Elettra Sincrotrone Trieste

S-BAND ACTIVITIES AT ELETTRA

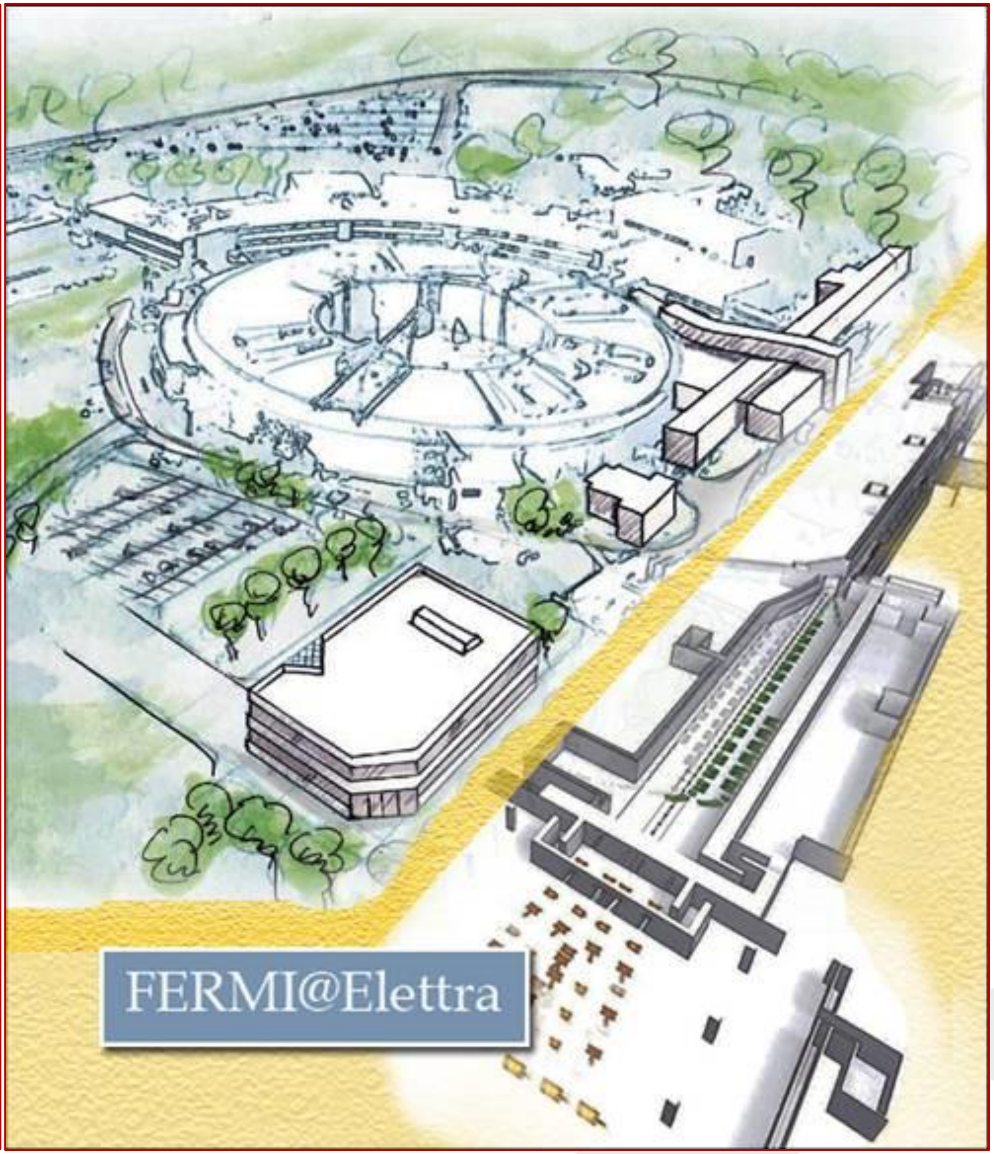
Nuaman Shafqat

on behalf of

S-Band RF Systems Team

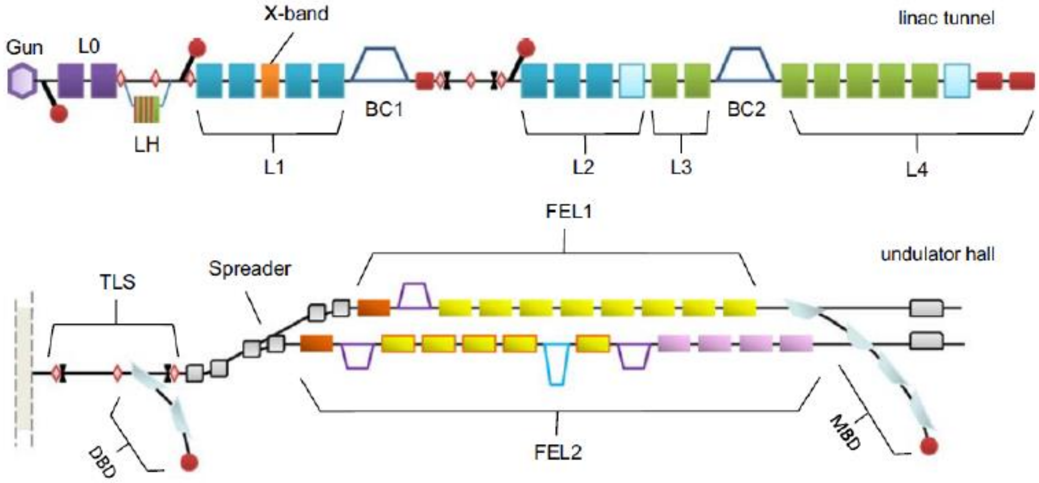
LAYOUT

- ❑ What is FERMI?
- ❑ FERMI Upgrade Plan
  - ❑ Beam Energy Upgrade
  - ❑ Beam Quality Upgrade
- ❑ FERMI LINAC
  - ❑ CERN Sections
  - ❑ Backward Travelling Wave Structures
- ❑ Beam Energy Upgrade
  - ❑ Pulse compressor @ CERN sections
  - ❑ HG structures in place of BTW structures
- ❑ S band Cavity Test Facility (CTF) of Elettra
- ❑ S band waveguide components
  - ❑ In-Vacuum Phase Shifter
  - ❑ Spherical Pulse Compressor
- ❑ Summary and conclusion



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**,



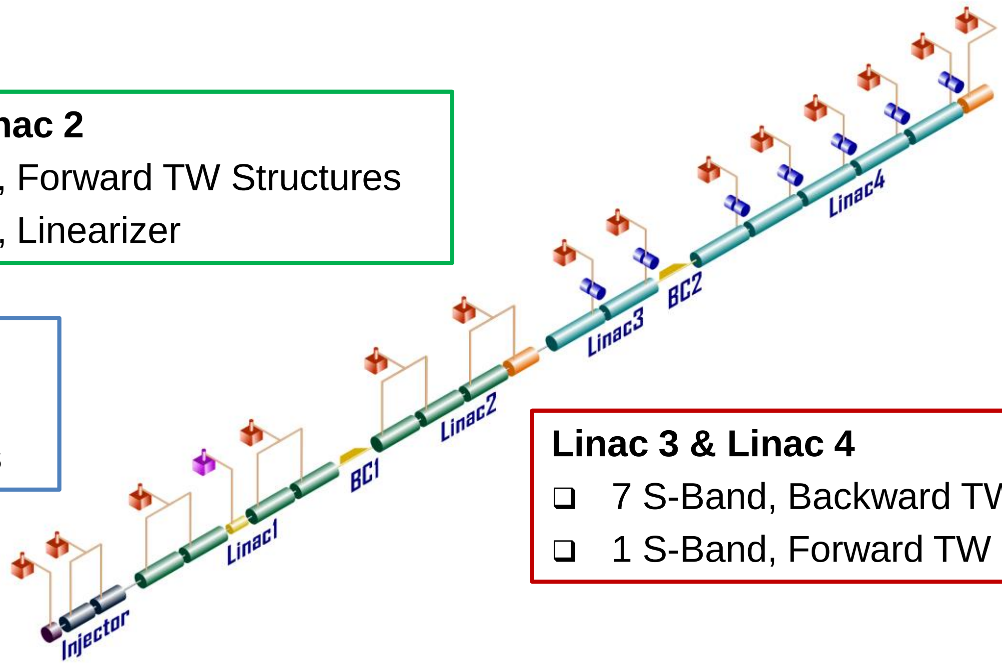
The FERMI facility comprises two separate coherent radiation sources, **FEL-1** and **FEL-2**.
FEL-1 operates in the wavelength range between **100 and 20 nm** via a single cascade harmonic generation, while the **FEL-2** is designed to operate at shorter wavelengths (**20-4 nm**) via a double cascade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

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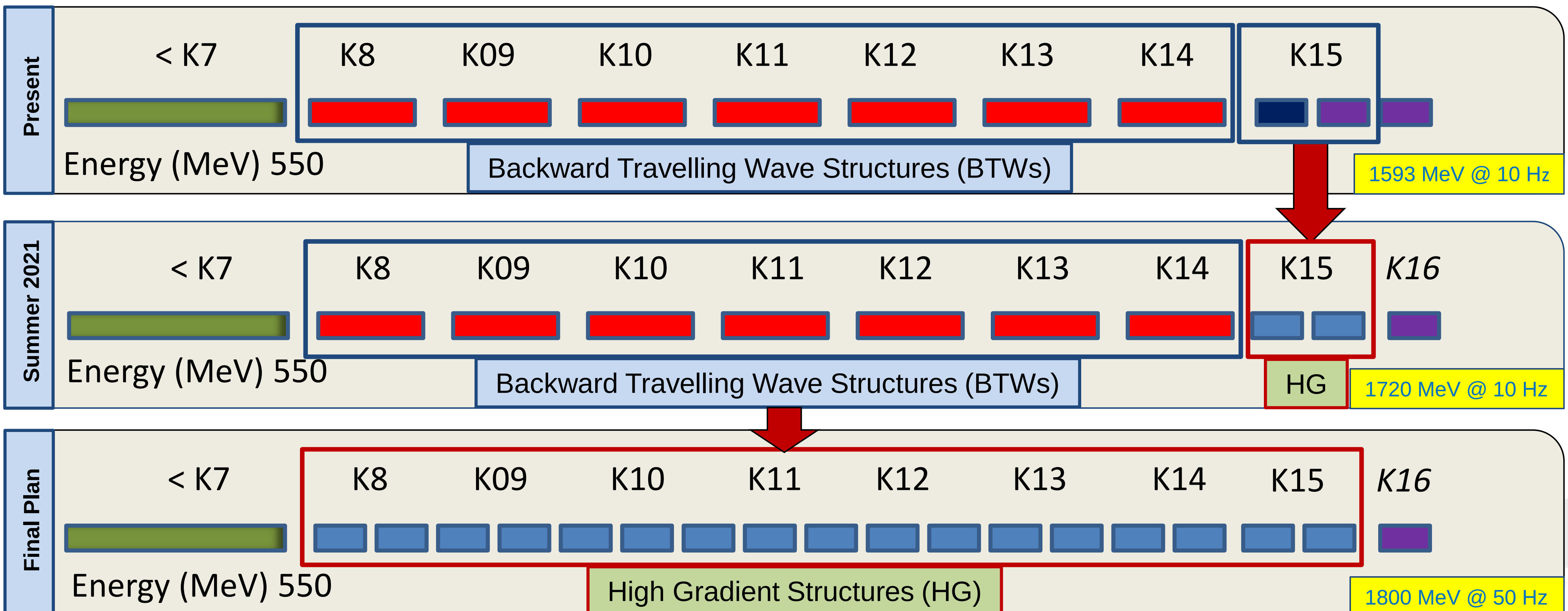
THE FERMI FEL UPGRADE PLAN
BEAM ENERGY UPGRADE

- **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**.



ISO 9001 OHSAS 18001 BUREAU VERITAS Certification

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

CERN SECTIONS TECHNICAL DETAILS

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Proceedings of the 1984 Linear Accelerator Conference, Seeheim, Germany

- Developed as injector of LEP Injector Linac (LIL) in **1984**
- Fed with **35 MW** klystrons
- Can reach to **17 MV/m** with LIP system (identical to SLED system)

Table III

NOMINAL LINAC PARAMETERS

Accelerating Sections

Frequency (30° under vacuum)	2998.55 MHz
Type	TW, quasi-constant gradient
Mode	2π/3
Length incl. coupling cavities	4.505 m
Filling Time	1.22 μs
Normal accelerating rate	13 MeV.m^{-1}

Klystrons

Power	35 MW
Pulse length (-3 dB)	4.5 μs

	Linac V		Linac W	
Number of sections (with LIPS	4		8	
(without LIPS)	–		4	
Number of klystrons	1[(a)] + 1		4	
Pulse repetition rate	100 Hz			
Beam pulse length (FWHH)	12 ns			
Energy	200 MeV		600 MeV	
Particles	e^-		e^+	e^-
Peak current	2.5 A		12 mA	60 mA
Emittance/π (mm.mrad)[(b)]	<1.3		4	<< 1
Relative energy spread (%)	<10		2	< 1

(a) powers both bunchers

(b) containing > 80% of resolved output current

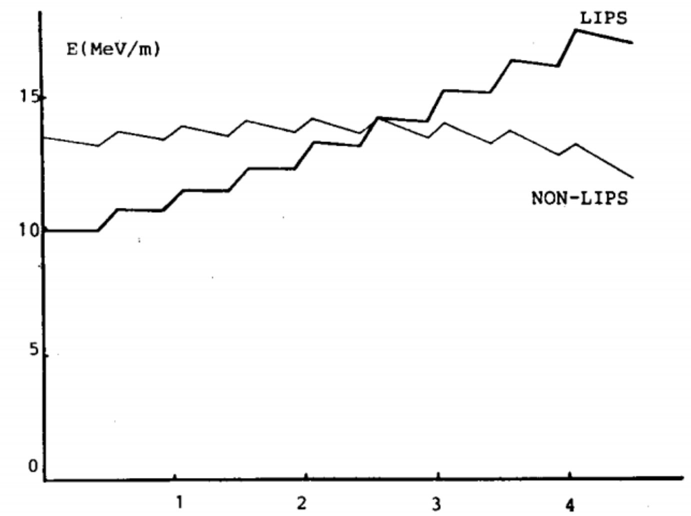


Fig. 3 - Computed acceleration rate versus longitudinal particle position in the LIL TW accelerating section for LIPS and non-LIPS. Main parameters : for non-LIPS as in Table I ; for LIPS Q(spheres) = 150 000, τ_p (RF pulse legth) = 3,9 μs, π phase-switch at τ_p minus 1.2 μs.

https://accelconf.web.cern.ch/l84/papers/wed0003.pdf

https://accelconf.web.cern.ch/l84/papers/wed0003.pdf

CERN SECTIONS
CURRENT STATUS & PROPOSED PLAN

Current Status

- ❑ **Seven CERN sections fed with four Klystrons of 45 MW, 4.5 us**
- ❑ **Total energy contribution: 400 MeV @ 12.6 MV/m**
- ❑ **Space consumed: 31.5 m @ 4.5 m**

Installation of Pulse Compressor

- ❑ Total energy contribution: 535 MeV @ 17 MV/m
- ❑ Net energy gain: 135 MeV

Replacing CERN sections with HG structures

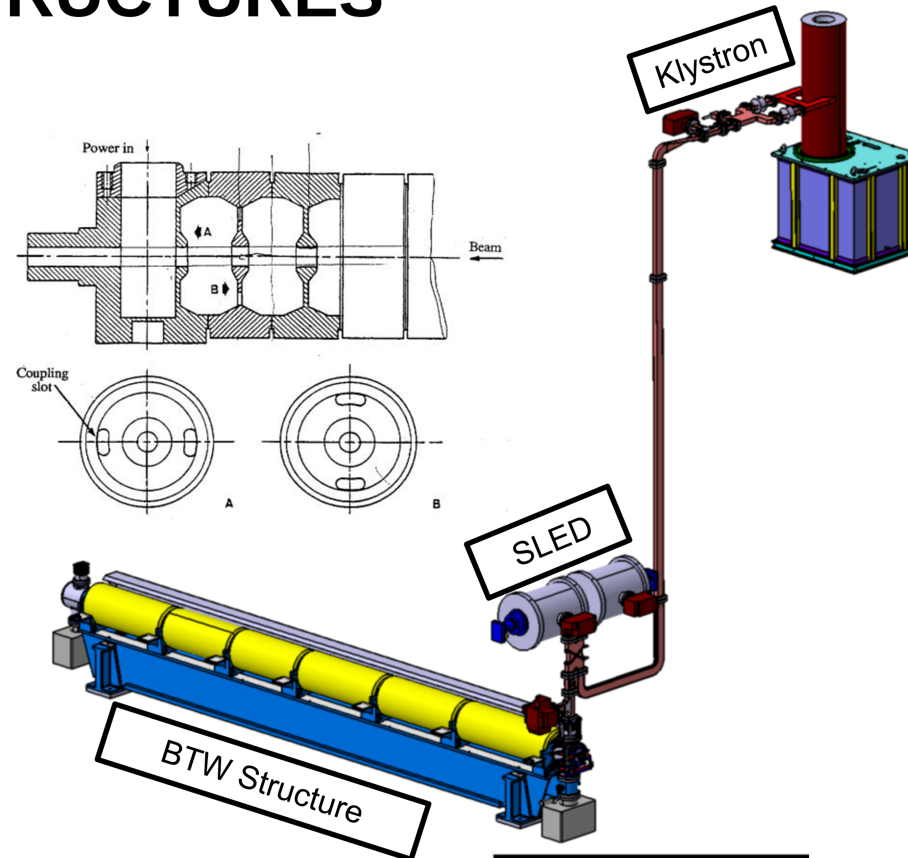
- ❑ Four HG modules (8 HG structures)
- ❑ Total energy contribution: 720 MeV @30 MV/m
- ❑ Net energy gain: 320 MeV

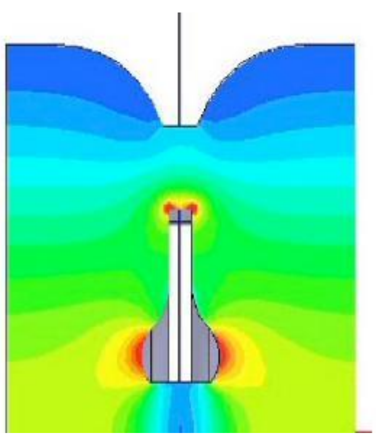
Comments

- ❑ Modular approach
- ❑ Utilization of the same space & power sources
- ❑ Possibility to go beyond 2.0 GeV

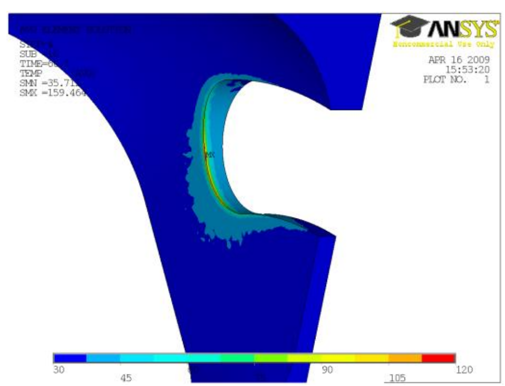
THE BTW STRUCTURES

- ❑ The Backward Traveling Wave (**BTW**) accelerating sections are **6.2 meters** long, made up of **160 cells**, magnetically coupled.
- ❑ BTW accelerating structures suffered heavy breakdown phenomena when pushed to **24MV/m** at repetition rate of **50 Hz**.

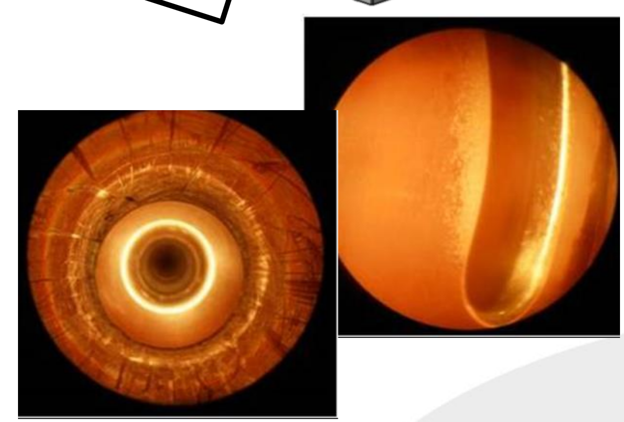




Peak surface electric field



Temperature increase due to RF pulse heating



Endoscopic pictures of inner surfaces of a regular cell of the FERMI BTW

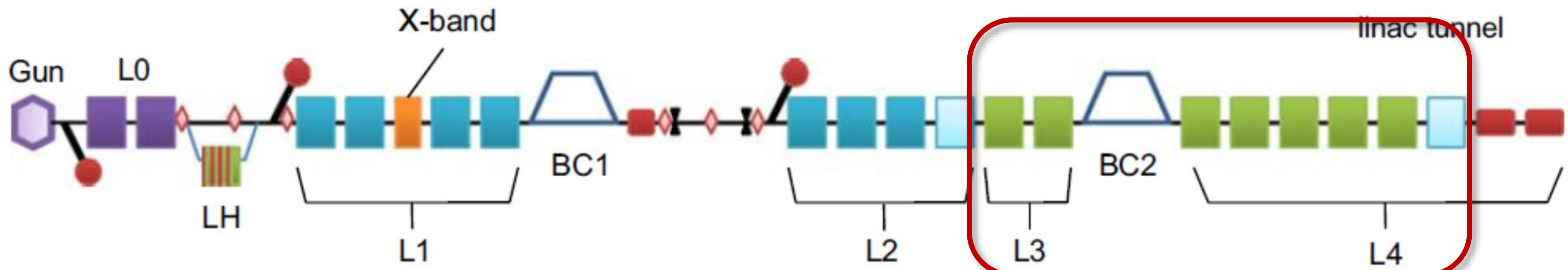
THE FERMI UPGRADE PROPOSAL

TO EXTEND THE RANGE TO SHORTHER WAVELENGTH UP TO 2 nm

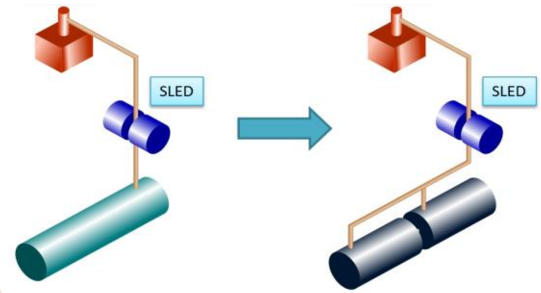
Actual Linac Energy
1.5 GeV @ 10Hz

Target Linac Energy
2.0 GeV @ 50Hz

Solution
High Gradient 30MV/m



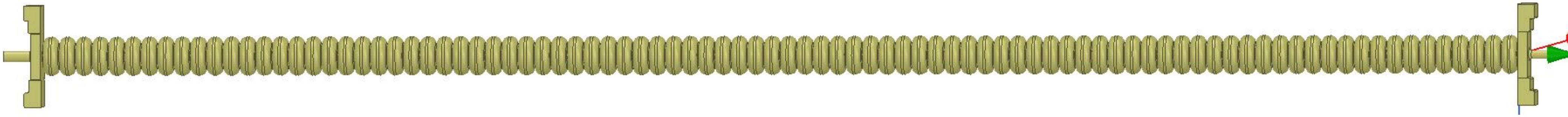
Replace 7 BTW with high gradient accelerating modules



$$BDR \propto E_a^{30} . t^5$$

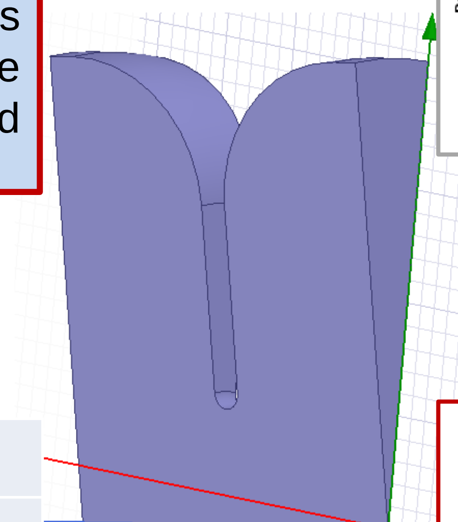
From 24MV/m to 30MV/m, the **BDR will increase by a factor of 800!!!**

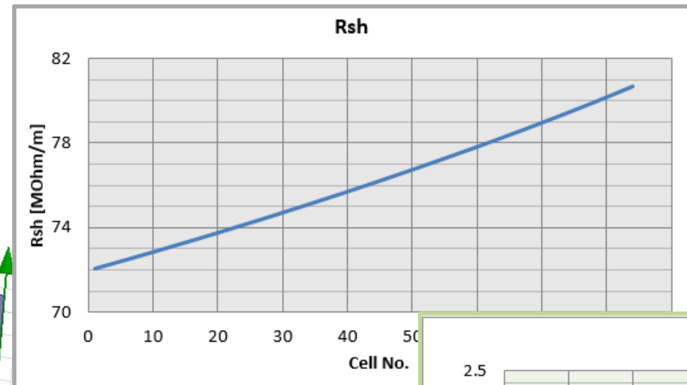
NEW ACCELERATING MODULE

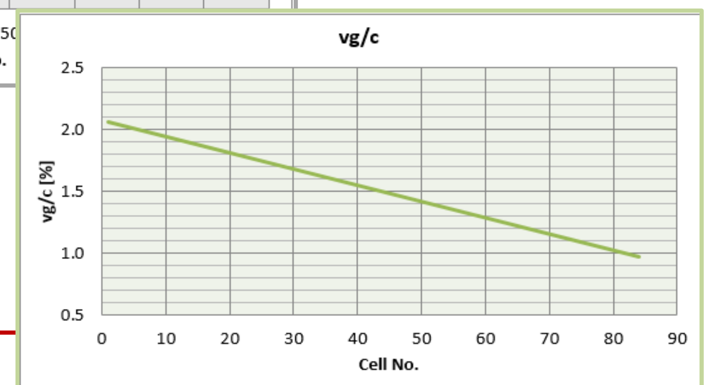


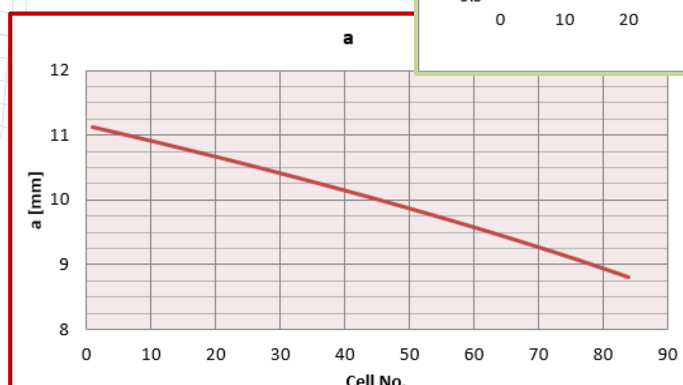
RF design was done by C. Serpico in collaboration with A. Grudiev (CERN)

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









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

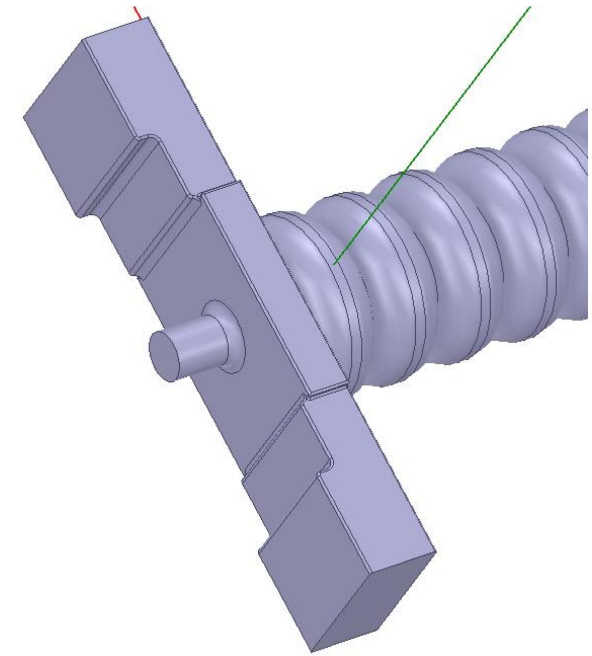
C. Serpico, N. Shafqat, A. Grudiev, and R. Vescovo, "High gradient high reliability, and low wakefields accelerating structures for the FERMI FEL", *Review of Scientific Instruments*, vol. 88, p. 073303, 2017

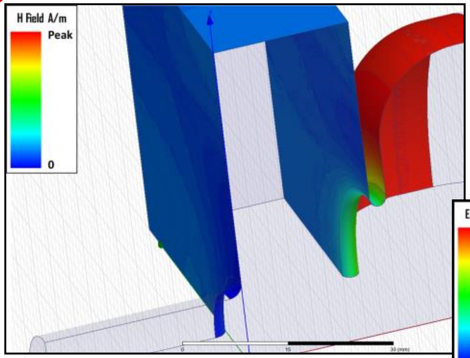
N. Shafqat, S. Di Mitri, C. Serpico, and S. Nicastro, "Design study of high gradient, low impedance accelerating structures for the FRRMI free electron laser upgrade", *Nuclear Instruments and Methods in Physics Research A*, vol. 867, pp. 78-87, 2017

RF COUPLERS' DESIGN

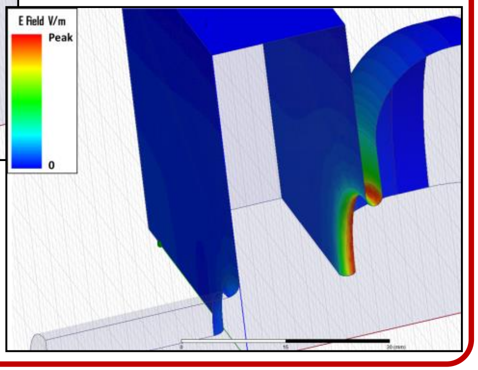
A customized version of dual-fed-electric coupled (EC) coupler is chosen for the new high gradient (HG) structures due to following

- ❑ Very low surface magnetic field
- ❑ Easy to machine
- ❑ Reduced cost of fabrication





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



	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]	1,956	1,319

C.Serpico, A. Grudiev, and R. Vescovo , "Analysis and comparison between electric and magnetic power couplers for accelerators in Free Electron Laser (FEL)", *Nuclear Instruments and Methods in Physics Research A*, vol. 833, pp. 8-14, Oct. 2016.

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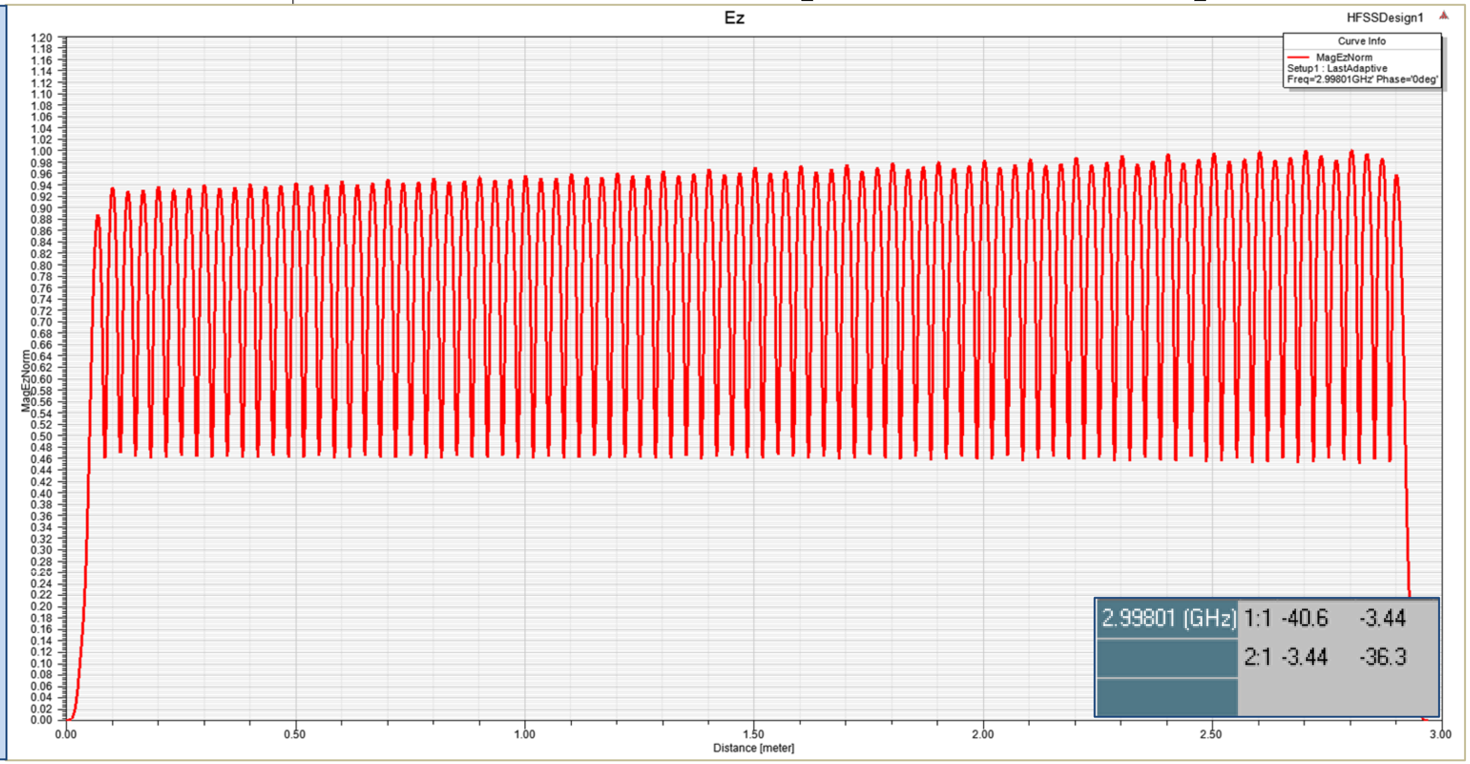
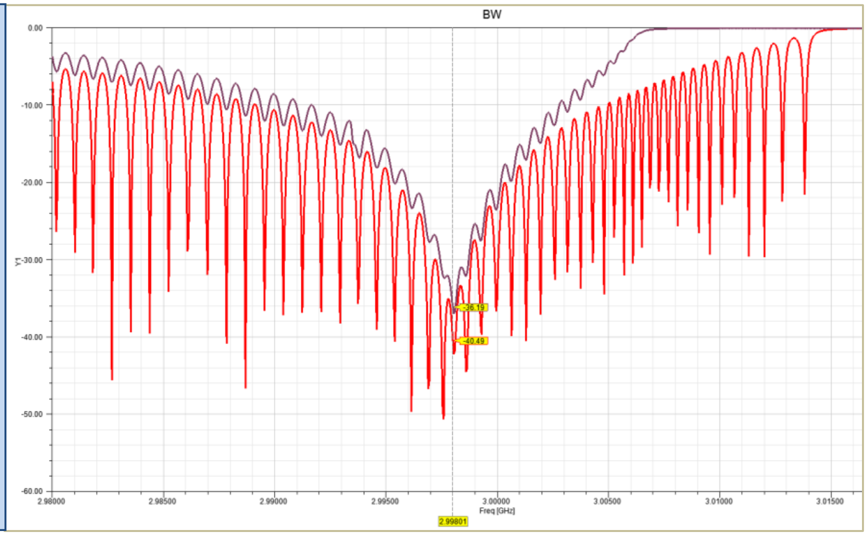
RF Analysis of Full HG Structure (3.0 meter)

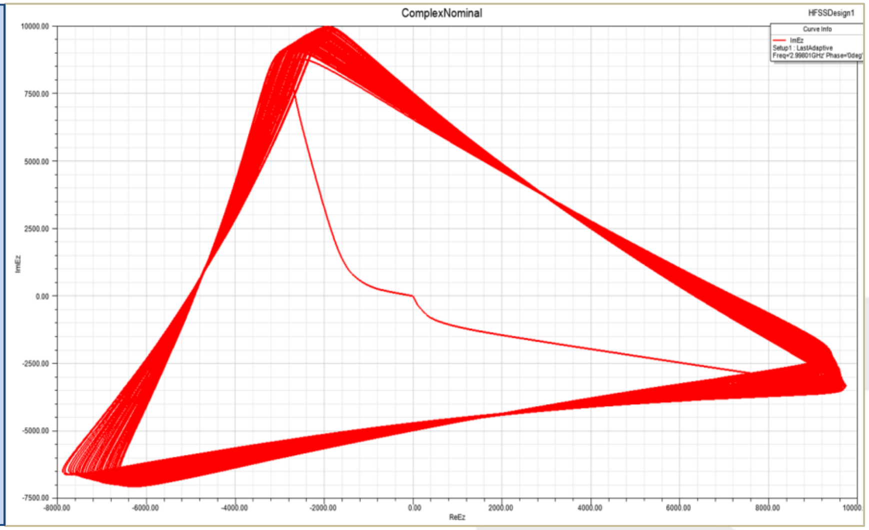
Normalized Magnitude of Ez



Bandwidth



ImEz vs ReEz

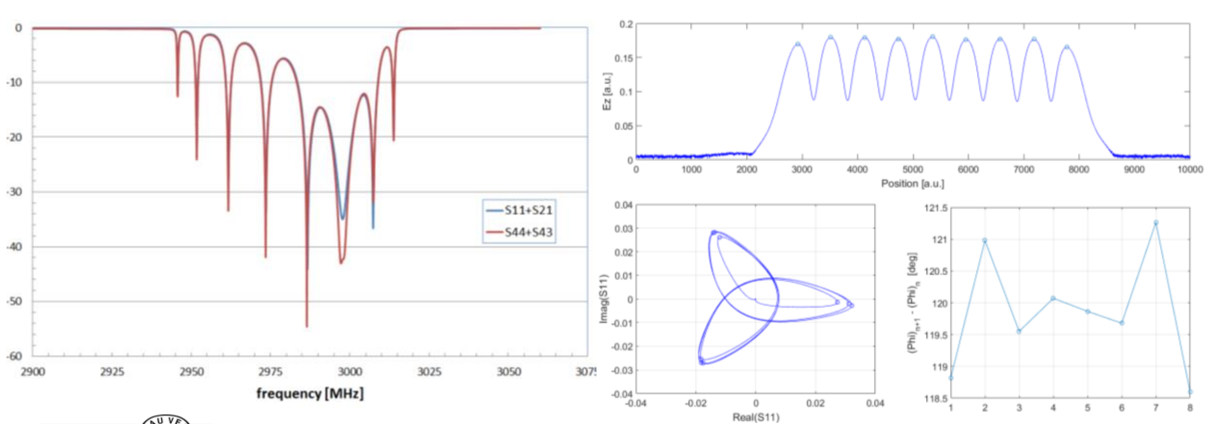


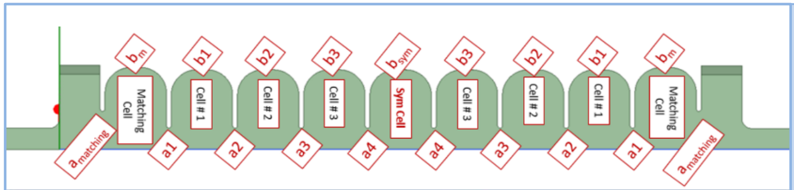
PSI PROTOTYPE
FACTORY ACCEPTANCE TEST

- 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.

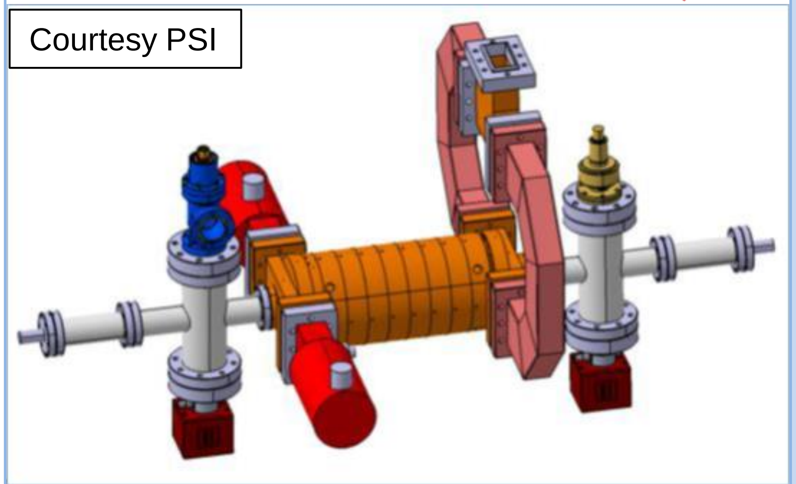
RF measurements and bead-pull rest at PSI

Courtesy PSI

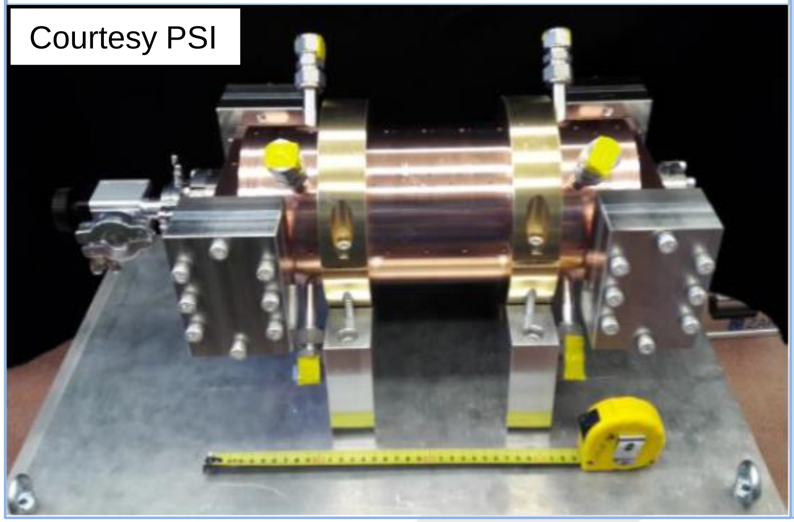




Courtesy PSI



Courtesy PSI



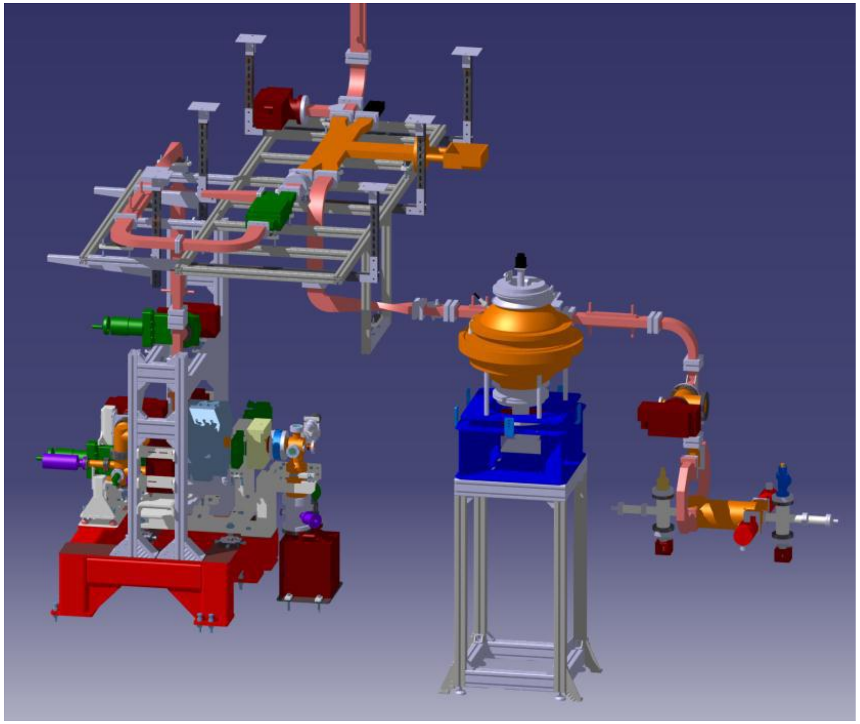
Short HG Prototype

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.

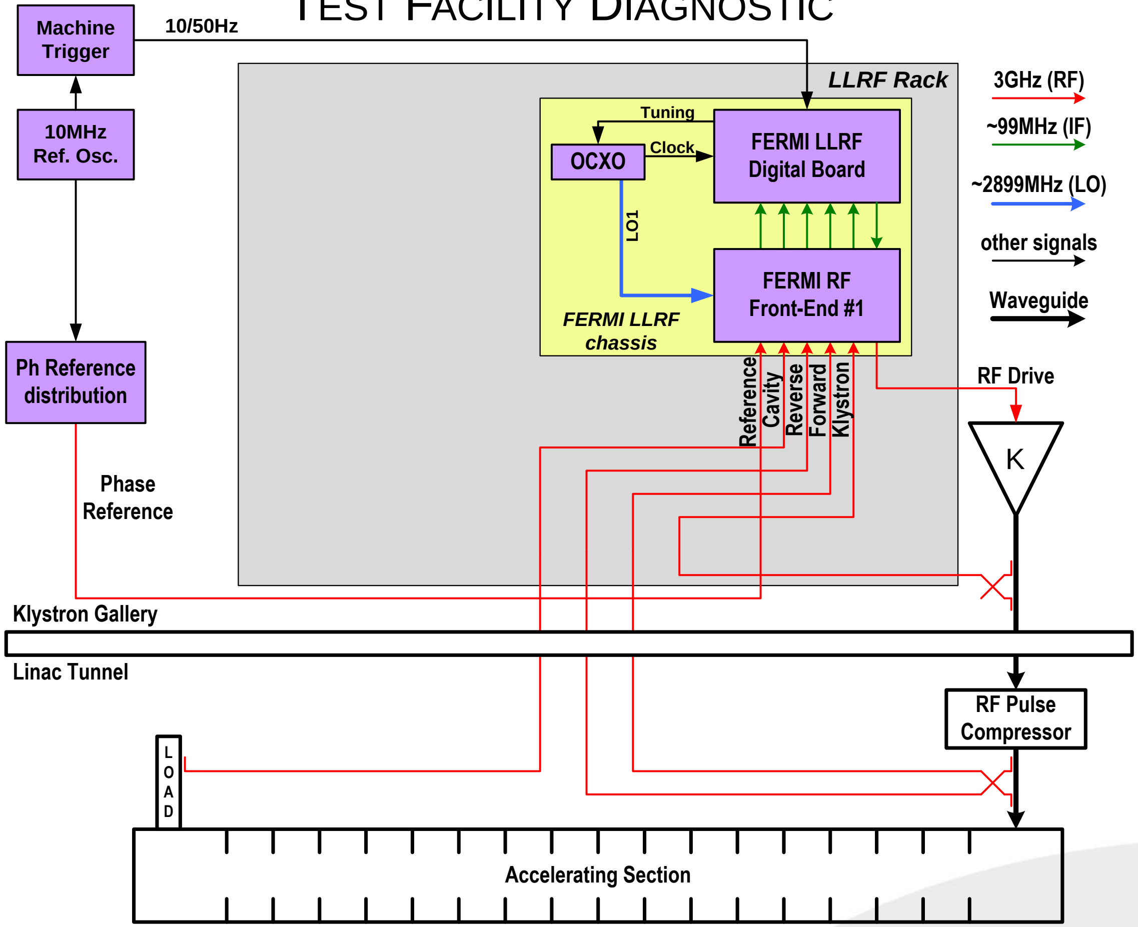
FERMI CAVITY TEST FACILITY

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

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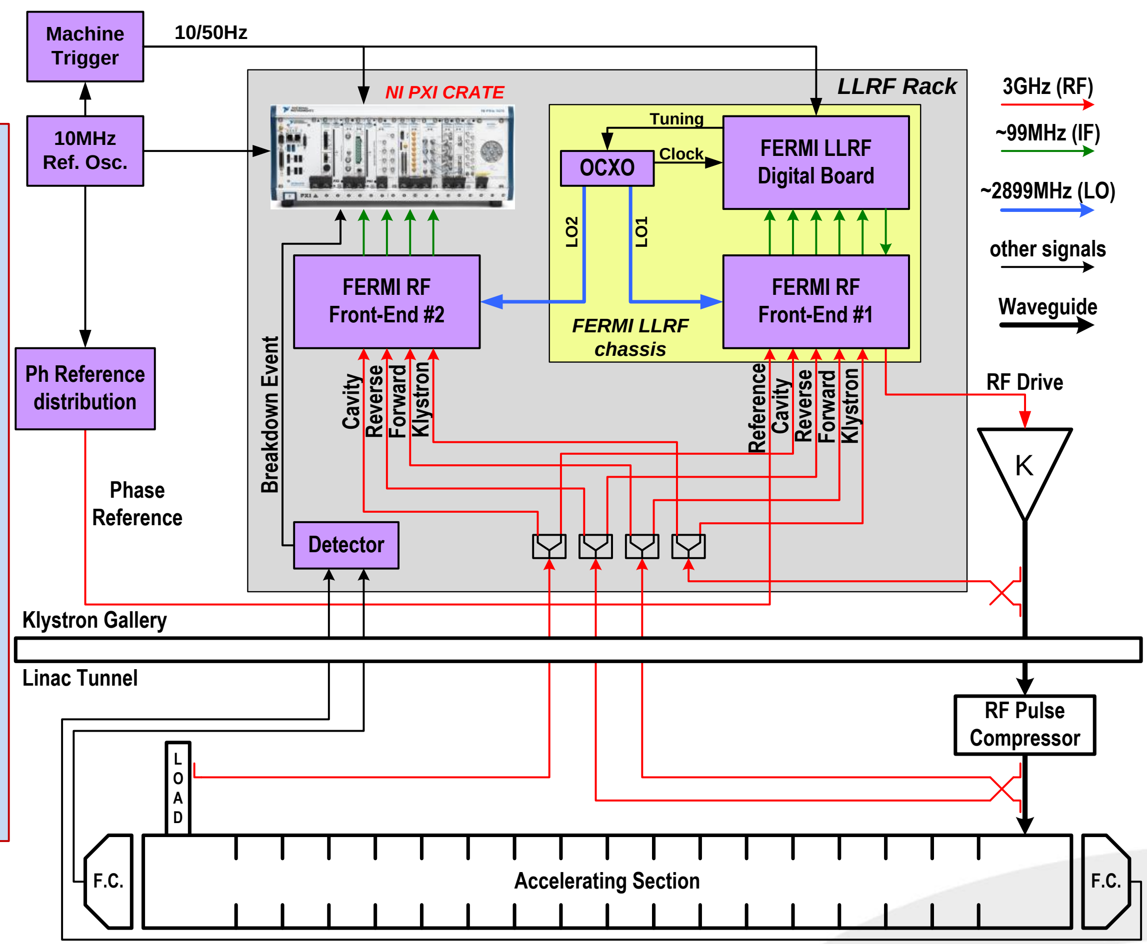
FERMI CAVITY TEST FACILITY

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



ISO 9001 OHSAS 18001 BUREAU VERITAS Certification

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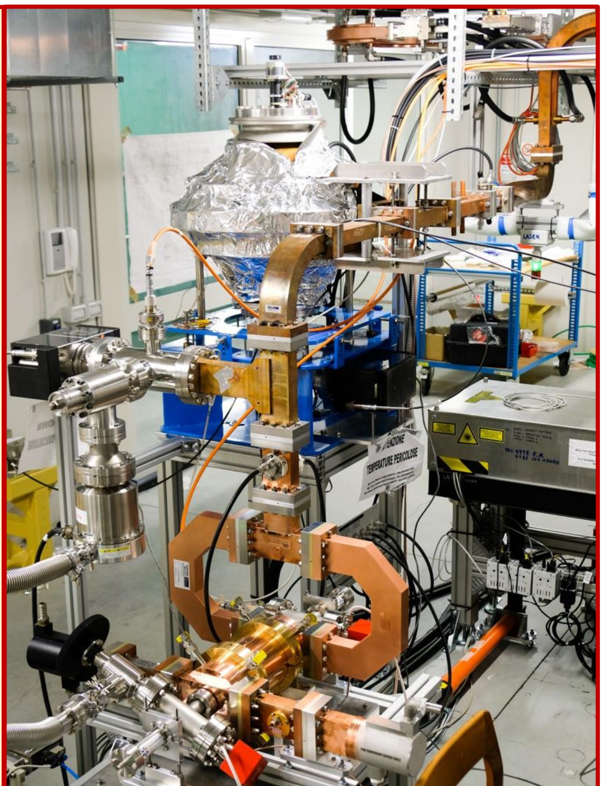
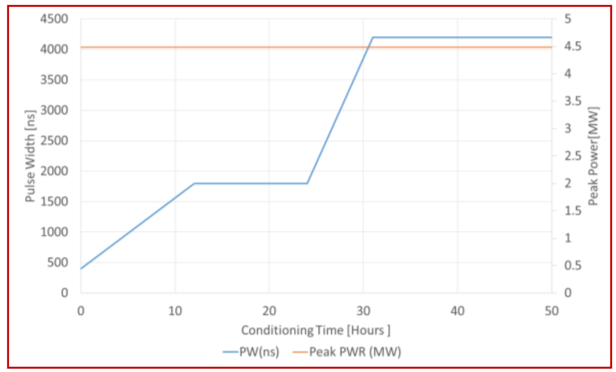
Conditioning Procedure

- During the **Spring Shutdown (April 2018)** the prototype was installed in FERMI Test Facility.
- Preliminary power tests were performed and all diagnostic was properly setup.
- But there was cooling system issue at FERMI delaying the start of conditioning by one month

Prototype installed in FRMI Tunnel





Cooling System issue

Total Conditioning History

Phase 1
- Rep. Rate: 10 Hz
- Start Date: 01-06-2018
- End Date: 20-08-2018
- Level Achieved: 72 MW

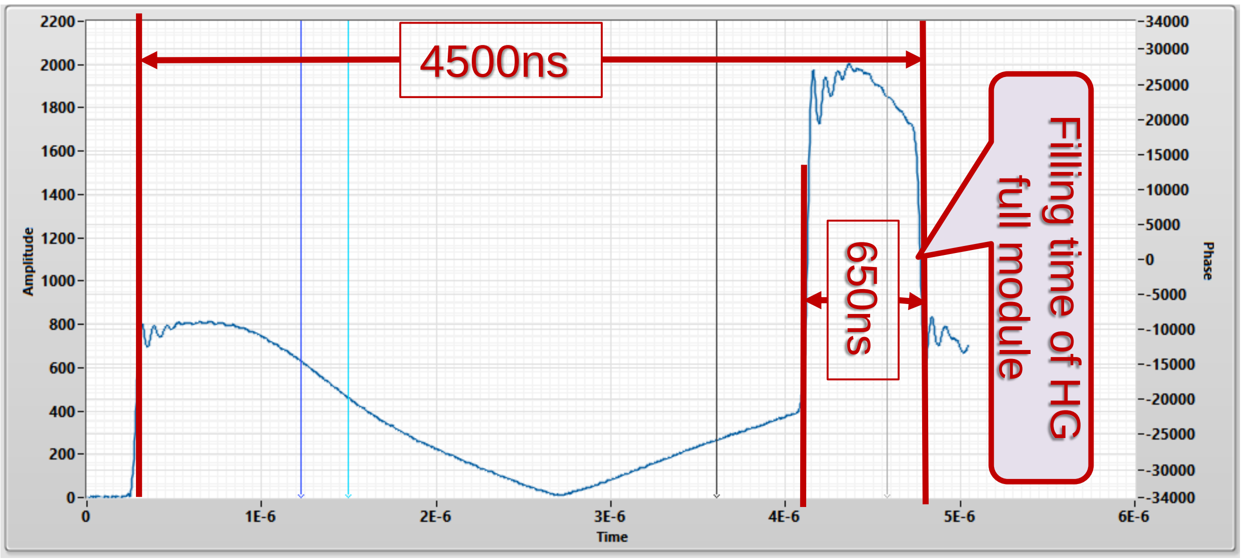
Phase 2
- Rep. Rate: 50 Hz
- Start Date: 07-09-2018
- End Date: 7-11-2018
- Level Achieved: 72 MW

Phase 3
- Rep. Rate: 50 Hz
- Start Date: 30-01-2019
- End Date: 21-05-2019
- Level Achieved: 94 MW

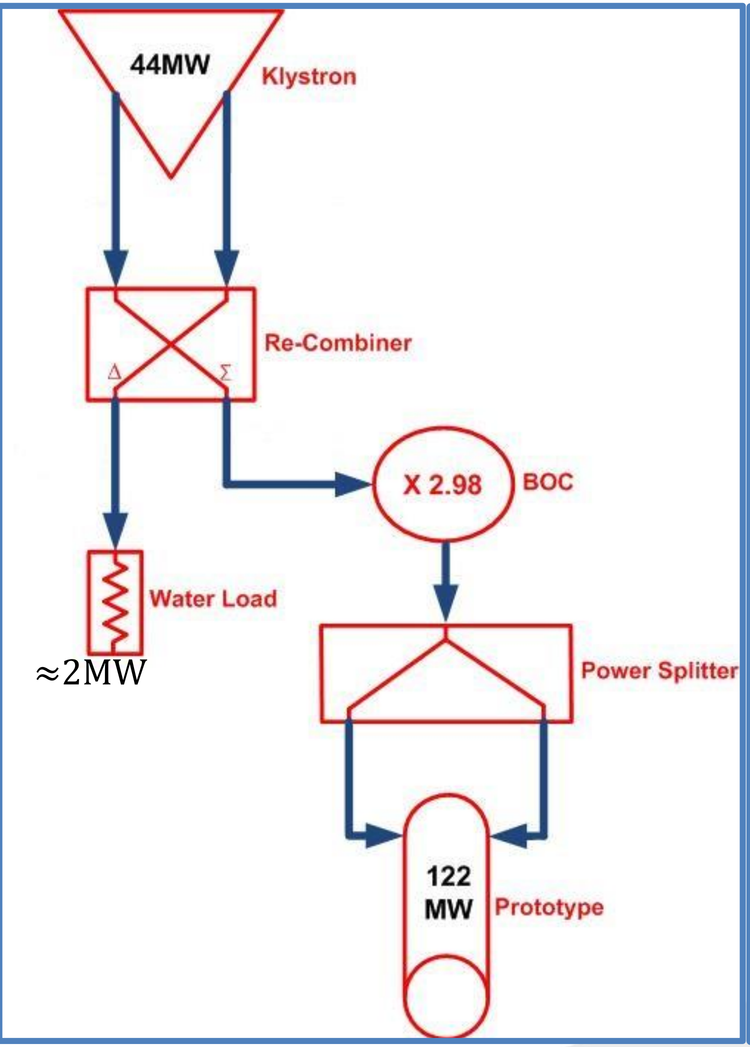
Phase 4
- Rep. Rate: 50 Hz
- Start Date: 31-08-2019
- End Date: 19-12-2019
- Level Achieved: 122 MW

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}



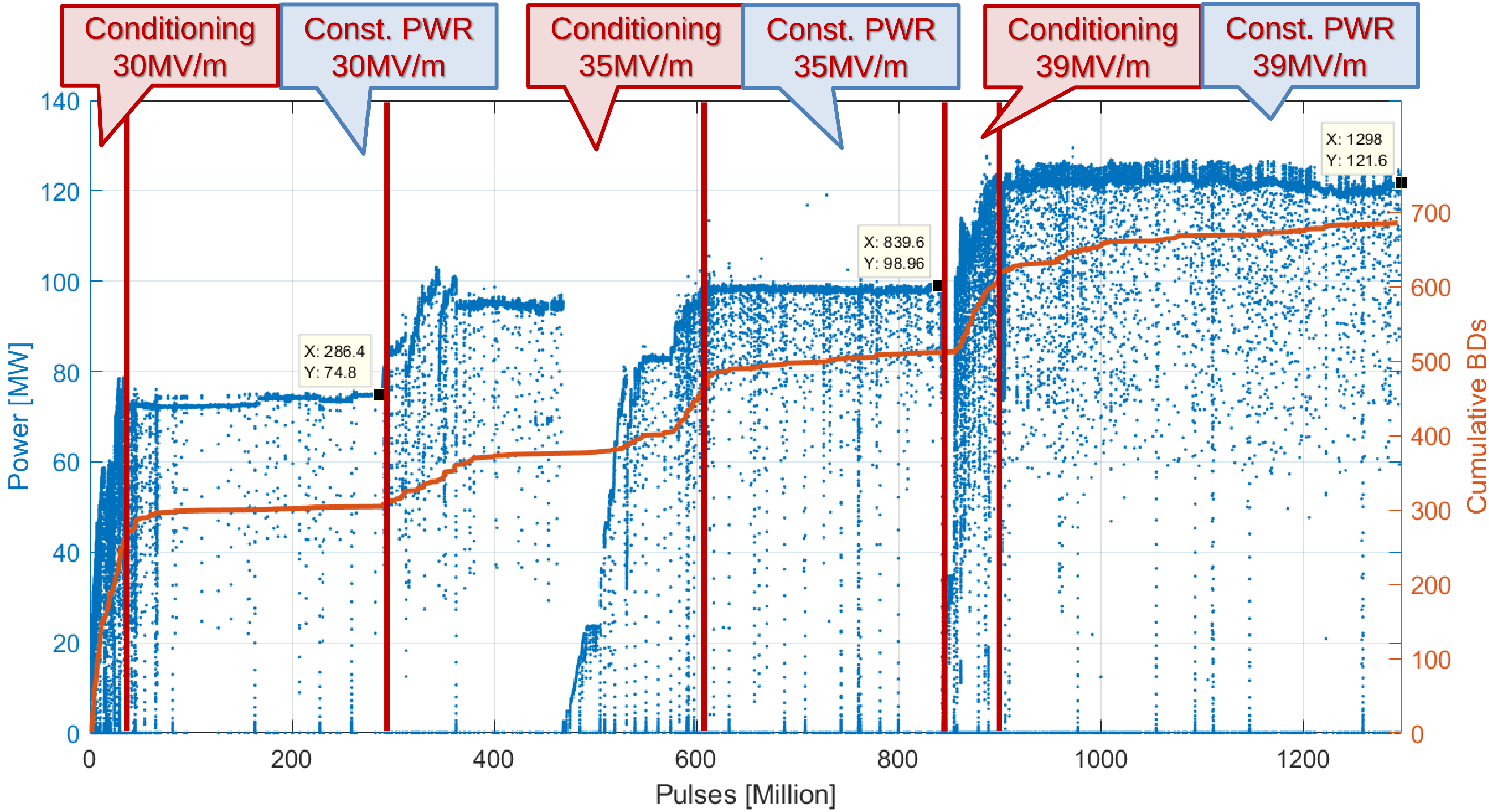
ESTIMATE OF RF POWER DISTRIBUTION IN CTF



*Original target was 40MV/m acc. Gradient

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

COMPLETE CONDITIONING HISTORY



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Conditioning HG Prototype Phase 4 @ 50 Hz

BOC Tuning Issue

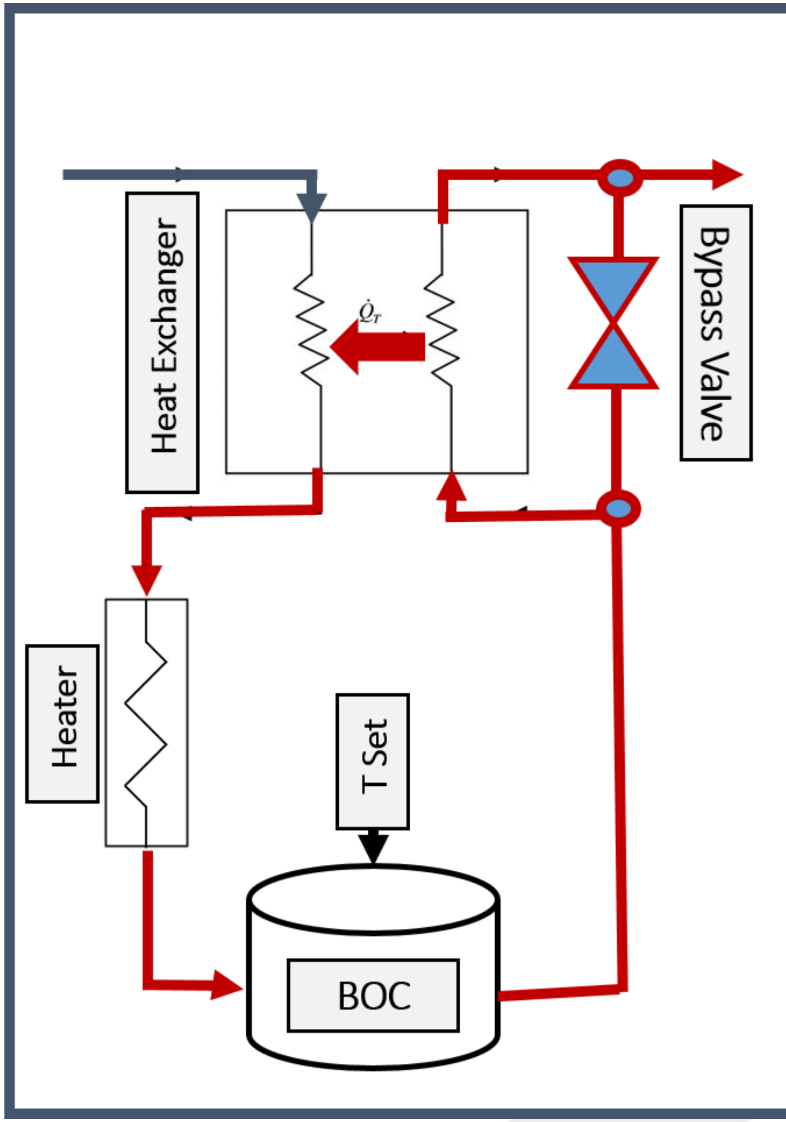
- **Beyond 100MW peak power it was not possible to tune BOC**

Phase IV (Conditioning)

- BOC is fine tuned by adjustment of cooling water temperature
- Flow and heat exchanger settings were adjusted to solve the tuning issue

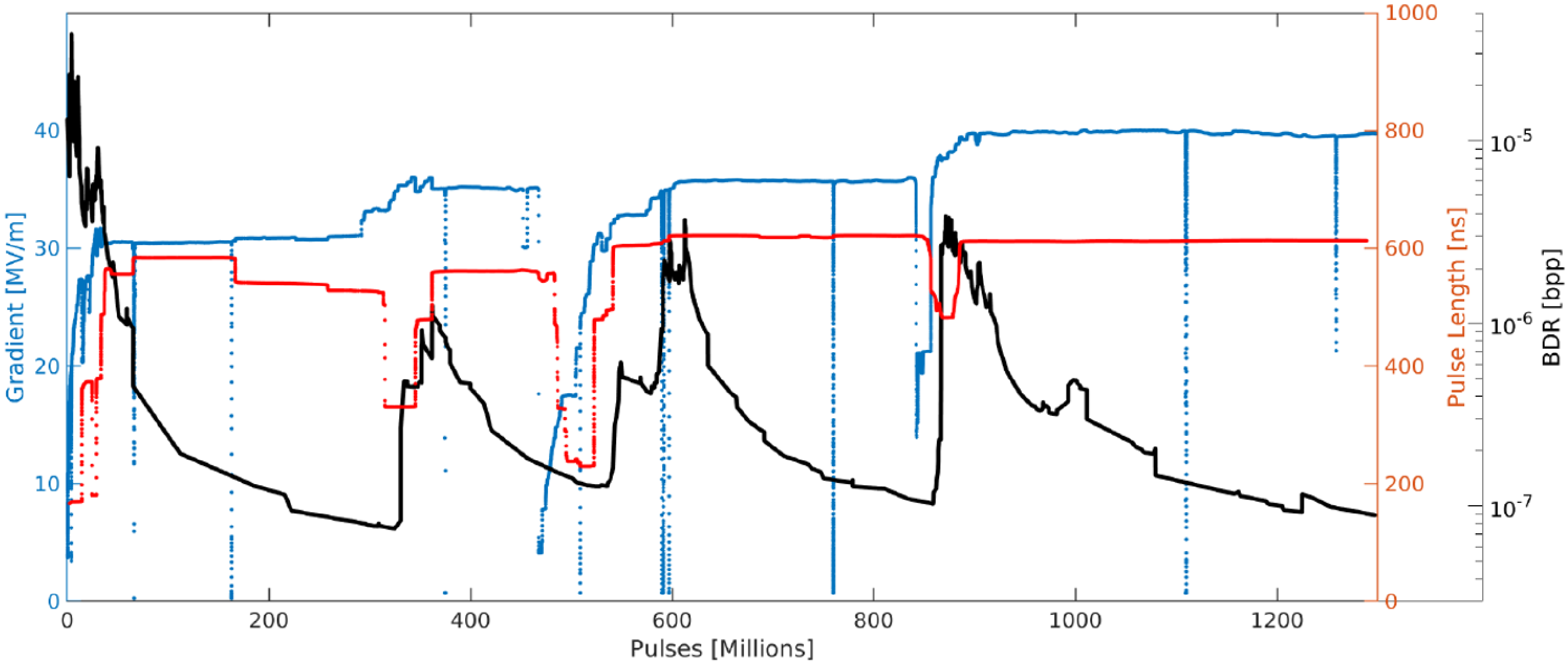
Power Splitter Issue

- CML Stub based design
- Arcing issue for power splitter exacerbated at higher power levels
- New power splitter has been designed, fabricated and tested at Elettra.

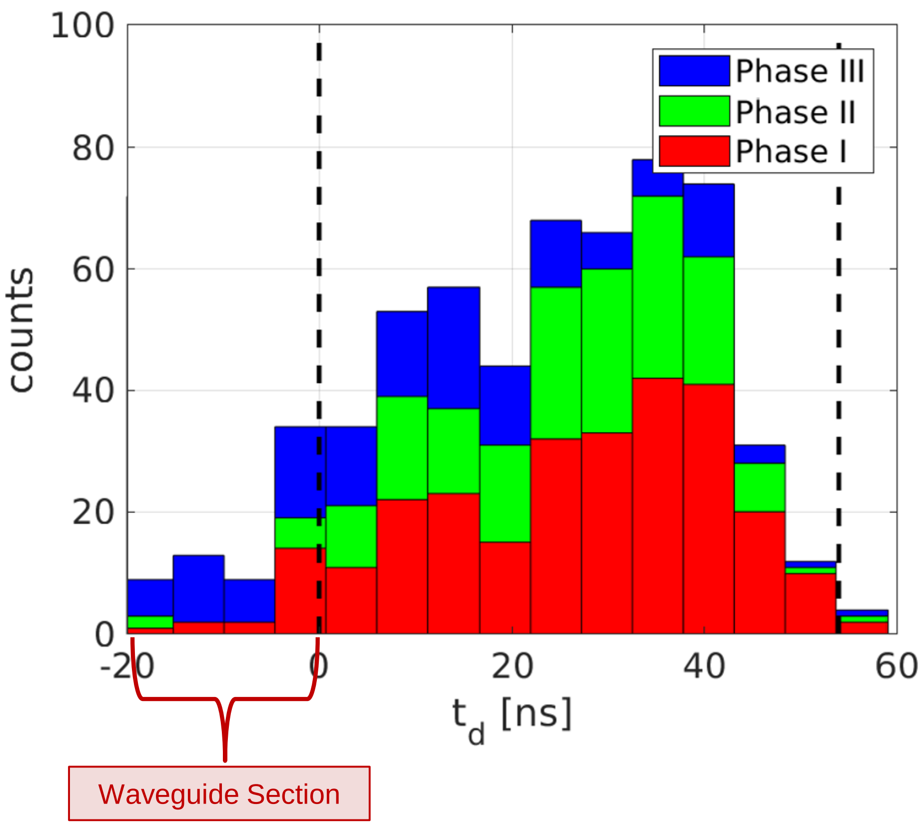


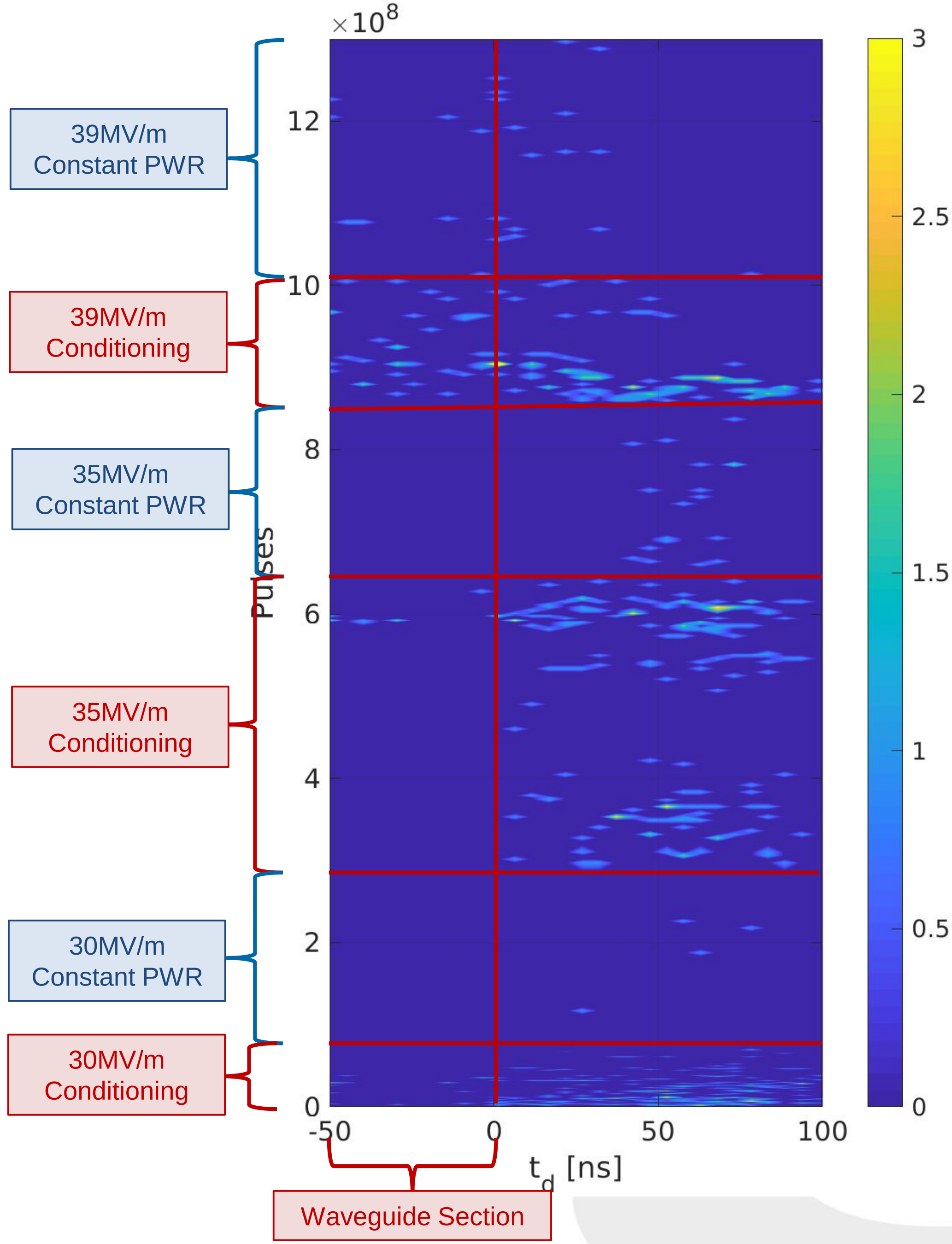
Cooling Loop of BOC at FERMI

COMPLETE CONDITIONING HISTORY PLOT



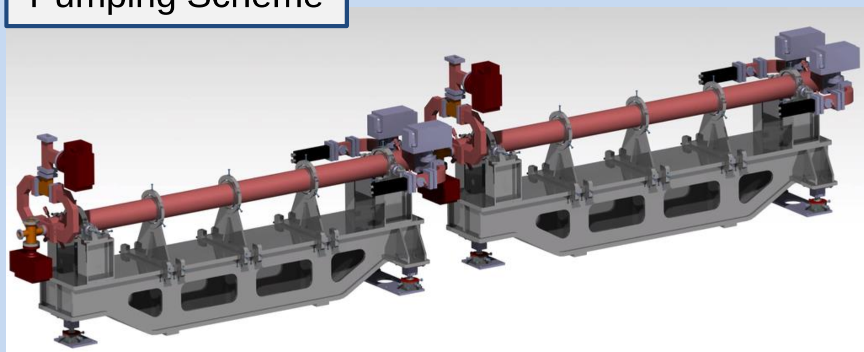
Complete Conditioning Breakdown Locations



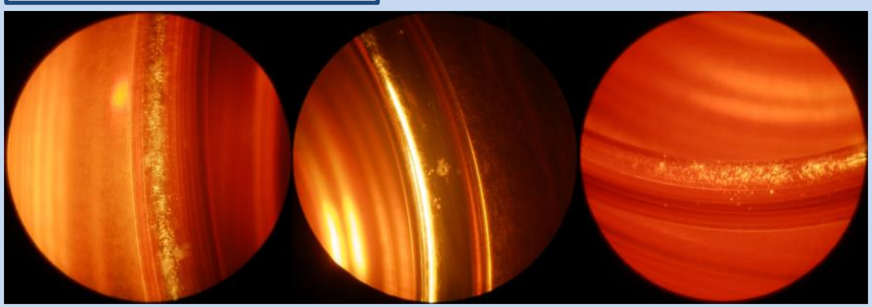


Complete Conditioning
Final Comments

Pumping Scheme

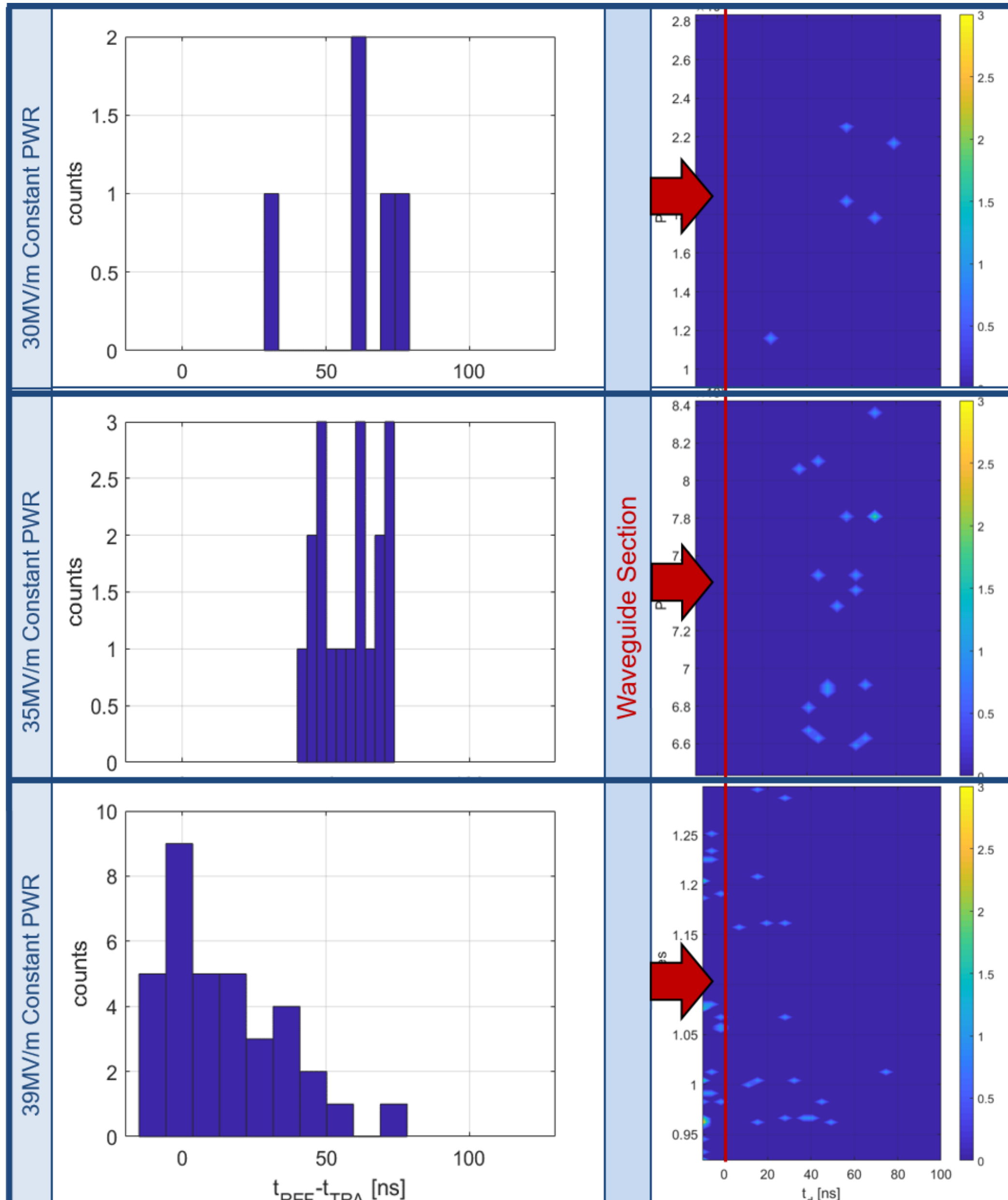


Endoscopic Results



Power & Gradient

Klystron PWR [MW]	Pulse duration [µs]	Sec. Input PWR [MW]	Av. Gradient [MeV]	En. Gain/Sec. [MeV]
38	4.0	60	29.4	82
42	4.0	67	31.1	87
42	4.5	72	32.2	90
60	4.0	95	37.1	103
60	4.5	100	38.0	105



Conclusion

Conditioning of HG prototype

- Successful conditioning of HG prototype at Cavity Test Facility of Elettra and subsequent data analysis of conditioning data.

Reliable operation at 30MV/m at 50Hz

- It is proven that HG prototype can work reliably at **30MV/m** with a breakdown rate of $2.0 \times 10^{-8} bpp$

Reliable operation at 35MV/m at 50 Hz

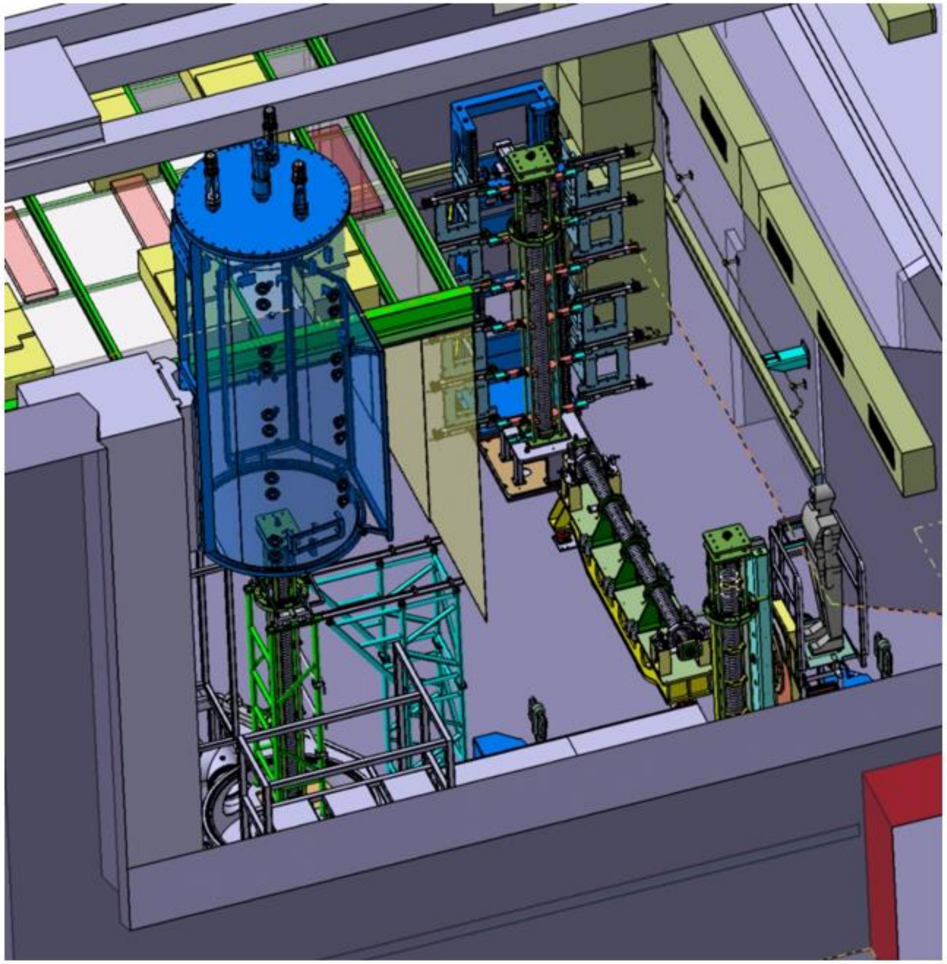
- It is proven that HG prototype can work reliably at **35MV/m** with break down rate of $7.3 \times 10^{-8} bpp$

Reliable operation at 39MV/m at 50 Hz

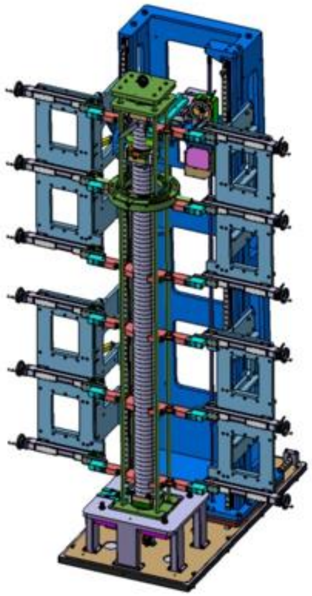
- It is proven that HG prototype can work reliably at **39MV/m** with break down rate of $7.9 \times 10^{-8} bpp$

Production Insights

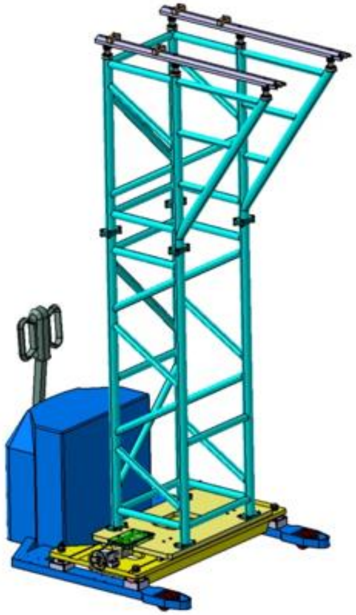
MINOR-Production site: Overview of toolings for the production of 3m-S-Band-Strucutres ELETTRA



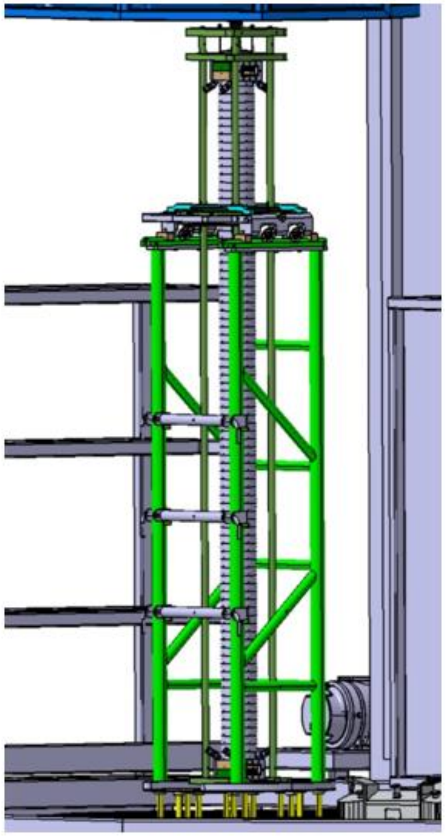
Production Insights



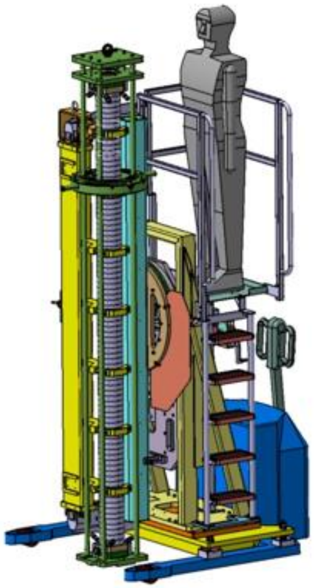
Stacking



Transport
to brazing
oven

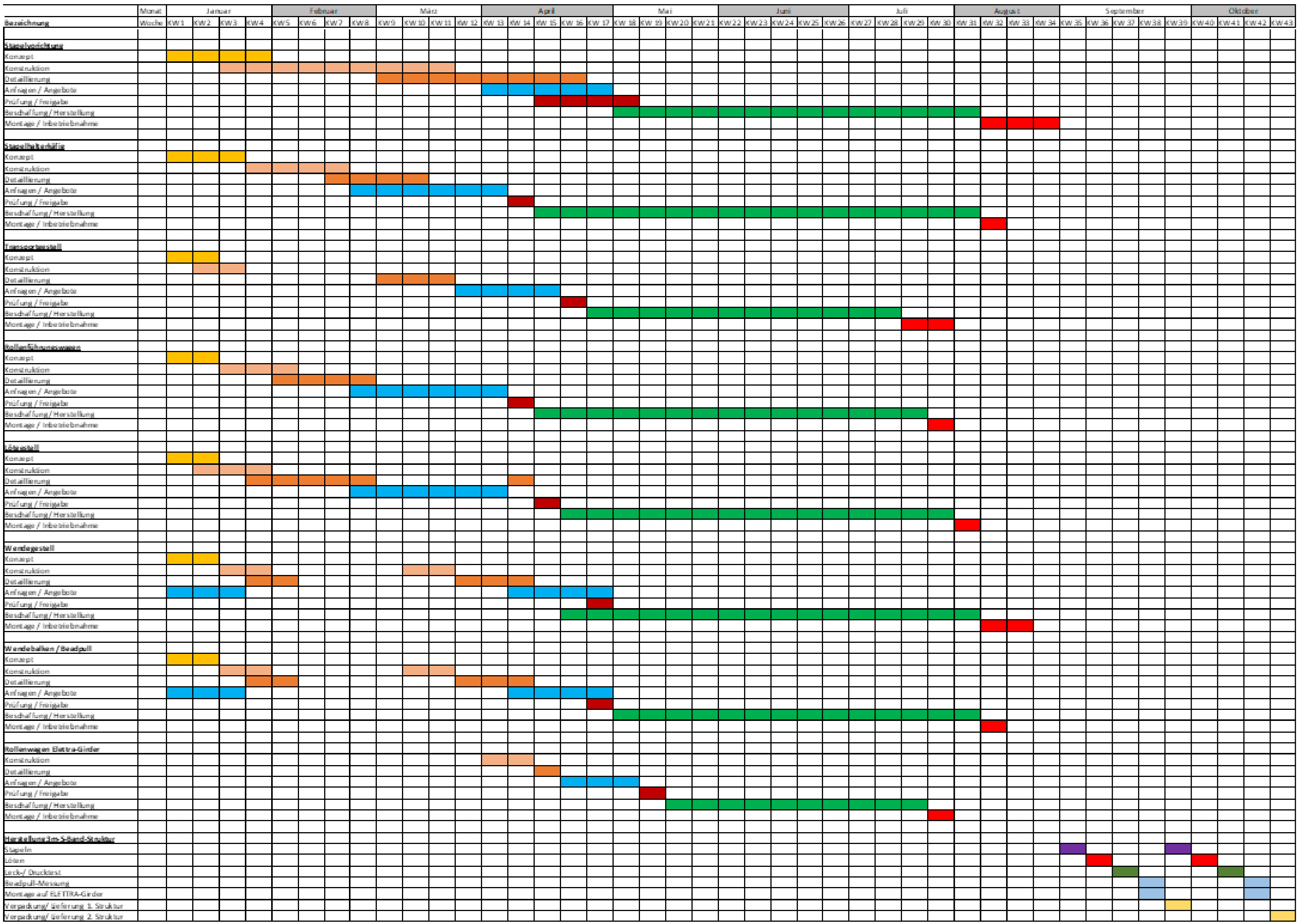


Inside
brazing oven



Handling/
beadpull/to
girder

Timeplan (also attached)

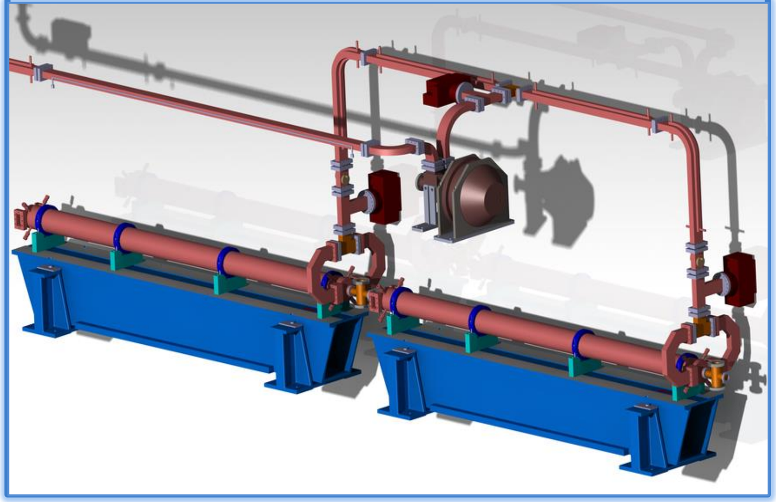


Next Steps And Time Schedule

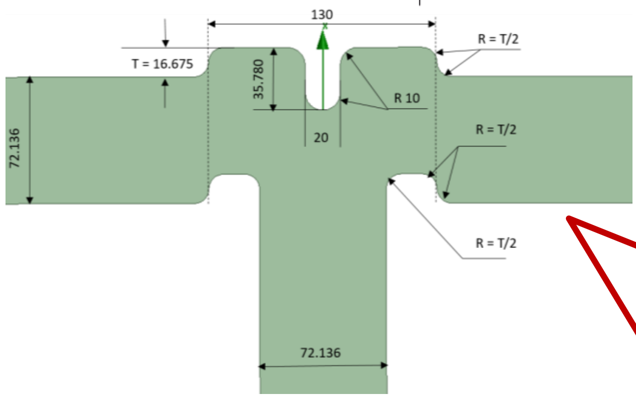
Full HG module timeline…

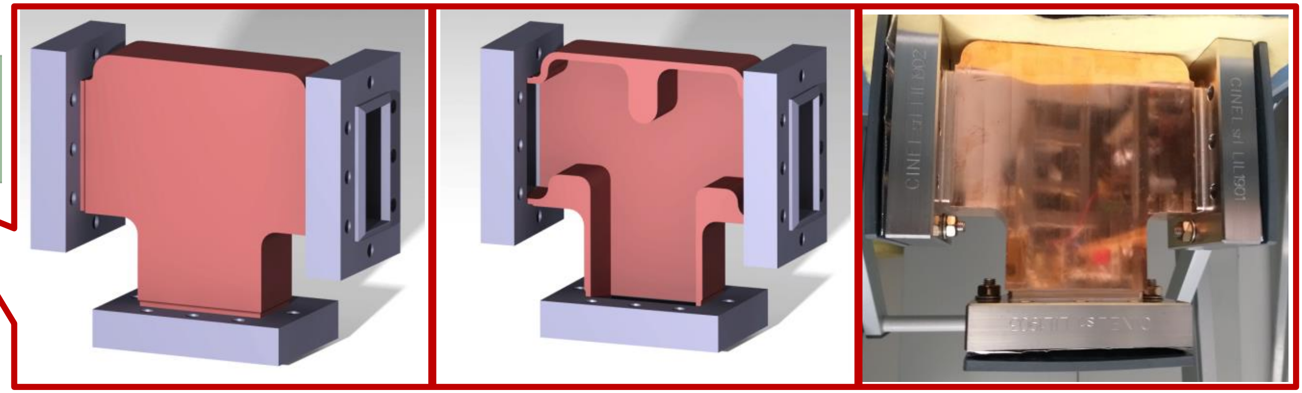
- By **Start of 2021**, HG module would be installed at CTF for high power testing and conditioning.
- By **Summer 2021** module would be installed in FERMI tunnel in place of one deflecting cavity (K15) for operation with beam.

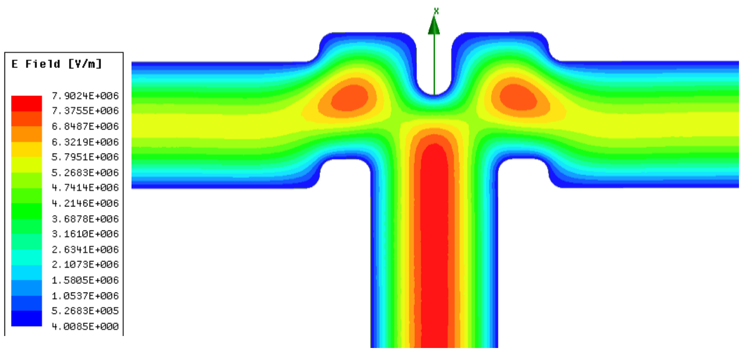
Layout of HG module in FERMI Tunnel



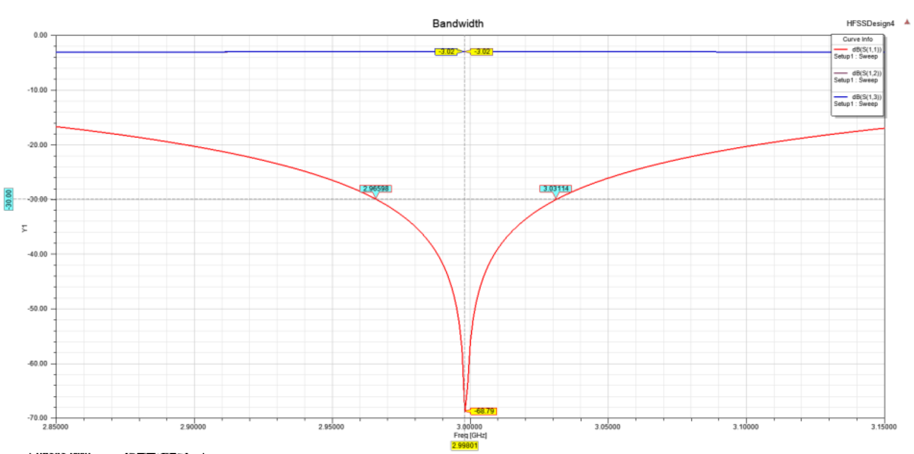
POWER SPLITTER







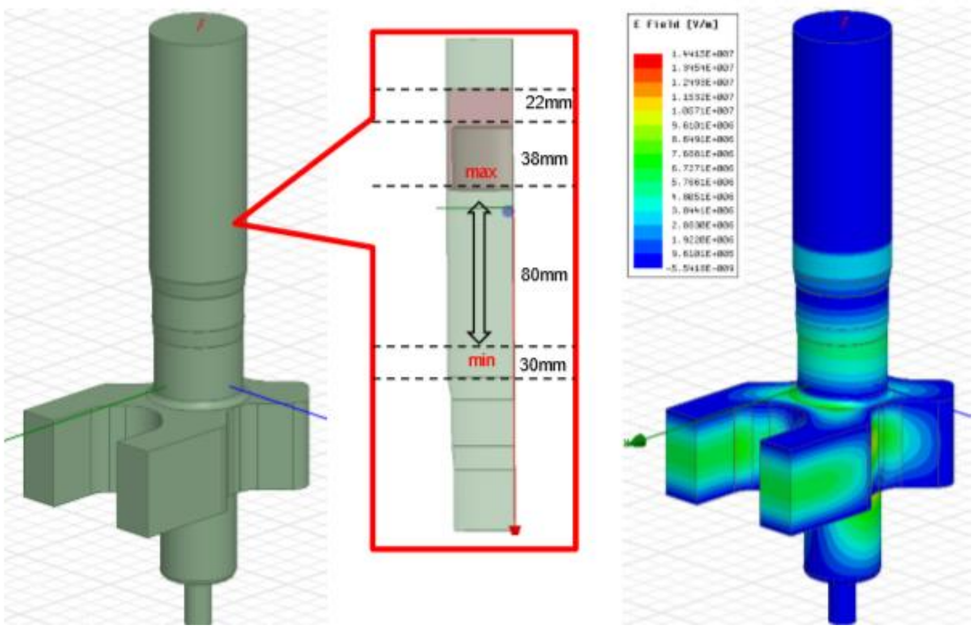
Freq		S:1:1	S:2:1	S:3:1
2.99801 (GHz)	1:1	-69.1	-3.02	-3.02
	2:1	-3.02	-6.03	-6.03
	3:1	-3.02	-6.03	-6.03

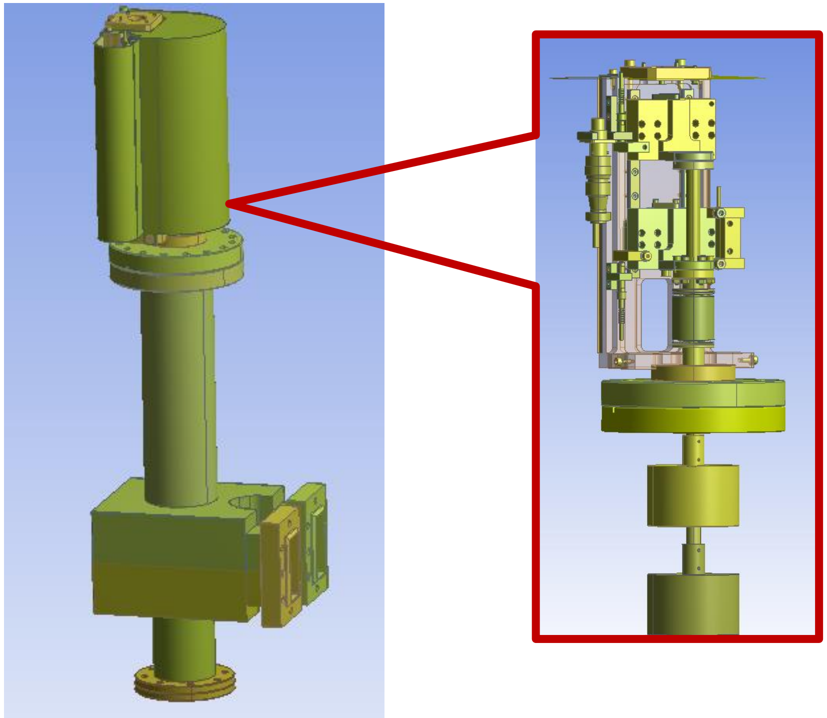


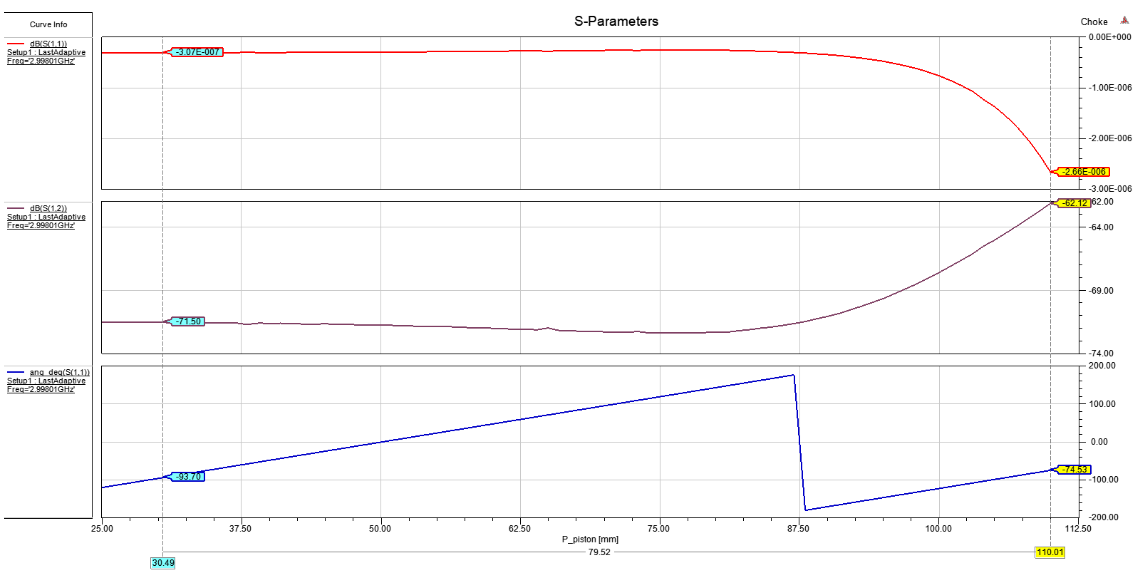
	Values	Units
f_0	2.99801	GHz
Bandwidth @ -30 dB	65	MHz
VSWR	<1.05	
Insertion loss	0.1	
Maximum Peak Power	120	MW
Maximum Average Power	---	KW

Elettra Sincrotrone Trieste

IN-VACUUM PHASE SHIFTER





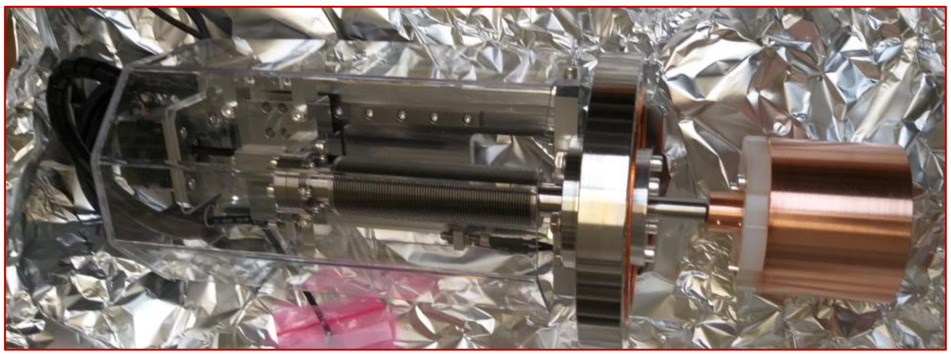


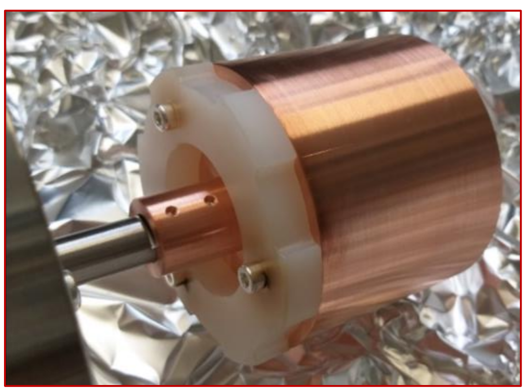
	Value	Units
f_0	2.99801	GHz
Bandwidth @ -30 dB	15	MHz
VSWR	<1.05	
Insertion loss	0.1	
Phase Range	±200	Degree
Max Peak Power	45	MW
Max Average Power	10.125	W

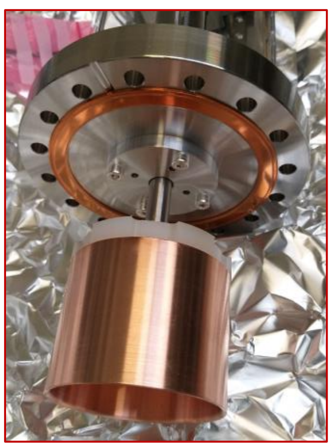
Nuaman Shafqat, 20/10/2021

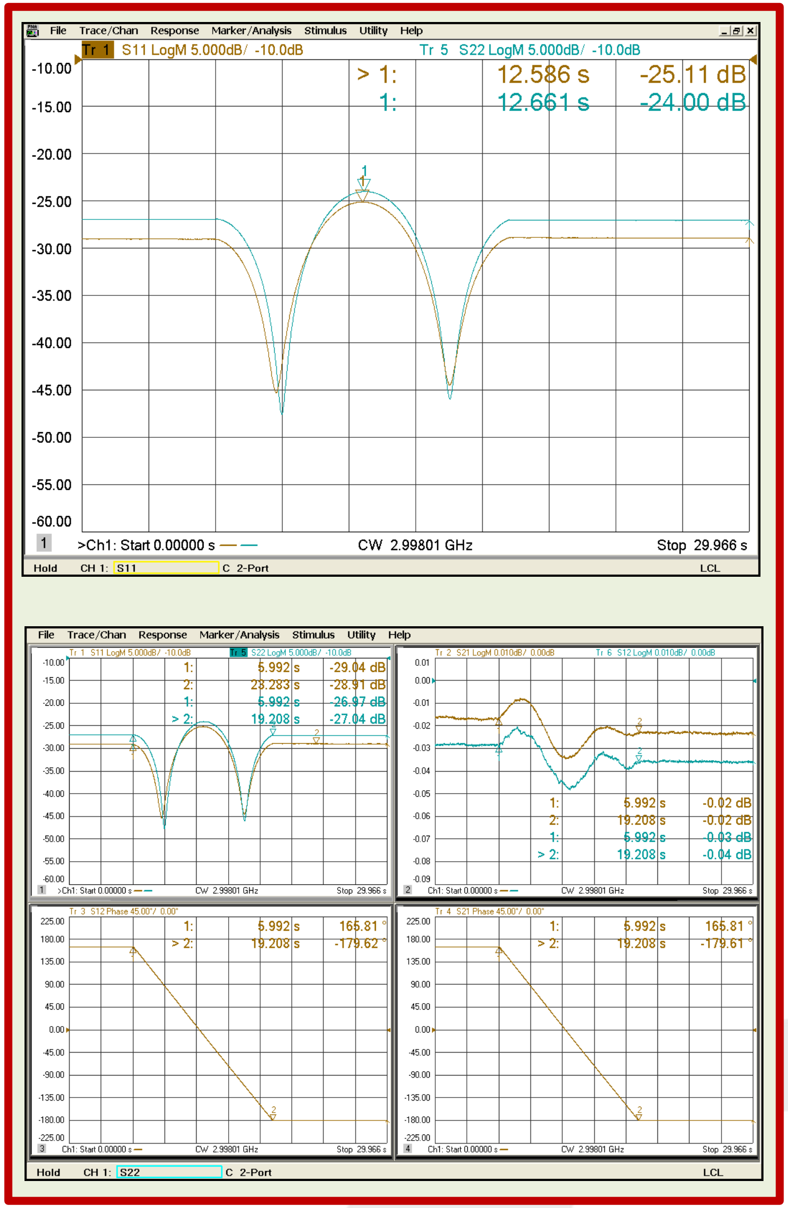
Elettra Sincrotrone Trieste

In-Vacuum Phase Shifter









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

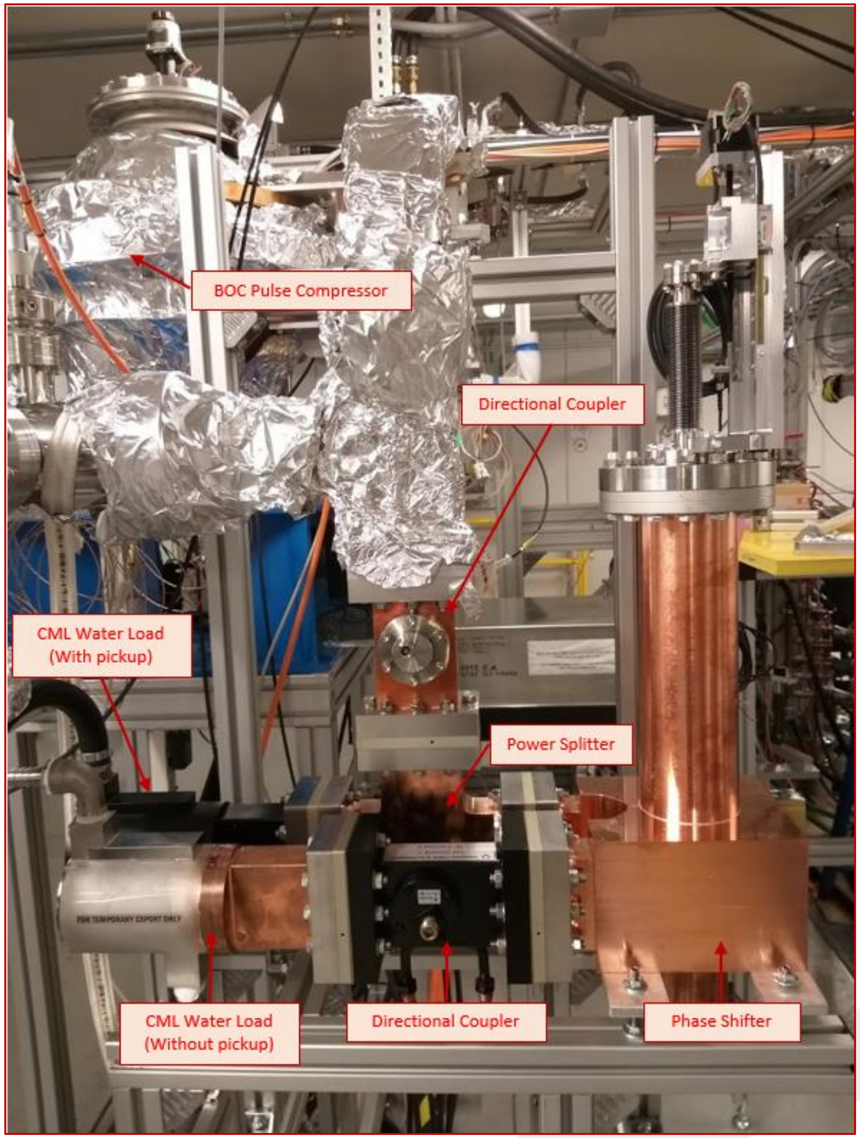
IN-VACUUM PHASE SHIFTER CONDITIONING...

Conditioning

- Start Date: 14th September 2021
- End Date: 24th July 2021
- Target Power: 45 MW
- Target Pulse width: 1000 ns
- Power achieved: 55 MW @ 1us

Remarks

- Power Splitter was also conditioned and tested up to peak power of 110 MW with the pulse width of 1000 ns

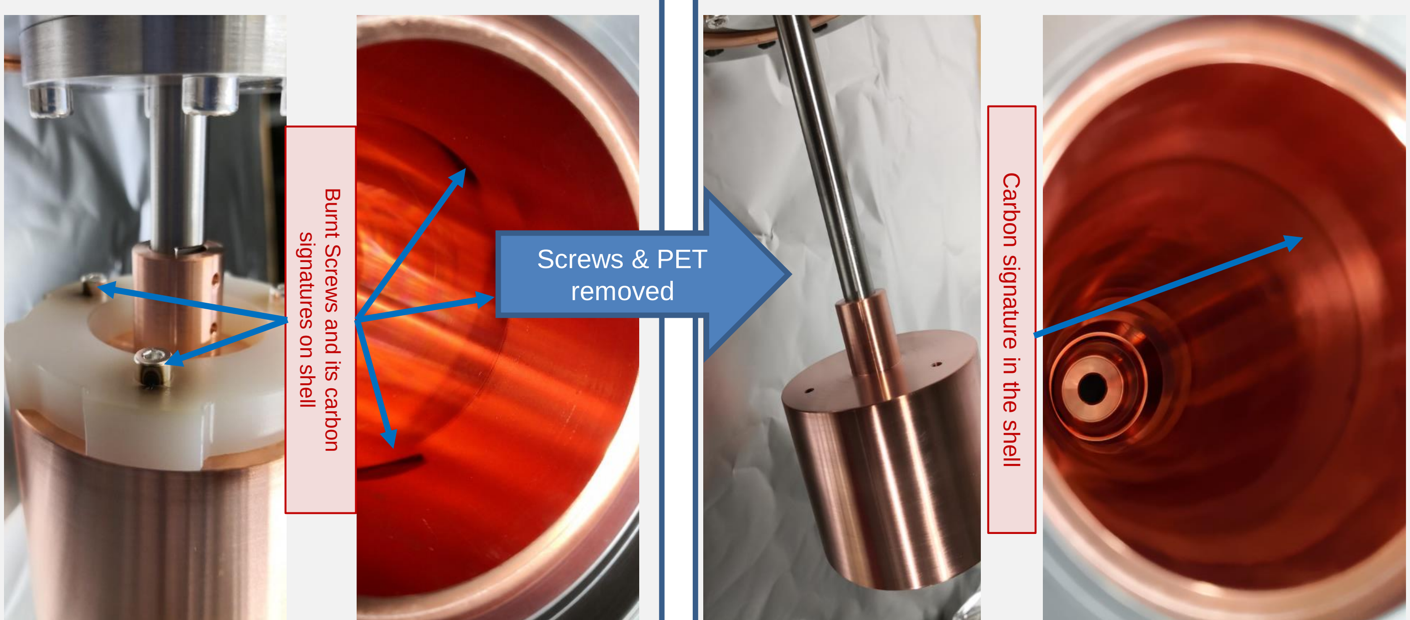


In-Vacuum Phase Shifter Conditioning...

Problems after **1st run** of Conditioning

Problems after **2nd run** of Conditioning

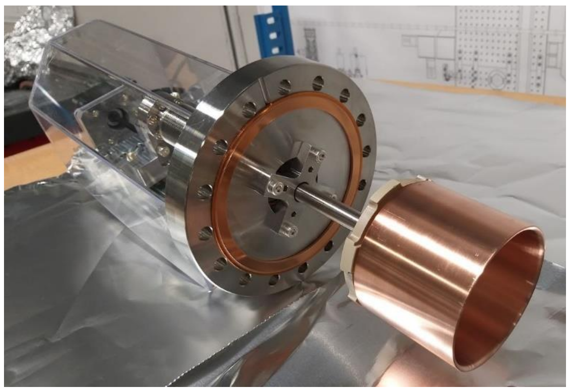
Settings for **3rd run** of Conditioning

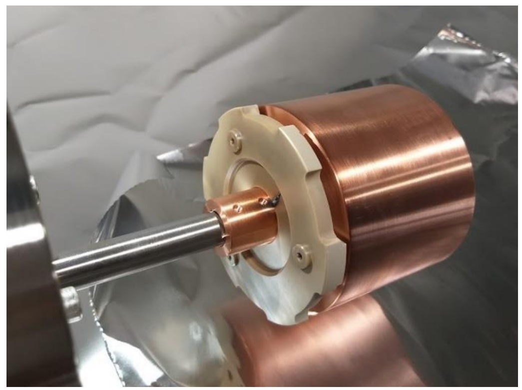


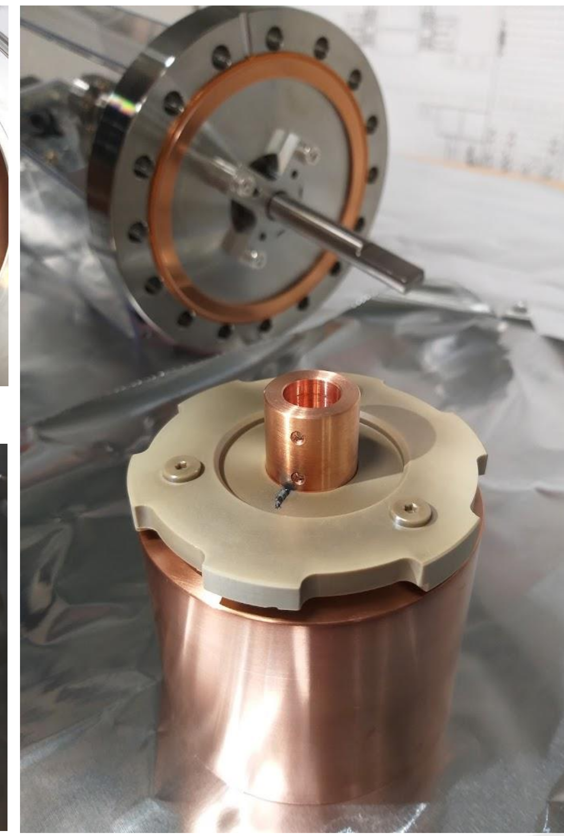
Vacuum Issue

- Issue of bad vacuum was resolved by baking out the plastic
- Metal screws were replaced with the plastic one
- Spacers were placed between the copper surface of choke and the plastic to avoid possibility of virtual leak
- Complete In Vacuum Phase shifter was installed at Test facility of Elettra for conditioning.

In-Vacuum Phase Shifter
Post Conditioning Analysis





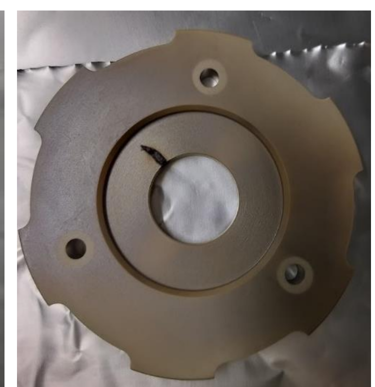


- Remarks

❑ Hard burnt spot on plastic with not surface damage.

❑ Discolouring of plastic

❑ Rest was all clean.



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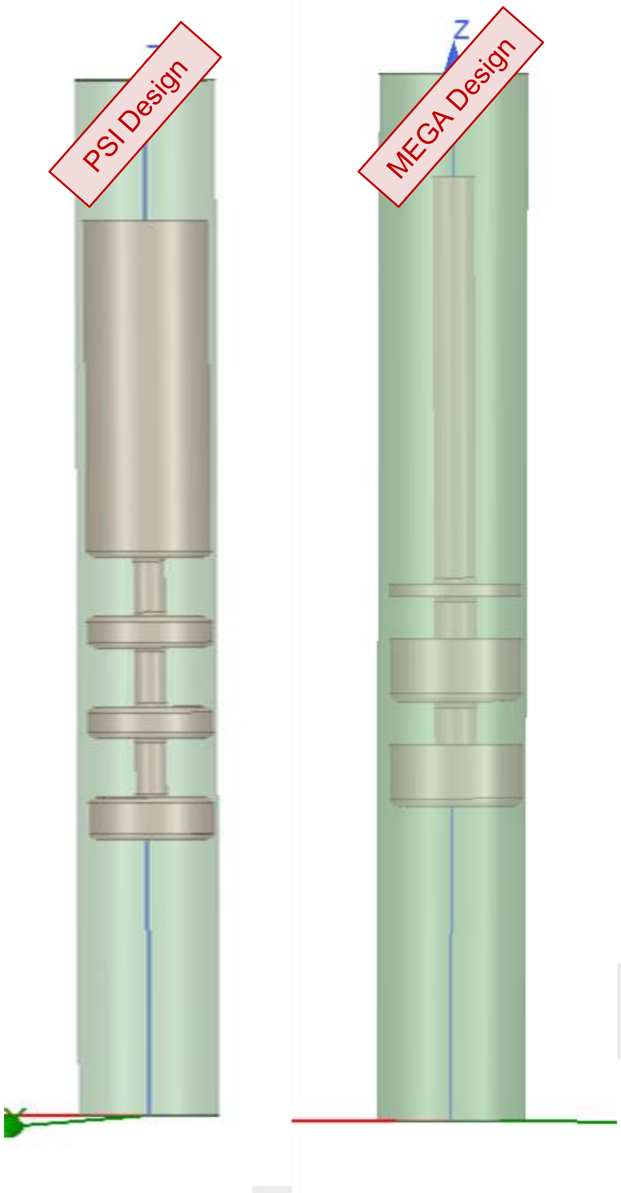
IN-VACUUM PHASE SHIFTER
OTHER CHOKE DESIGNS

Elettra and PSI agreement

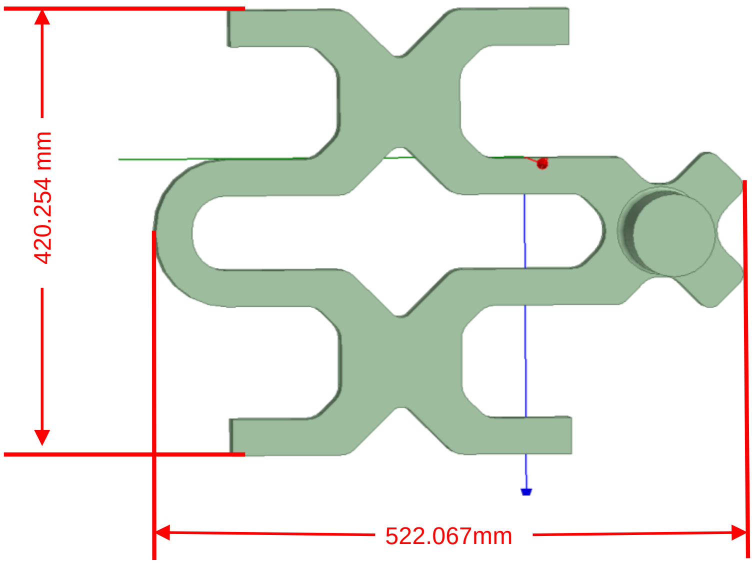
- Elettra and PSI signed an agreement to exchange ideas and knowhow to in the development of S-band waveguide components

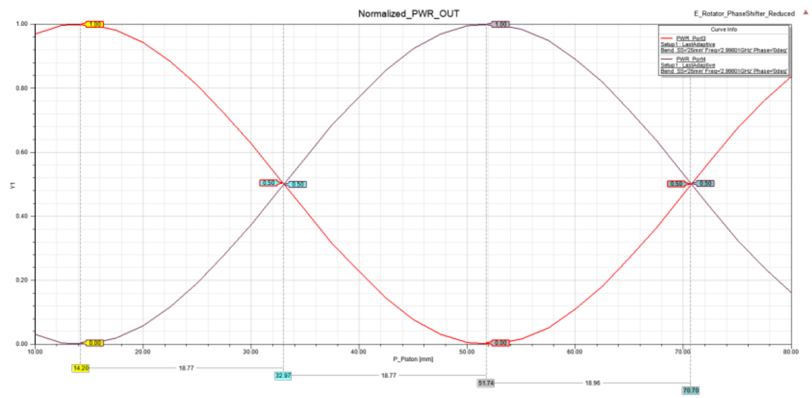
Remarks

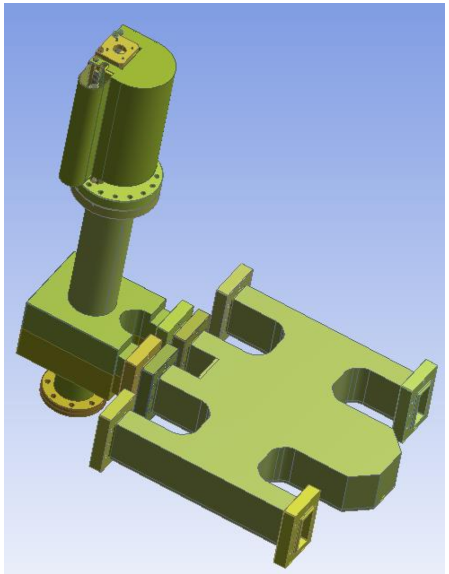
- PSI choke design intends to have 4 mm clearance between choke and guide to avoid any possibility of contact
- PSI choke design was customized to fit with the Elettra E-Rotator which have bigger circular waveguide of 35.6 mm in radius



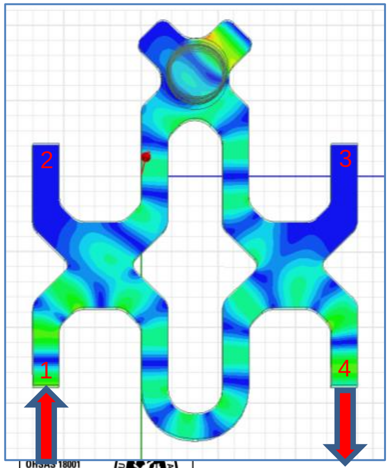
In-Vacuum Variable Power Divider



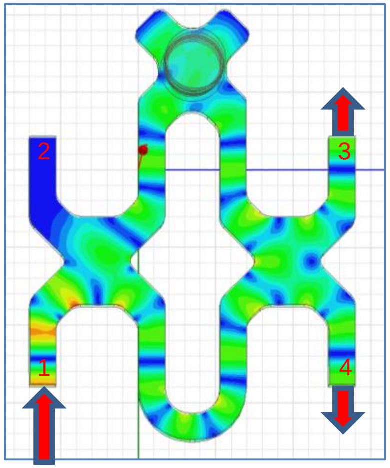




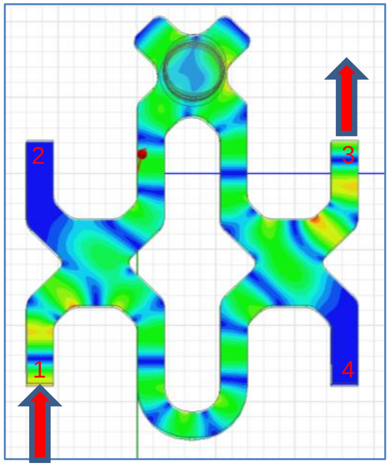
All Power to PORT4



3dB Point



All Power to PORT3



	Value	Units
f_0	2.99801	GHz
Bandwidth @ -30 dB	15	MHz
VSWR	<1.05	
Max Peak Power	45	MW
Max Average Power	10.125	W

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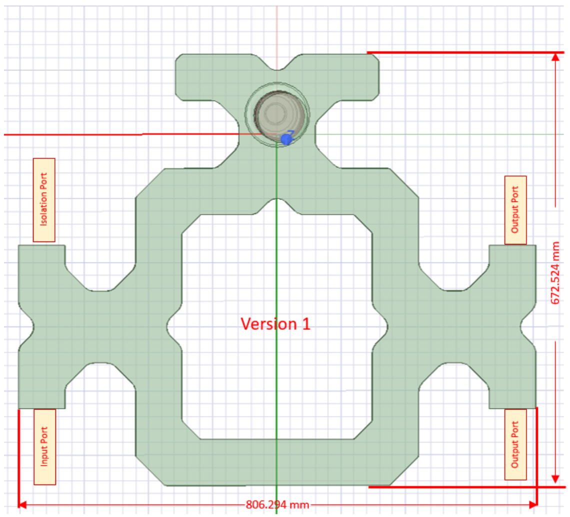
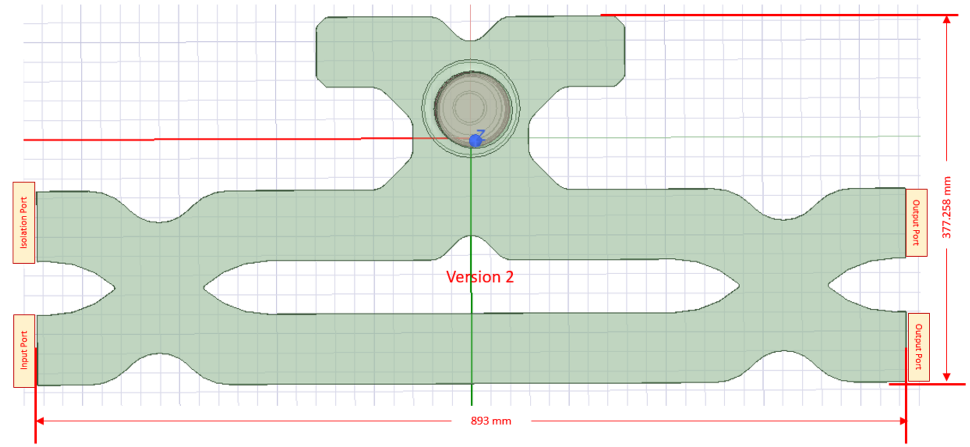
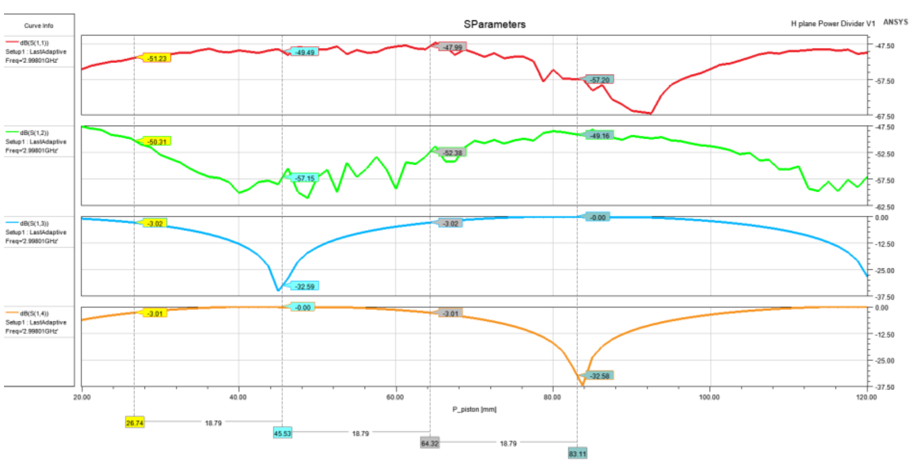
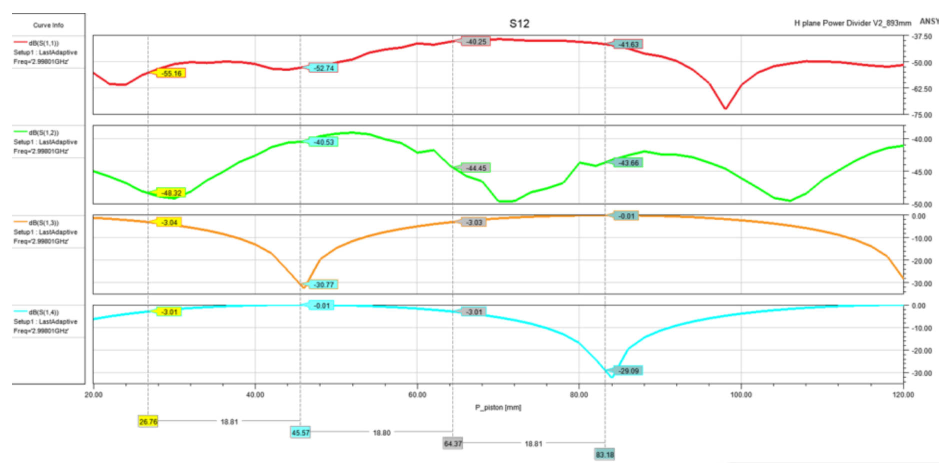
In-Vacuum Variable Power Divider H-Plane

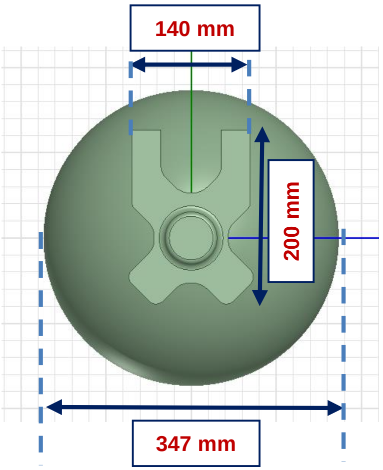


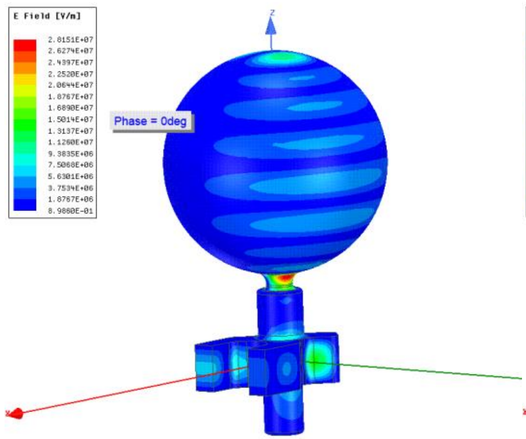


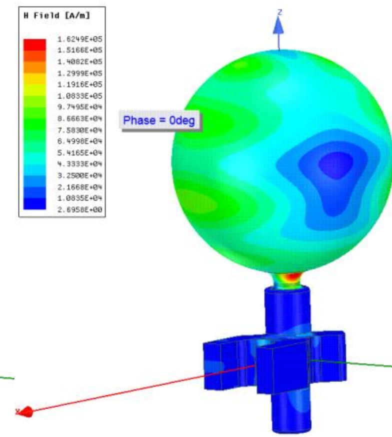


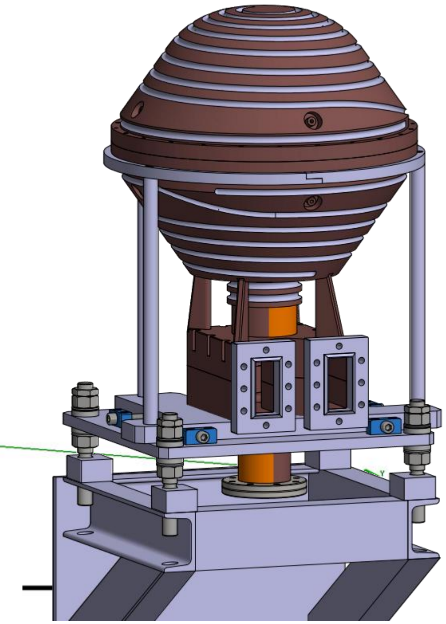


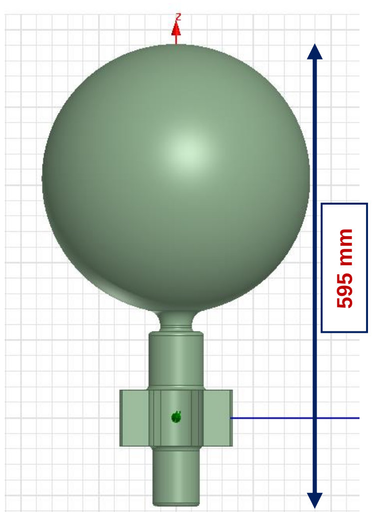
RF Pulse Compressor



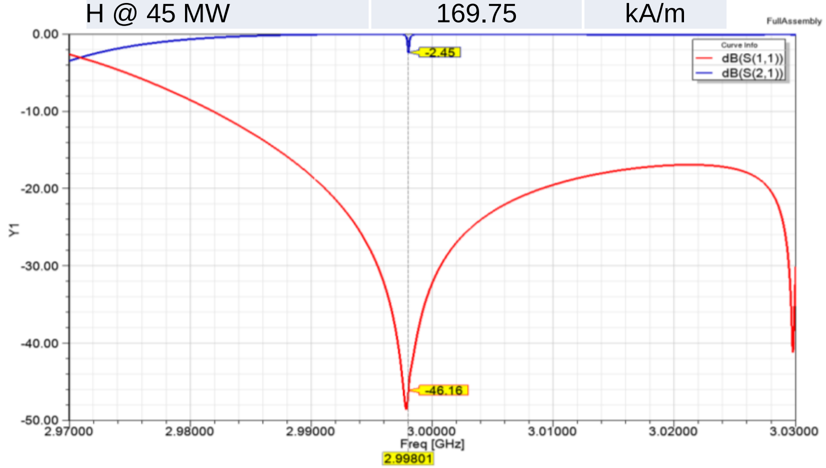


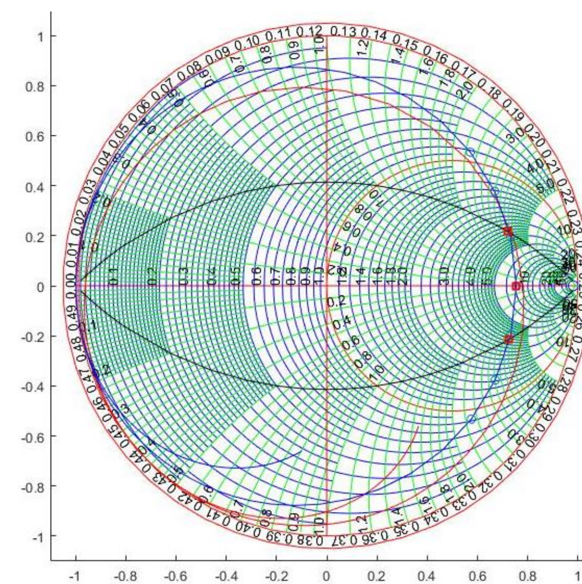






RF Parameters		
f_0	2.99801	GHz
Nominal Temperature	35	^oC
Mode	TM13	
Q0	≈140000	
Coupling Coefficient	7.2±0.1	
E @ 45 MW	28.16	MV/m
H @ 45 MW	169.75	kA/m





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Elettra Sincrotrone Trieste

FERMI RF TEAM

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A. Milocco

F. Gelmetti

M. Predonzani

C. Serpico

Elettra Sincrotrone Trieste

T.G. Lucas

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R. Zennaro

PAUL SCHERRER INSTITUT PSI

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Thank you!

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