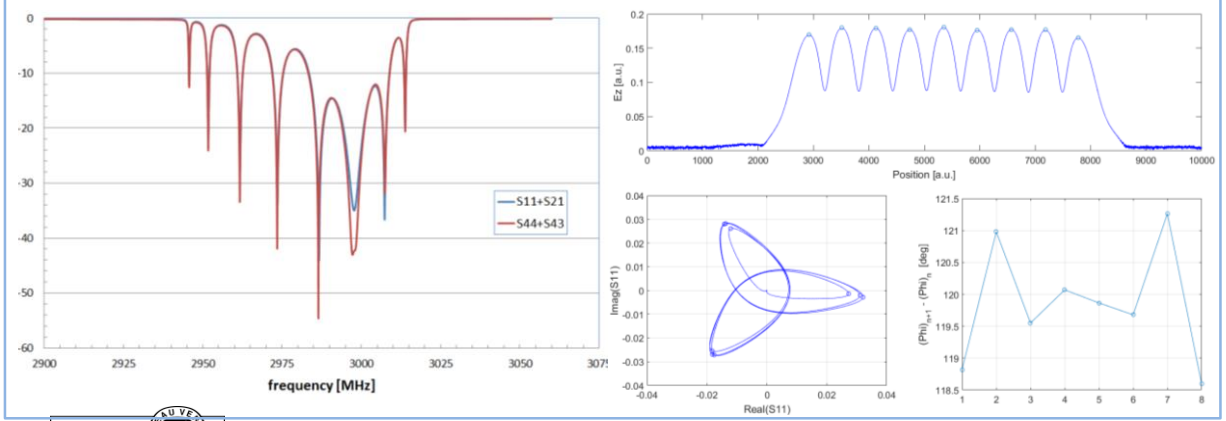


Short HG Prototype

RF measurements and bead-pull rest at PSI

Courtesy PSI

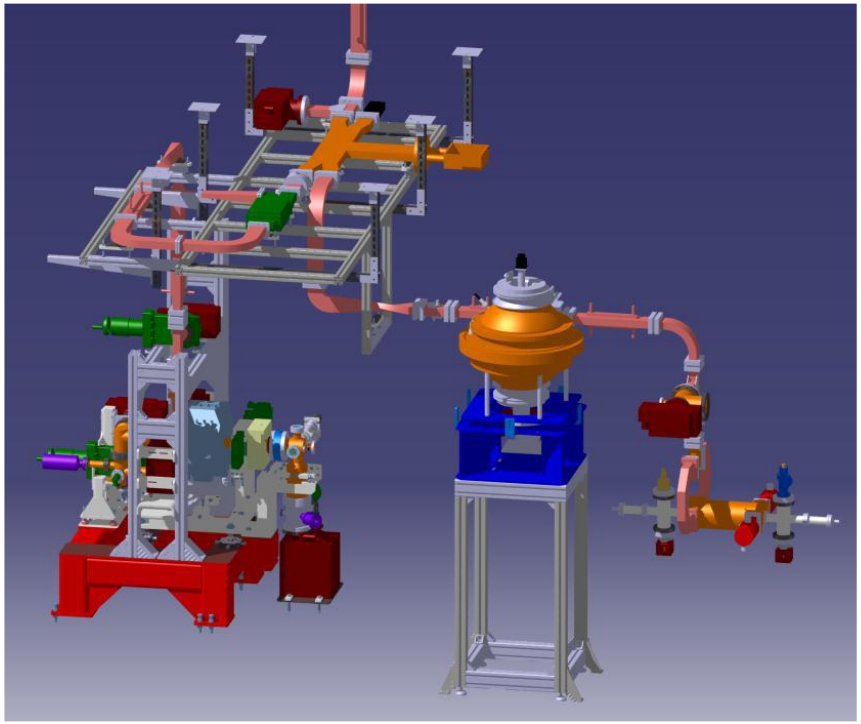


U. Ellenberger et al., "Status of the Manufacturing Process for the SwissFEL C-Band Accelerating Structures" , in *Proc. 35th Int. Free Electron Laser Conf. (FEL'13)*, New York, NY, USA, Aug. 2013, paper TUPSO17 , pp. 245-249.

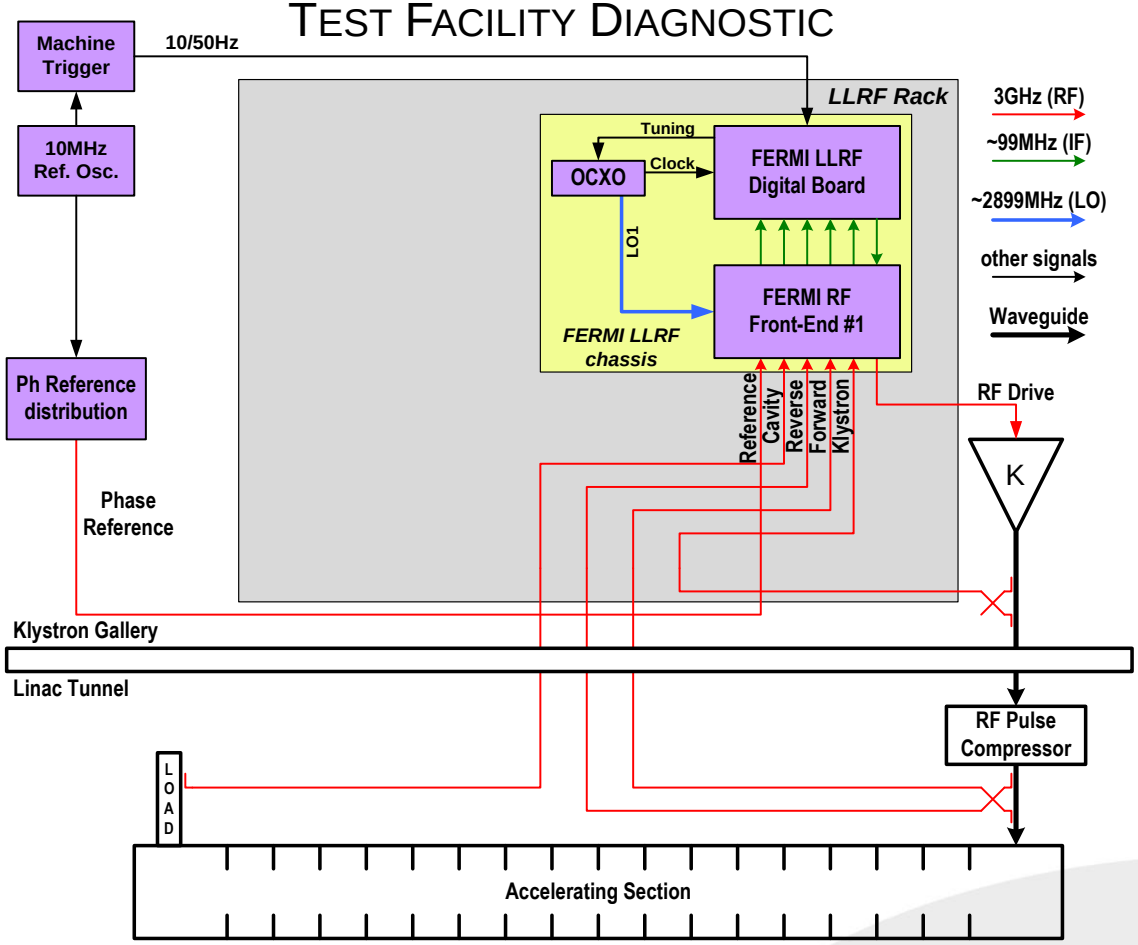
FERMI CAVITY TEST FACILITY

FERMI linac stations hot spare, has been upgraded to act also as a complete S-Band RF Cavity Test Facility (CTF)

TEST FACILITY @ ELETTRA



TEST FACILITY DIAGNOSTIC



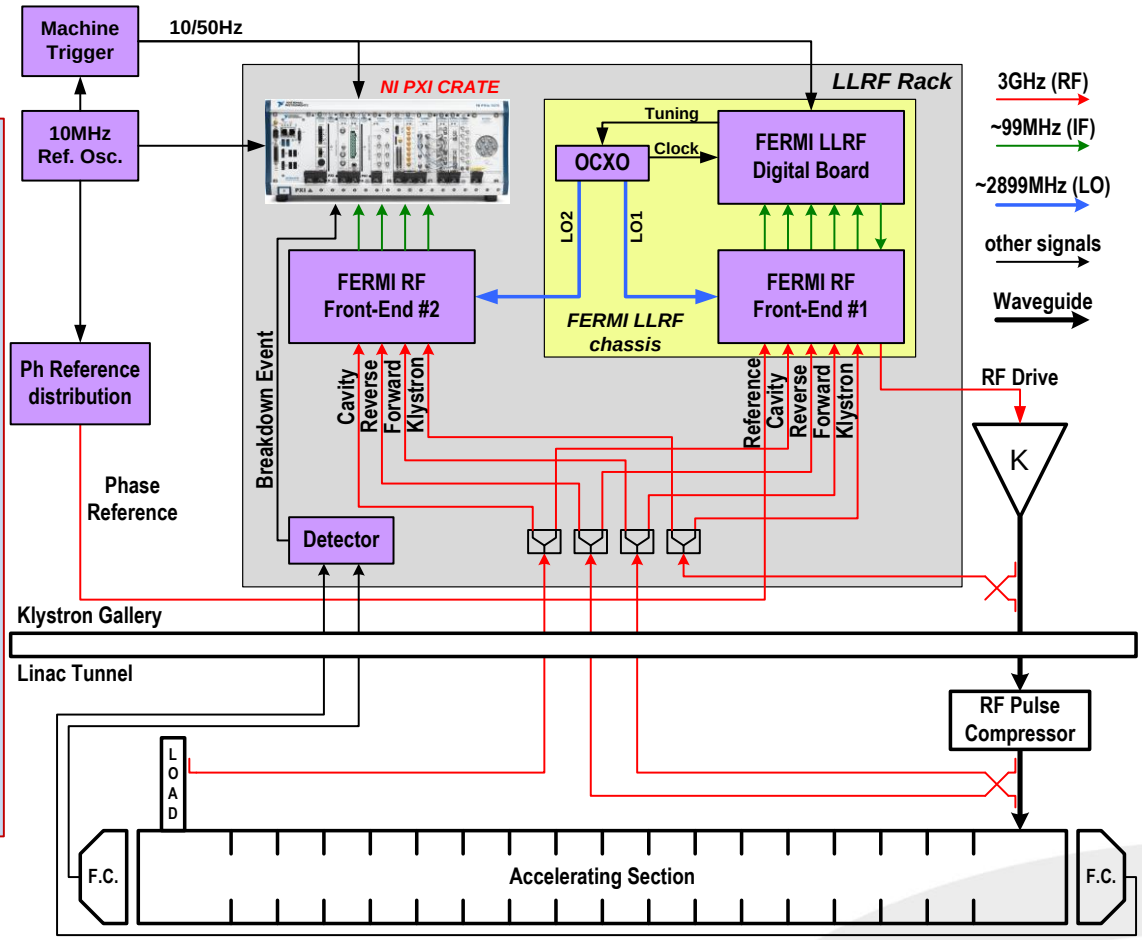
N. Shafqat et al., "Commissioning of S-Band cavity test facility at Elettra for conditioning of high gradient structures for the FERMI Linac upgrade" , *in Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, JACOW-IPAC19-WEPRB021

FERMI CAVITY TEST FACILITY

FERMI linac stations hot spare, has been upgraded to act also as a complete S-Band RF Cavity Test Facility (CTF)

TEST FACILITY @ ELETTRA

- Test of Standing Wave structures/RF Guns to 25MW peak power.
- Test of Travelling Wave structures & RF components up to 150 MW peak power.
- Hardware for breakdown diagnostic is subset of CERN breakdown diagnostic
- National Instrument (NI) hardware is integrated with FERMI LLRF for breakdown rate measurements and localization



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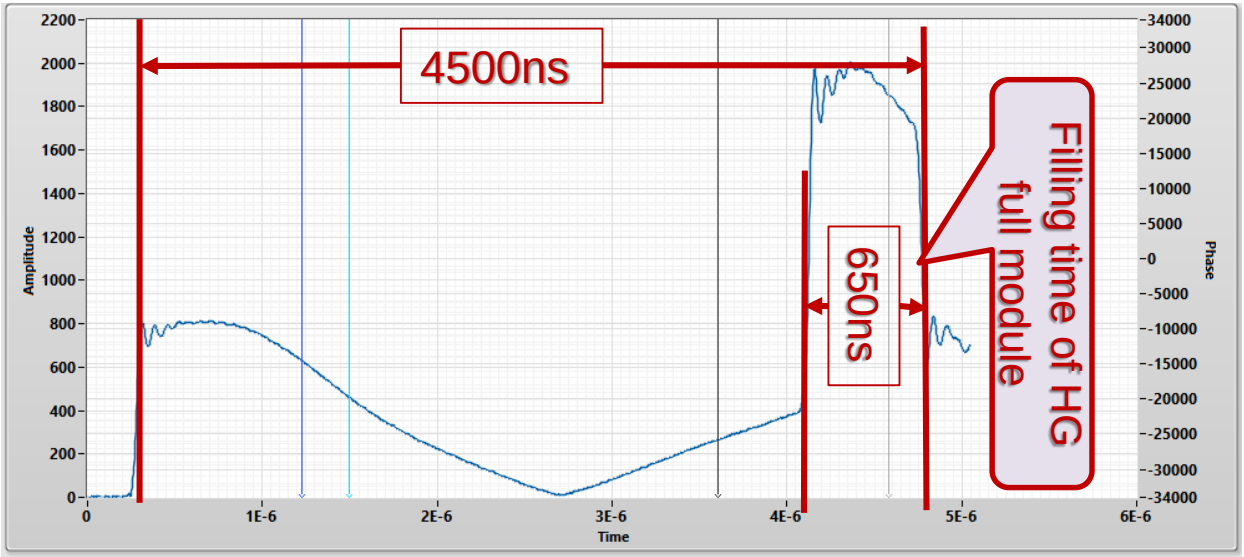
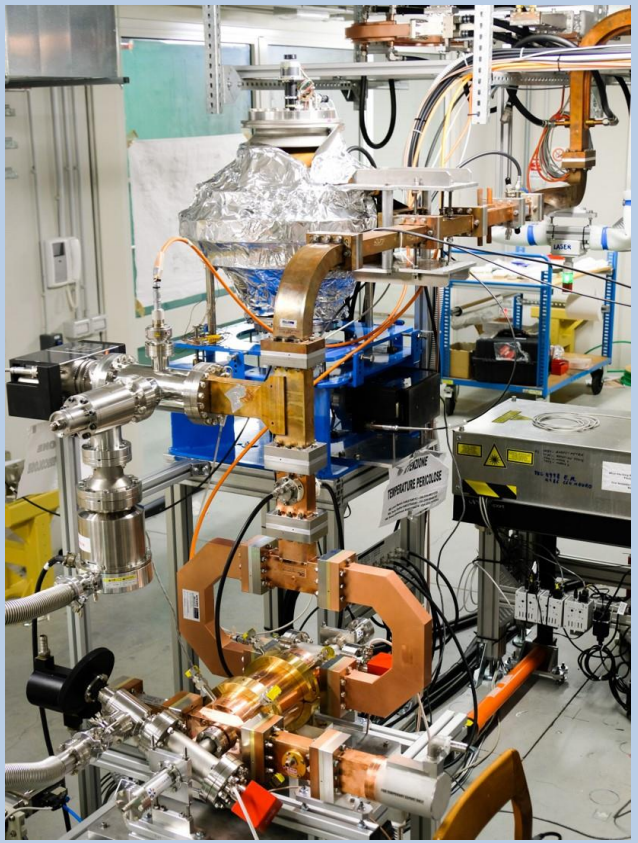
COMPLETE CONDITIONING HISTORY

Acc. Gradient (MV/m)	PWR @ Ptype (MW)	Start Date	End Date	# of Pulses (Million)	BDR (bpp)
30	72	01-06-2018	07-11-2018	225	2.0×10^{-8}
35	98	30-01-2019	21-05-2019	229	7.3×10^{-8}
39*	122**	31-08-2019	19-12-2019	400	7.9×10^{-8}



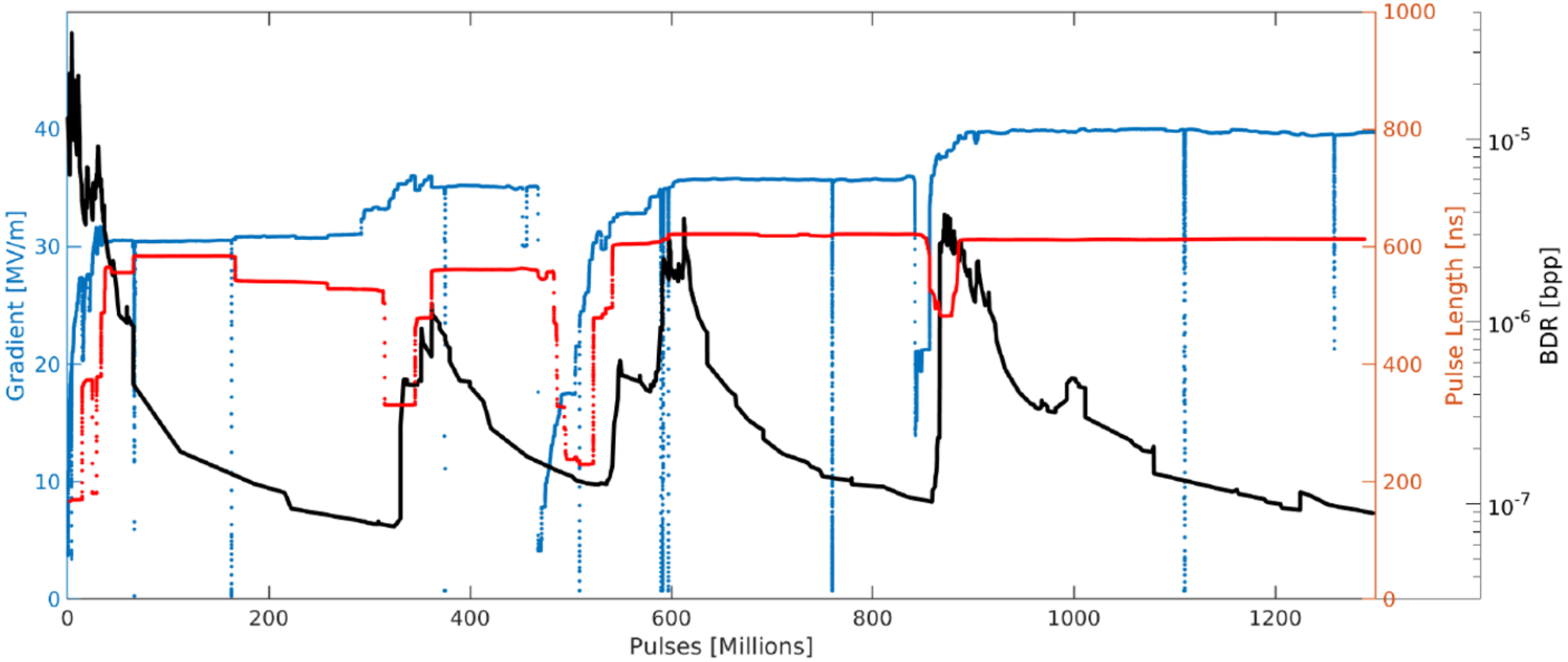
During the **Spring Shutdown (April 2018)** the prototype was installed in FERMI Test Facility.



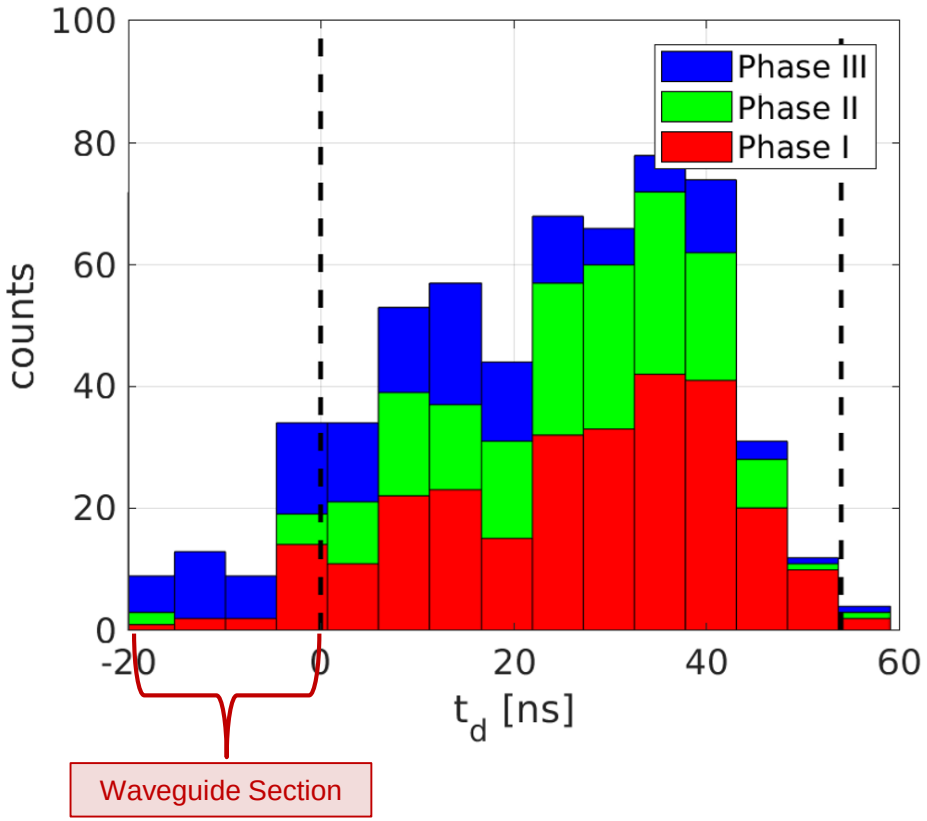
*Original target was 40MV/m acc. Gradient

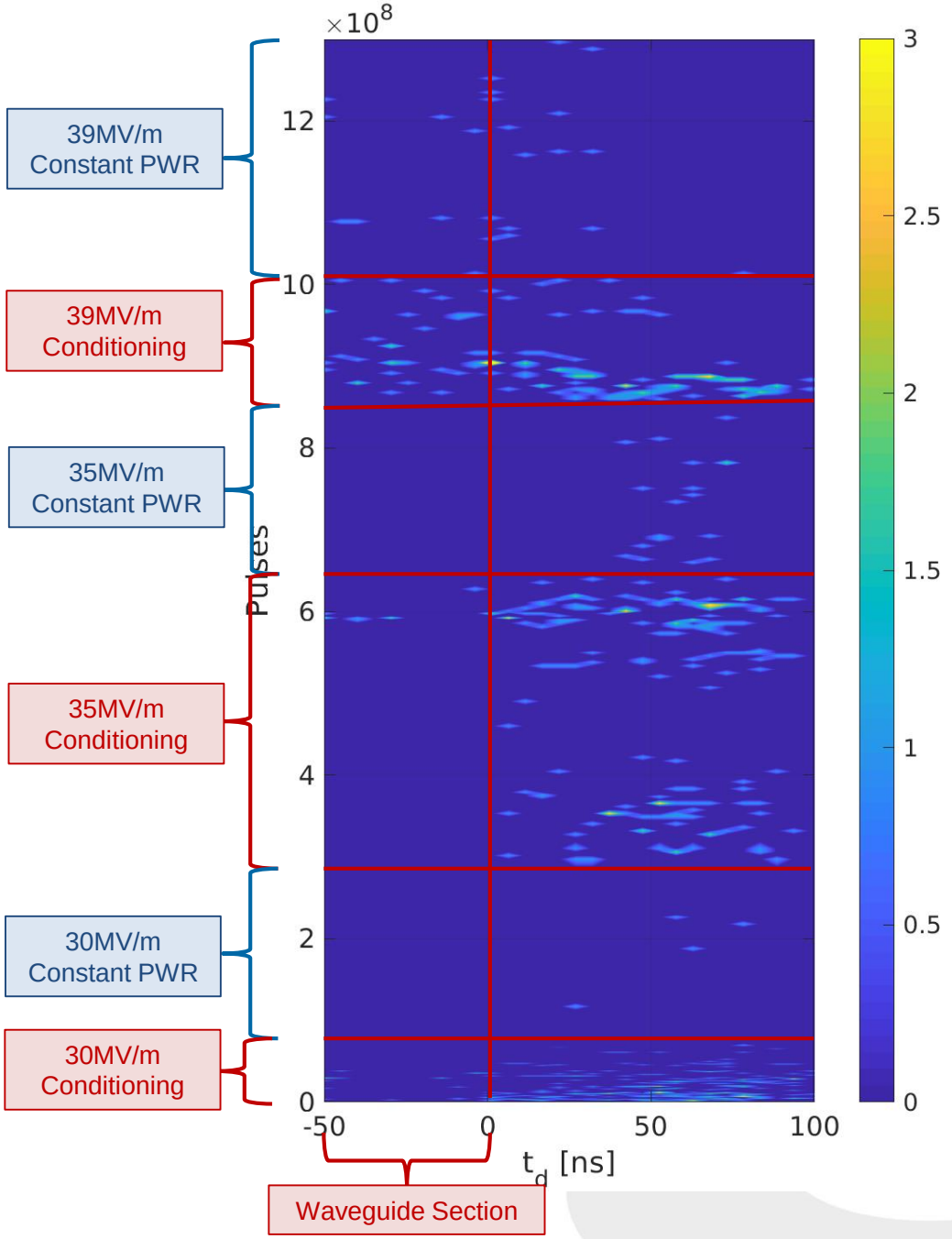
** Maximum available power at prototype with full power from Klystron

Complete Conditioning History Plot



Complete Conditioning Breakdown Locations





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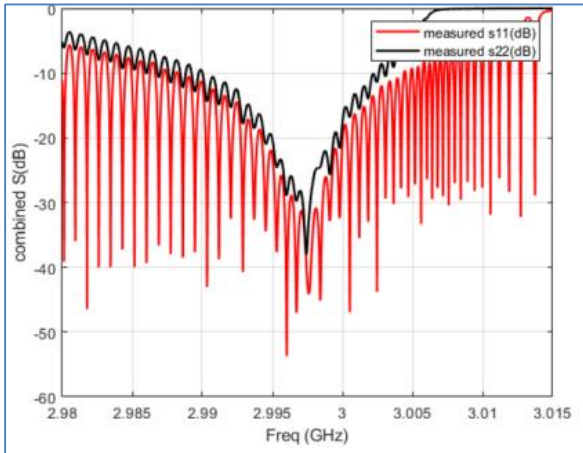
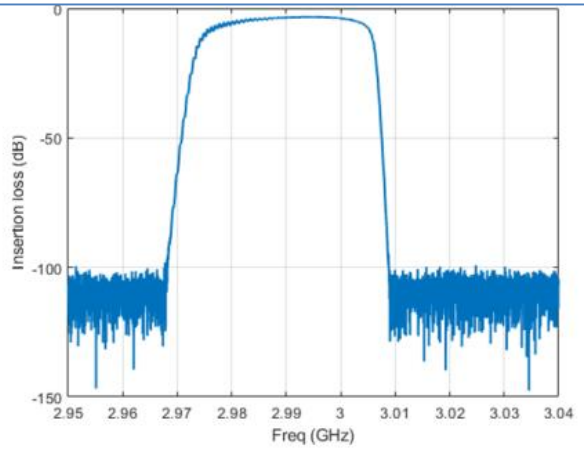
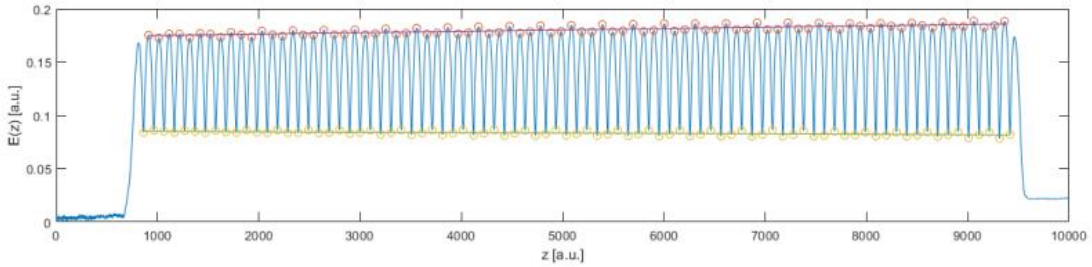
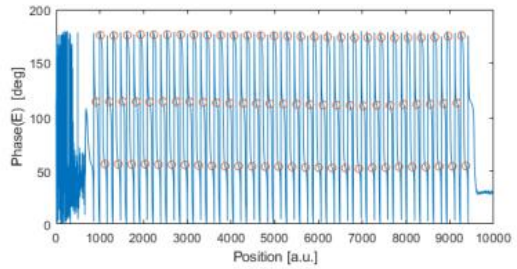
First HG Structure Low Power Measurements

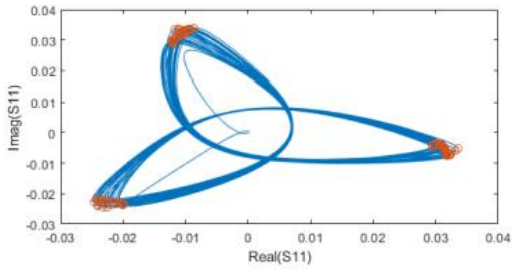


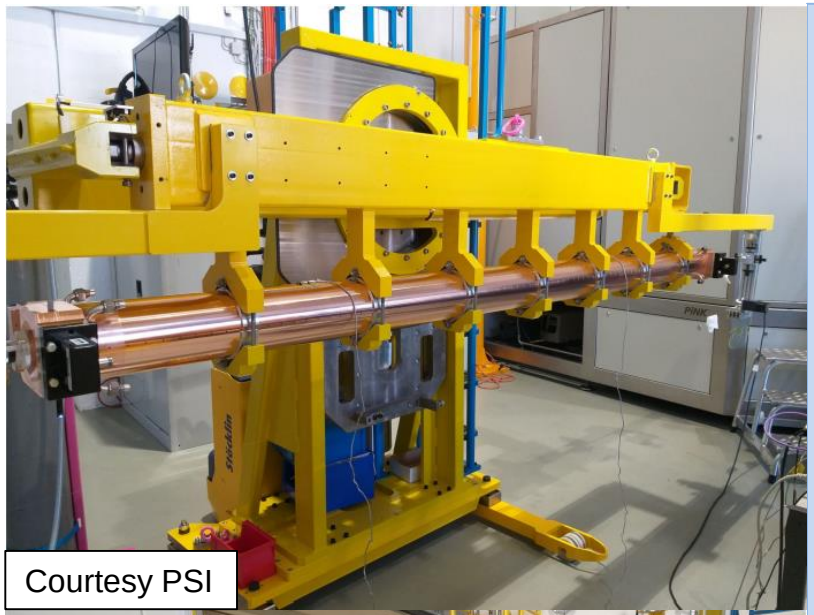


RF measurements and bead-pull test









Courtesy PSI

Courtesy PSI

3,0 m HG Structure

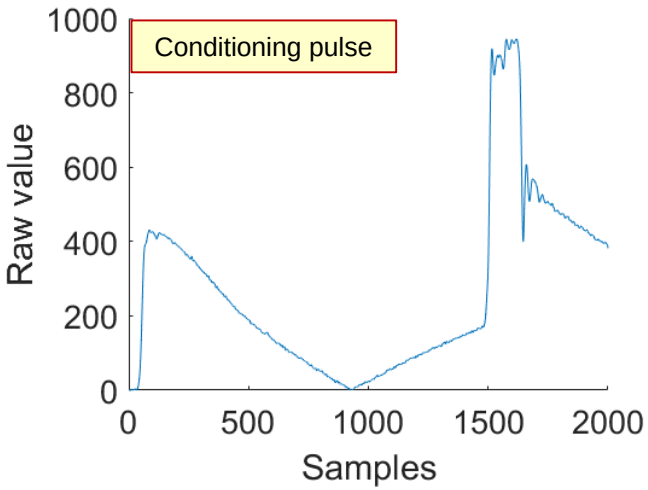
First HG Structure Conditioning

- During the **Spring Shutdown (April 2022)** the HG structure was installed in FERMI Test Facility.
- Preliminary power tests were performed and all diagnostic was properly setup.

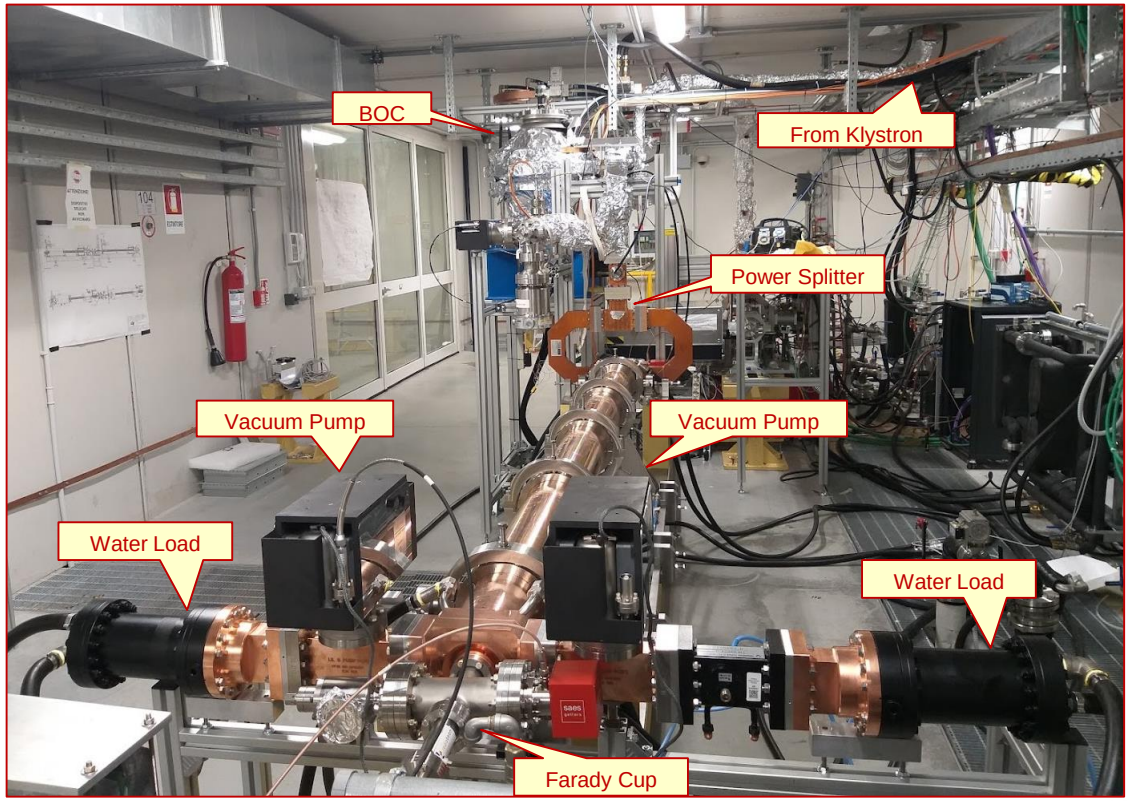
Conditioning Plan

Phase 1

- Rep. Rate: 50 Hz
- Start Date: 28-04-2022
- Target:
  - Pulse Width: 700 ns
  - Power Level: 75 MW
- Level Achieved:
  - Pulse Width:350 ns
  - Power Level:66 MW
  - # of pulses in million: 1353

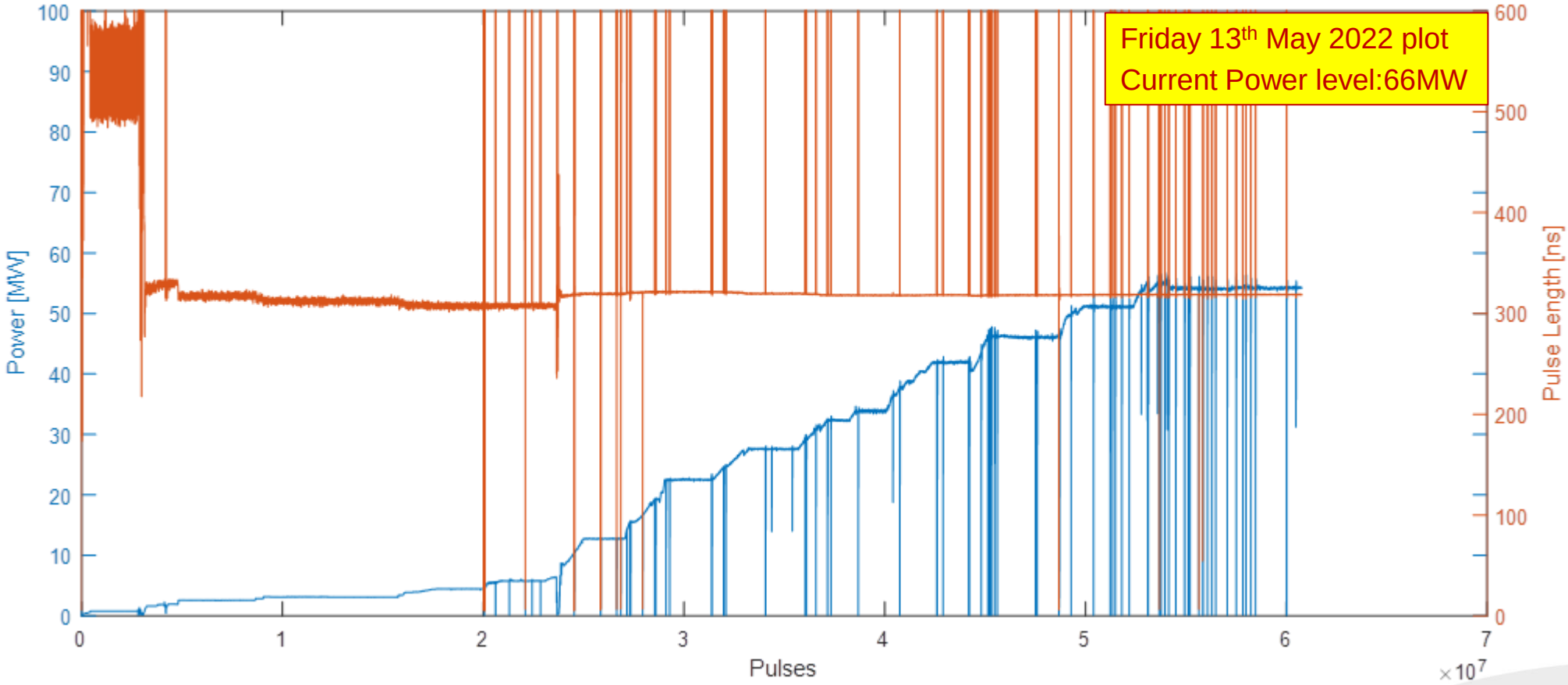


HG Structure installed at test facility in FRMI Tunnel



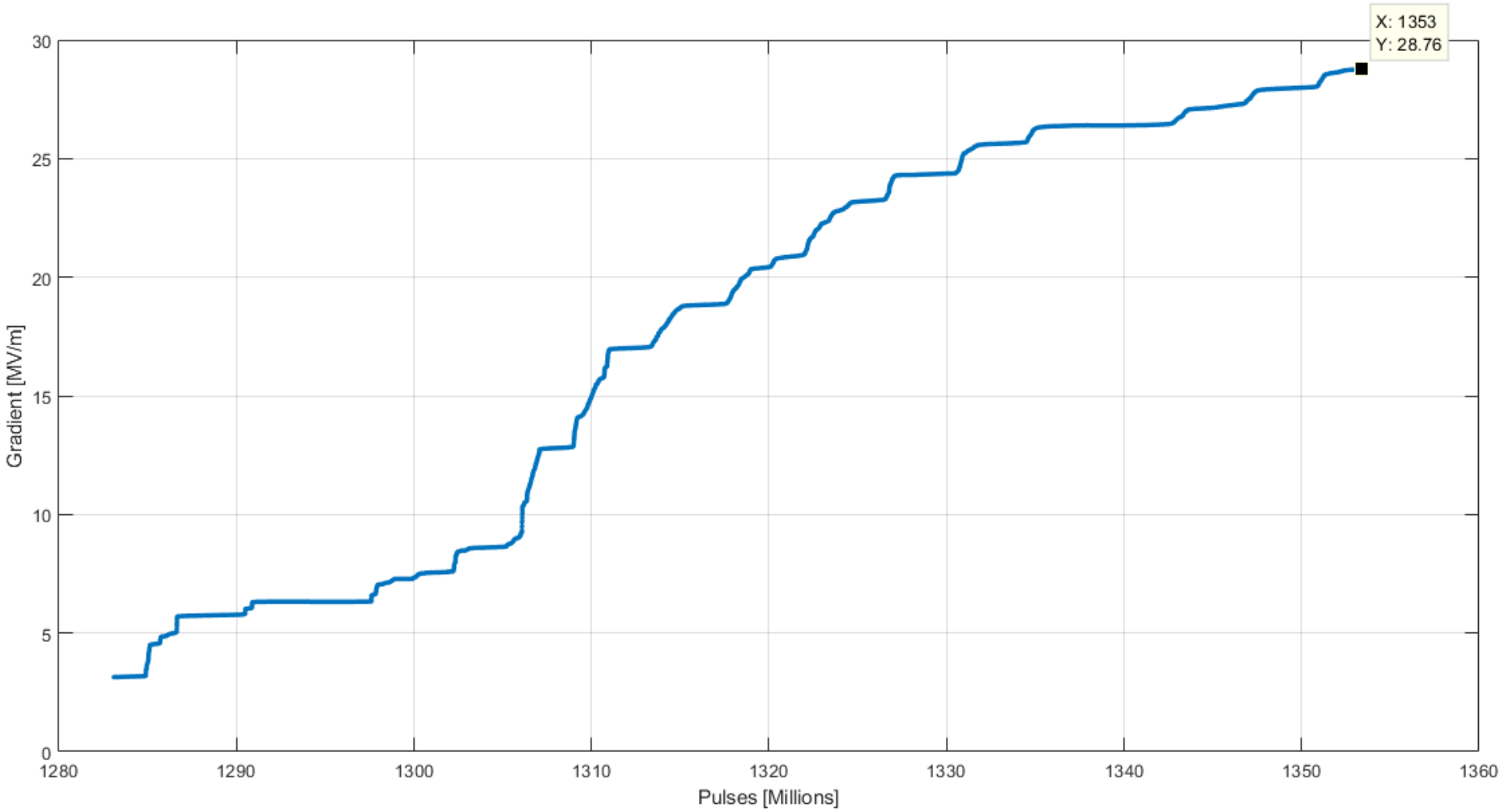
First HG Structure Conditioning

MATLAB conditioning plot (Power curve)



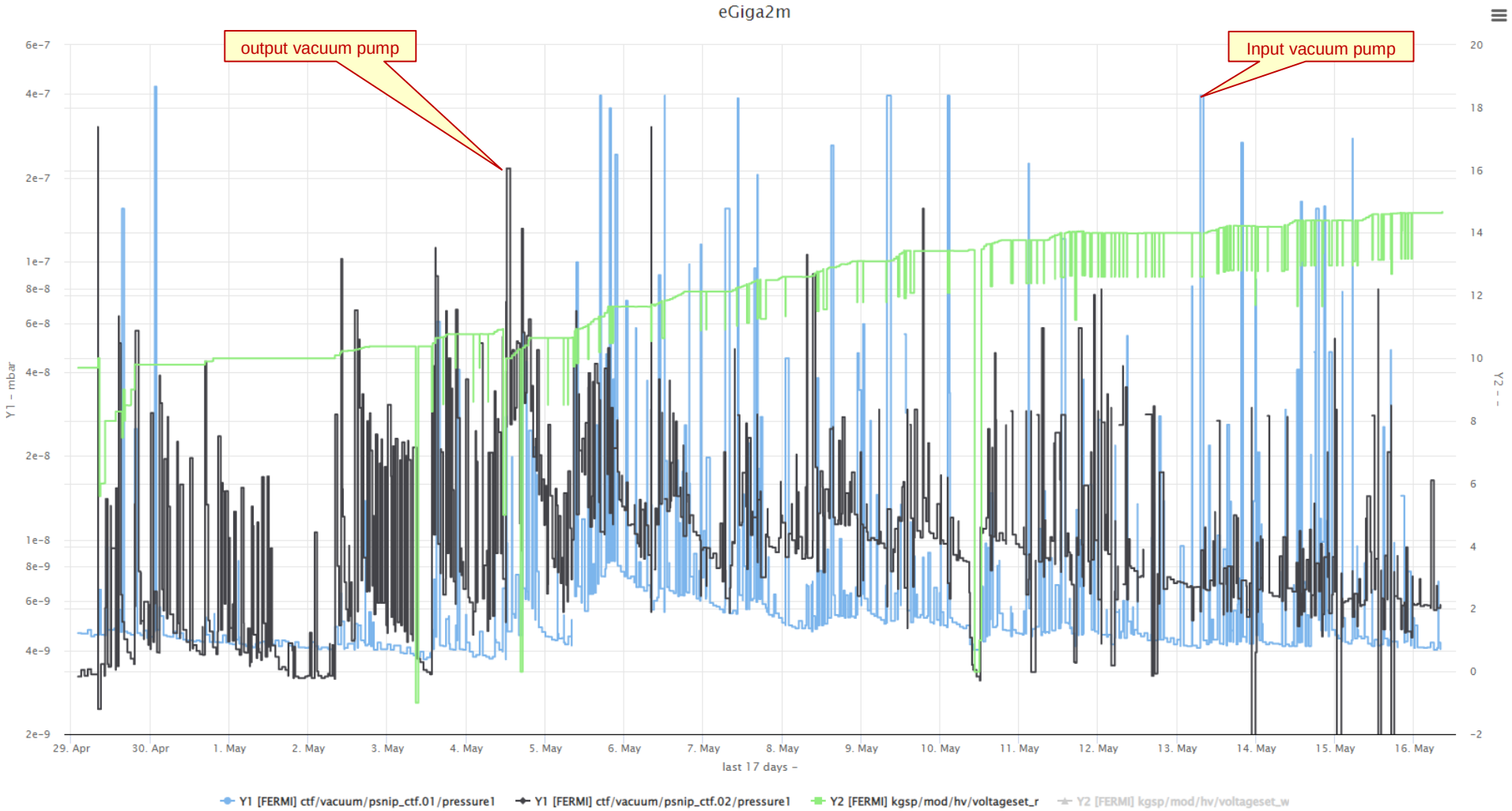
First HG Structure Conditioning

MATLAB conditioning plot (Accelerating Gradient)



First HG Structure Conditioning

MATLAB conditioning vacuum at the structure



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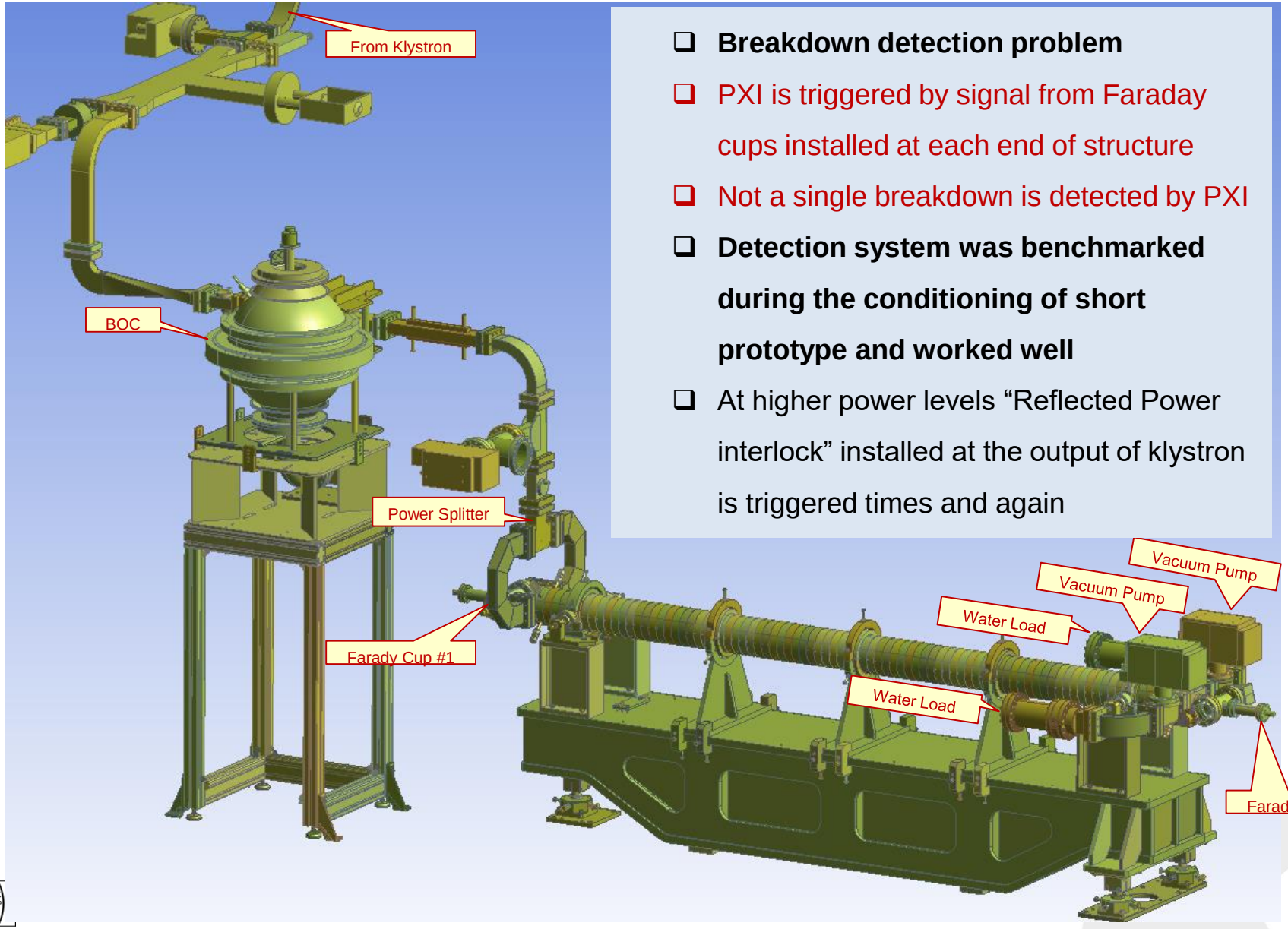
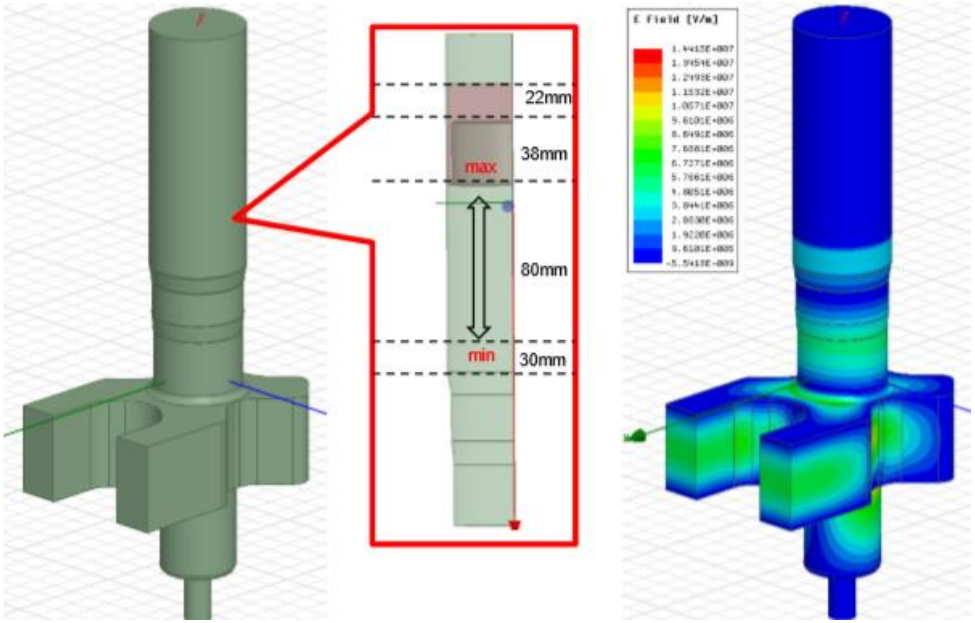
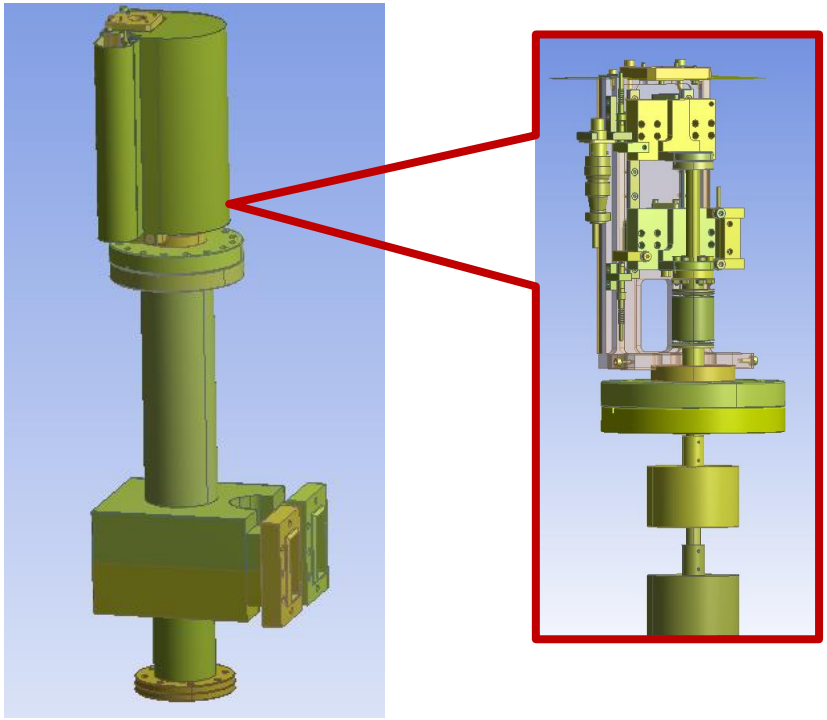
First HG Structure Conditioning

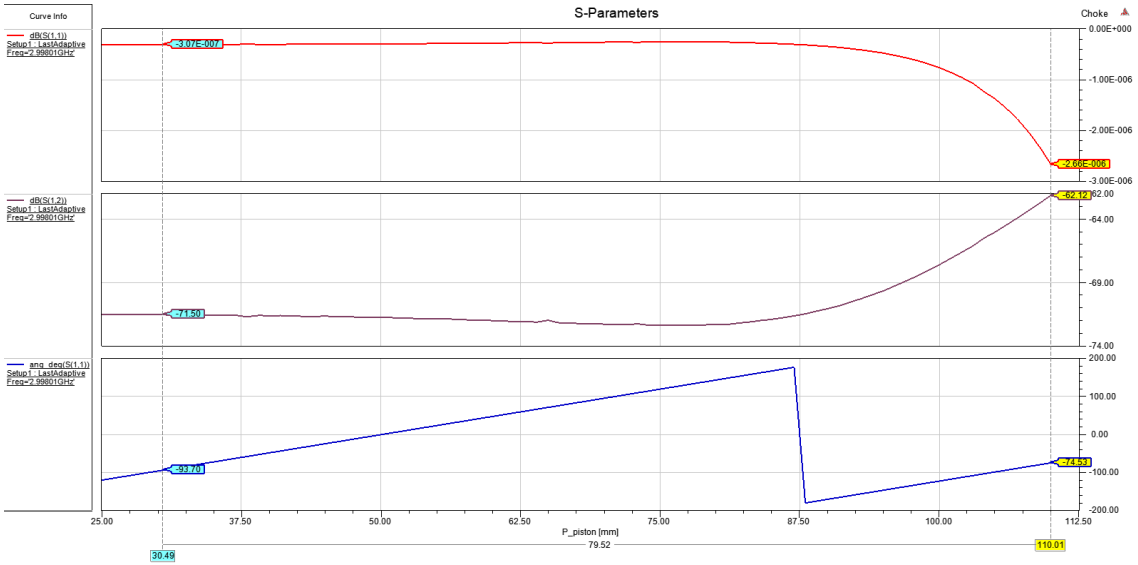


- **Breakdown detection problem**
- PXI is triggered by signal from Faraday cups installed at each end of structure
- Not a single breakdown is detected by PXI
- **Detection system was benchmarked during the conditioning of short prototype and worked well**
- At higher power levels “Reflected Power interlock” installed at the output of klystron is triggered times and again

IN-VACUUM PHASE SHIFTER

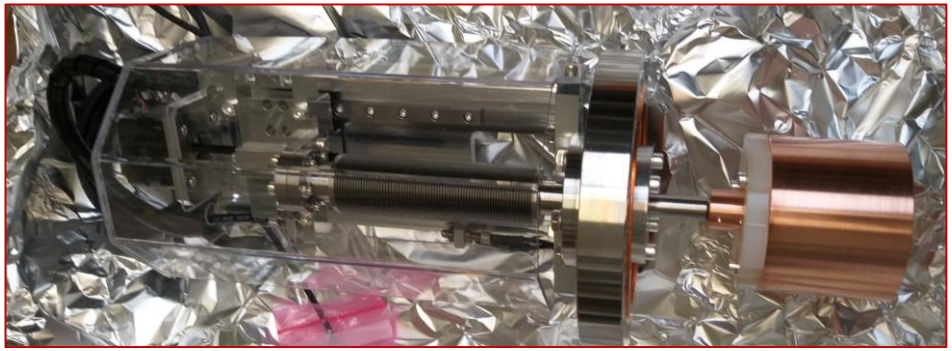


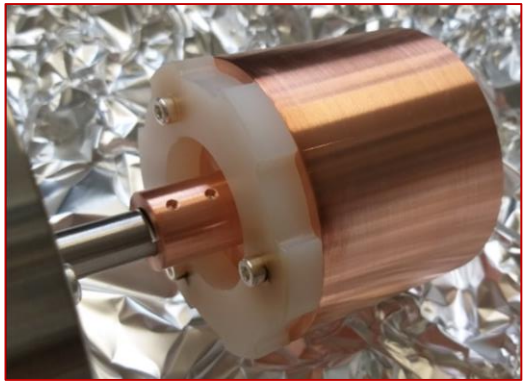


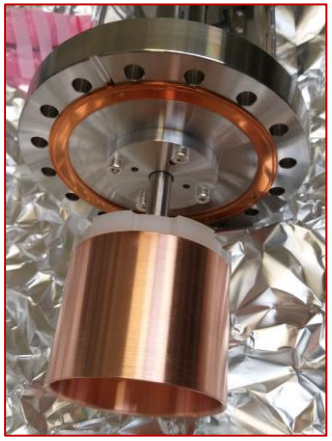


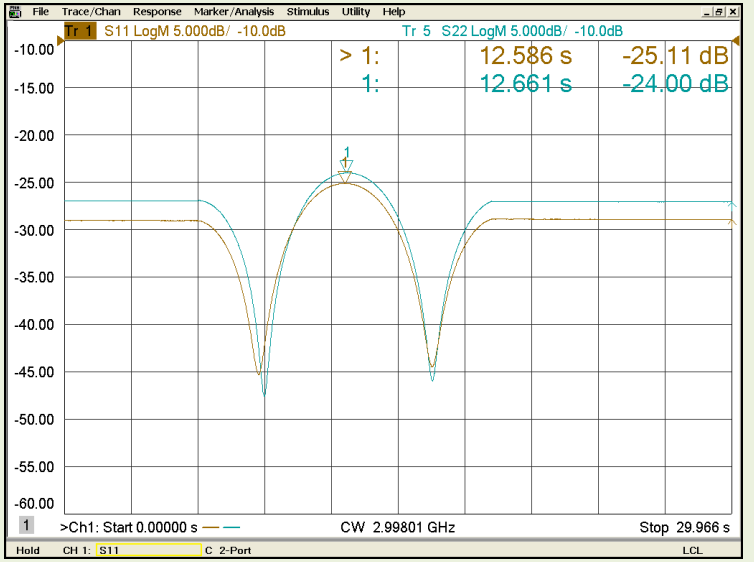
	Value	Units
f_0	2.99801	GHz
Bandwidth @ -30 dB	15	MHz
VSWR	<1.05	
Insertion loss	0.1	
Phase Range	±200	Degree
Max Peak Power	45	MW
Max Average Power	10.125	W

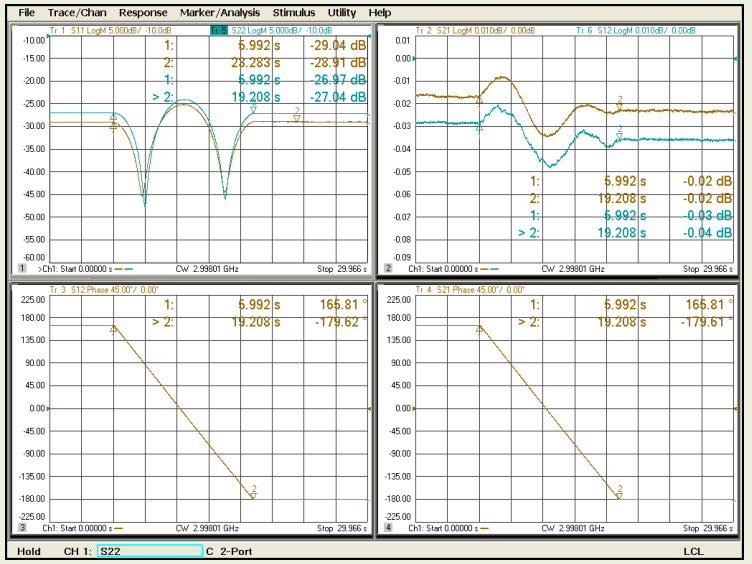
IN-VACUUM PHASE SHIFTER







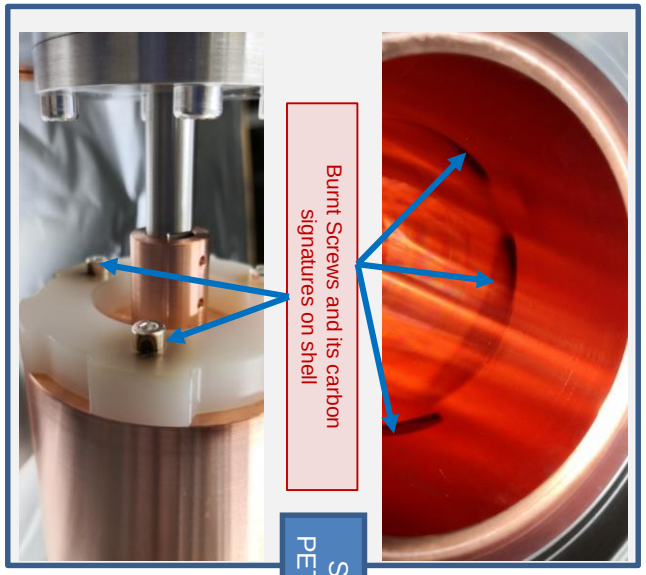




https://media.mcam.com/fileadmin/quadrant/documents/QEPP/Global/English/Product_Data_Sheets_AEP/Ketron_GF30_PEEK_PDS_GLOB_E_19092016.pdf

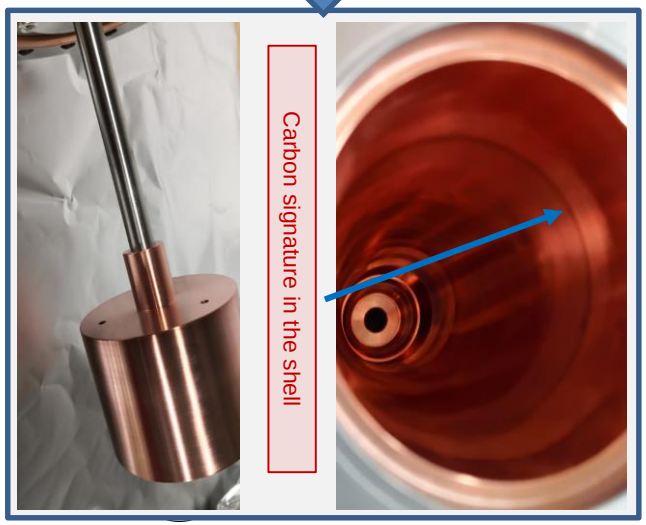
In-Vacuum Phase Shifter Conditioning...

1st run



Screws & PET removed

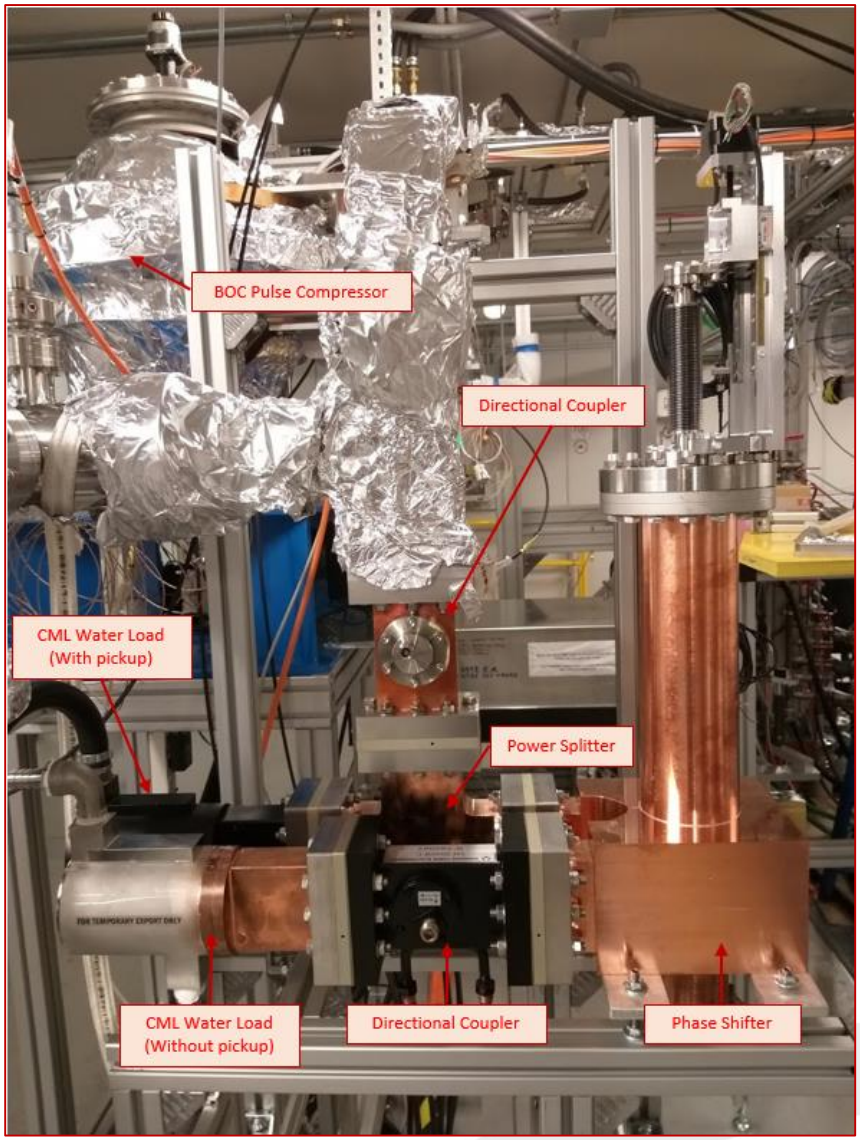
2nd run



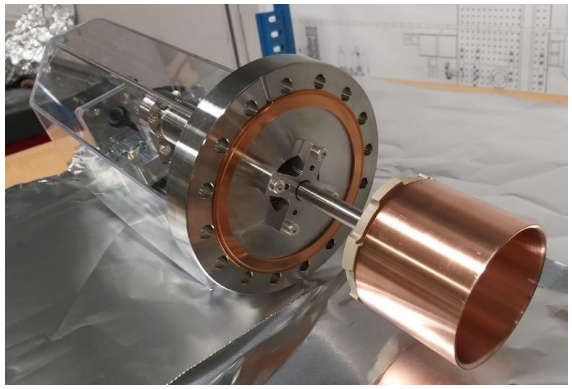
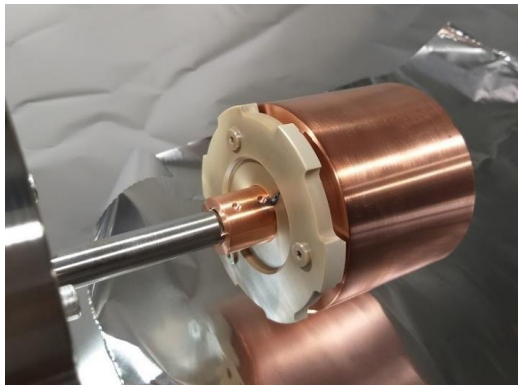
3rd run

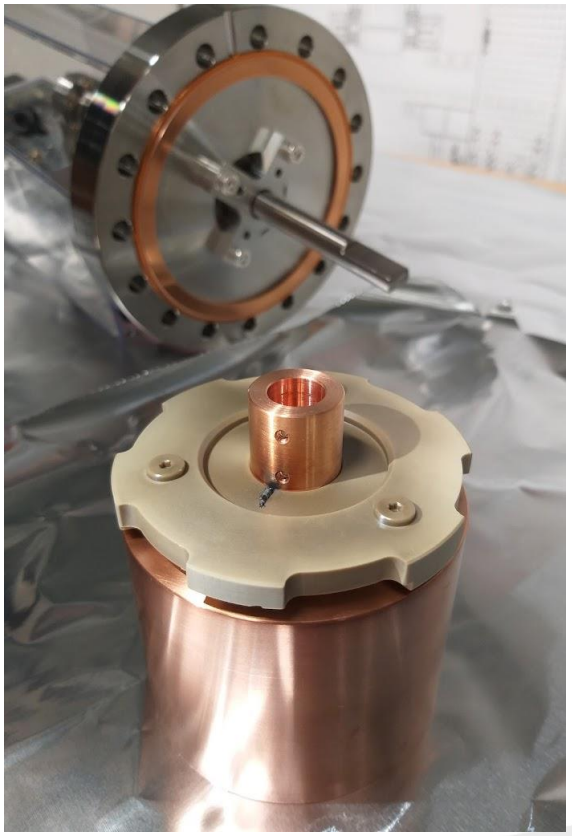
Vacuum issue

- ❑ Baking out of plastic
- ❑ Replacement of metal screws with plastic ones.
- ❑ Spacers were introduced between copper choke & the plastic to avoid virtual leak.

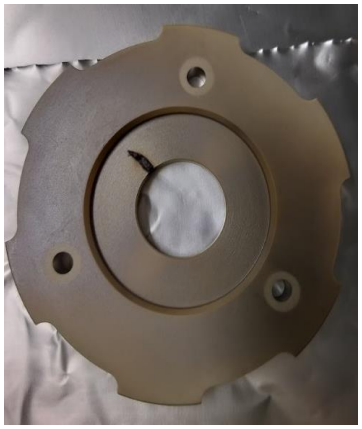


In-Vacuum Phase Shifter Post Conditioning Analysis

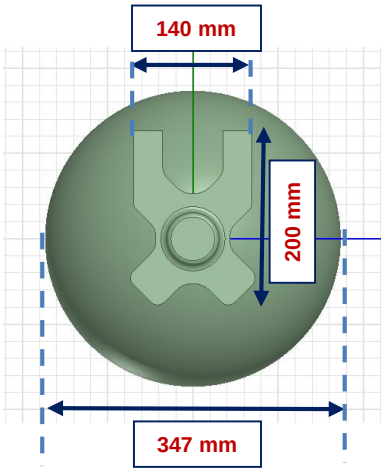



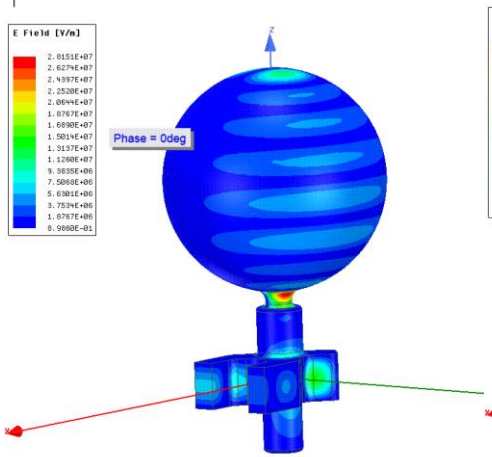


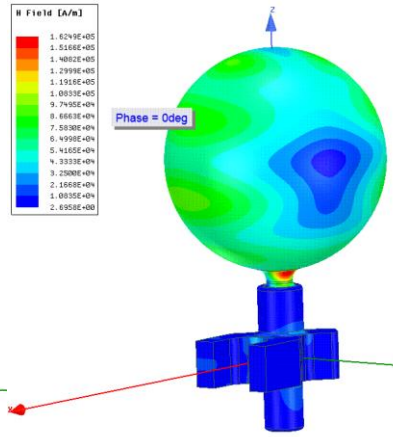
- **Power level achieved**
- 50 MW
- Pulse width: 1000 ns
- **Post conditioning inspection**
- Hard burnt spot on plastic
- Discoloring of plastic

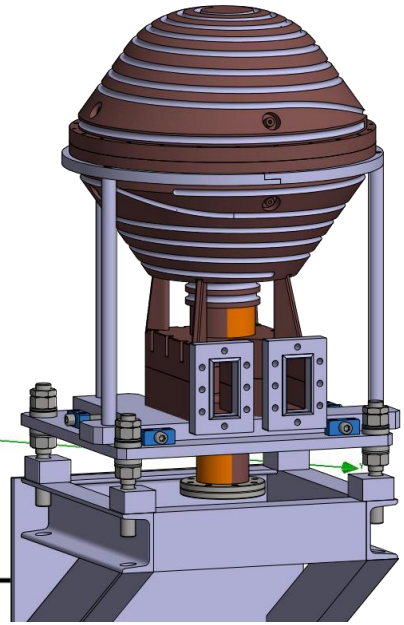



RF Pulse Compressor

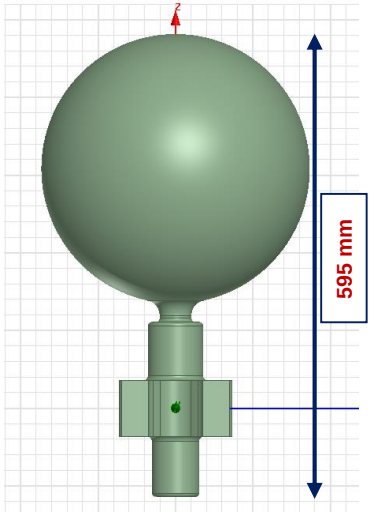


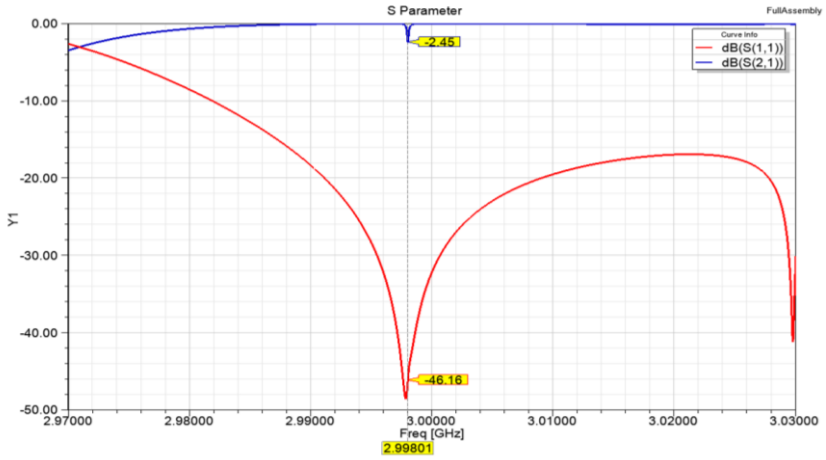




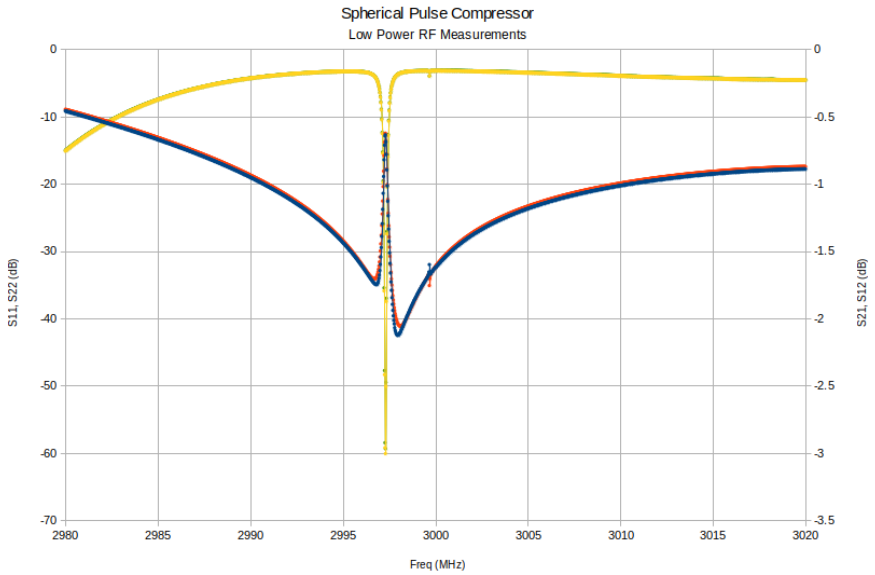


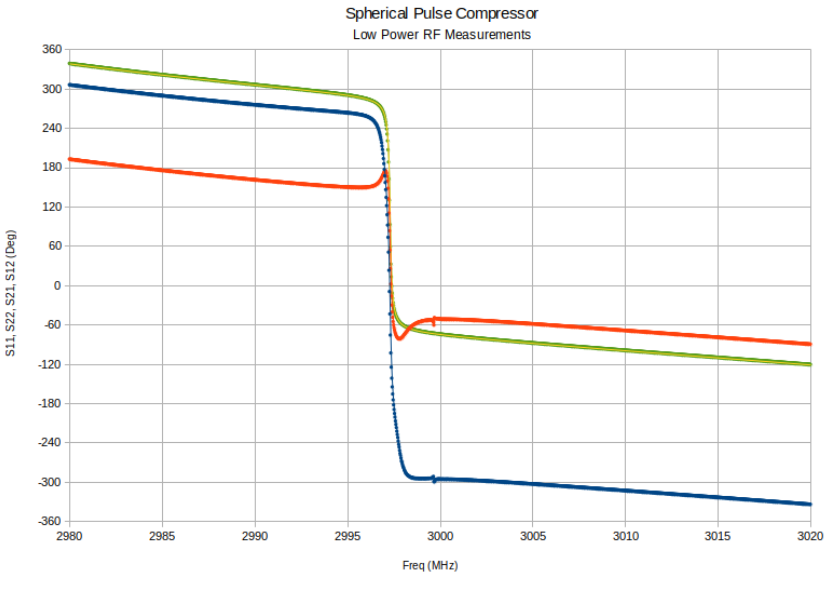
RF Parameters		
f_0	2.99801	GHz
Nominal Temperature	35	^oC
Mode	TM13	
Q0	≈140000	
Coupling Coefficient	7.2 ± 0.1	
E @ 45 MW	28.16	MV/m
H @ 45 MW	169.75	kA/m





RF Pulse Compressor Low Power Mesurements





Measurement Setup

- ❑ Ambient temperature: 25,7 C
- ❑ Coupling frequency: 2997,3 MHz

CONCLUSION

Conditioning of HG prototype

- Successful conditioning of HG prototype at Cavity Test Facility of Elettra up to an accelerating gradient of **40MV/m** with break down rate of $\underline{7.9 \times 10^{-8} bpp}$.

Conditioning of 1st 3,0m HG structure

- First 3,0m HG structure is installed at Cavity Test Facility of Elettra and is under conditioning from **28 April 2022**.

S-Band In-Vacuum Phase Shifter

- Successful design, fabrication and high power testing of S-Band In-Vacuum Phase Shifter up to RF power of **50 MW** with pulse width of **1000 ns**

S-Band Spherical Pulse Compressor

- Low power measurement done after successful brazing of Spherical Pulse Compressor.

Next Steps And Time Schedule

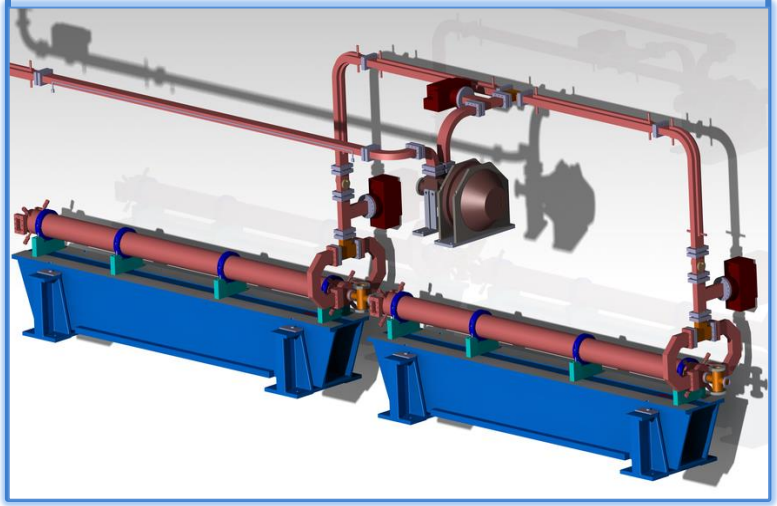
Full HG module timeline…

- By **August 2022**, 2nd HG structure would be fabricated and shipped to Elettra.
- During **Summer 2022 shutdown** **full HG Module** would be installed in FERMI tunnel in place of one accelerating section and deflecting cavity (K15) for operation with beam.

Spherical Pulse Compressor…

- In the **last week of May 2022**, Spherical pulse compressor would be installed at Elettra for tuning and low power measurements at the right temperature.
- During the shutdown of **Summer 2022** Spherical Pulse Compressor would be installed at Cavity Test Facility for conditioning and high power testing

Layout of HG module in FERMI Tunnel



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T.G. Lucas

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R. Zennaro

PAUL SCHERRER INSTITUT PSI

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Thank you!

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