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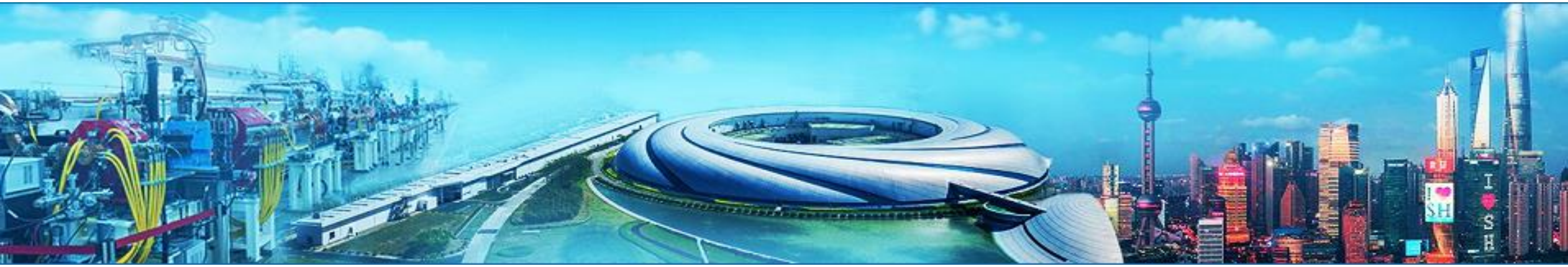


International Workshop on Breakdown Science and High Gradient Technology (HG2018)

A High Gradient Solution for Increasing the Energy of the FERMI Linac

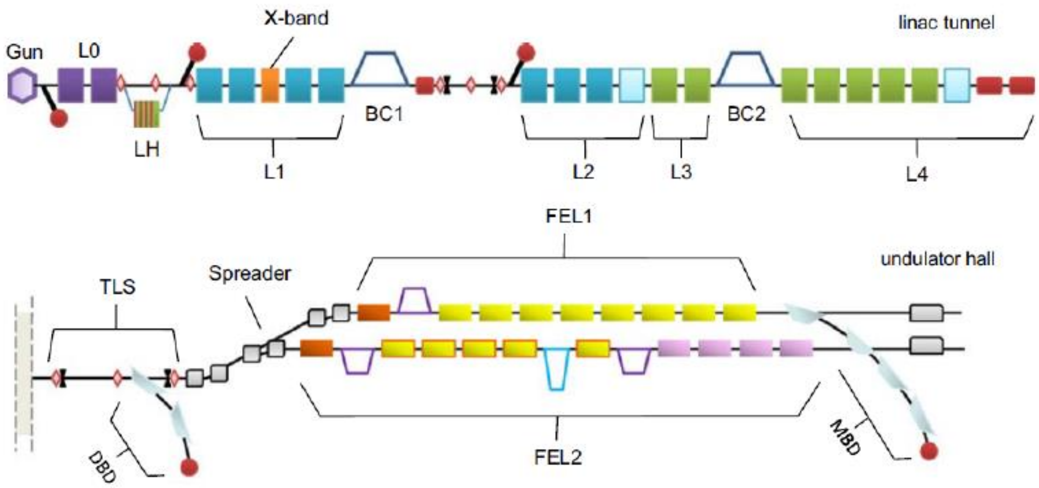
Claudio Serpico

on behalf of

FERMI RF Team

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.**



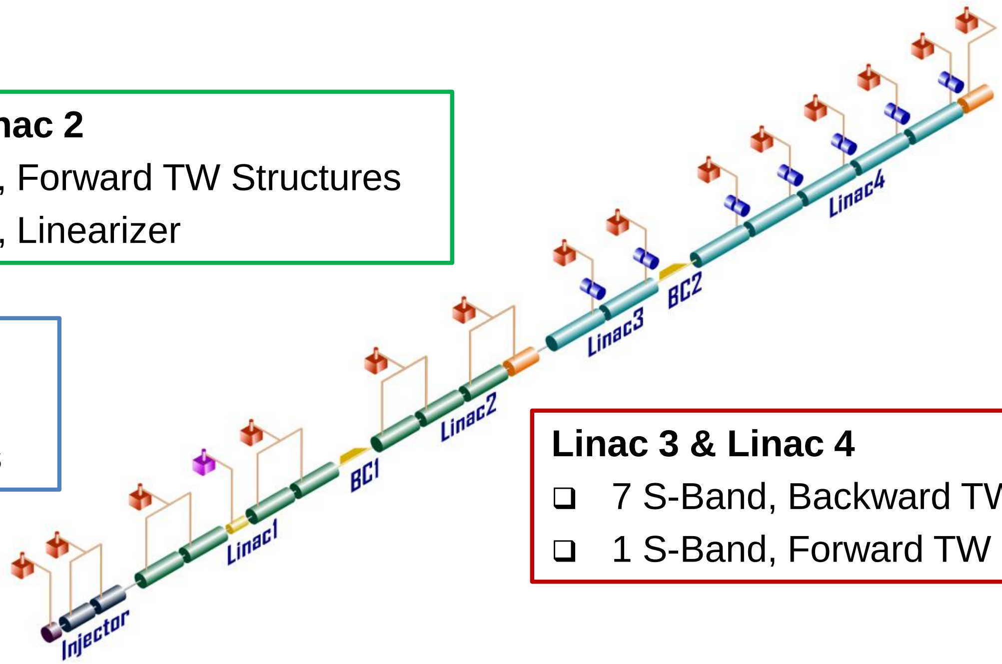
The FERMI facility comprises two separate coherent radiation sources, **FEL-1** and **FEL-2**.
FEL-1 operates in the wavelength range from **100** to **20 nm** via a single cascade harmonic generation, while the **FEL-2** is designed to operate at shorter wavelengths (**20-4 nm**) via a double cascade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

THE FERMI FEL

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



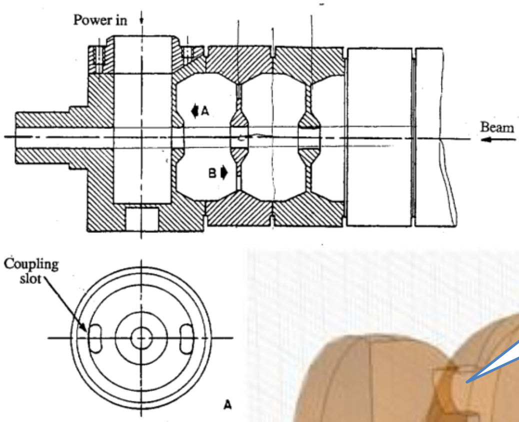
Linac 3 & Linac 4
- 7 S-Band, Backward TW Structures
- 1 S-Band, Forward TW structure

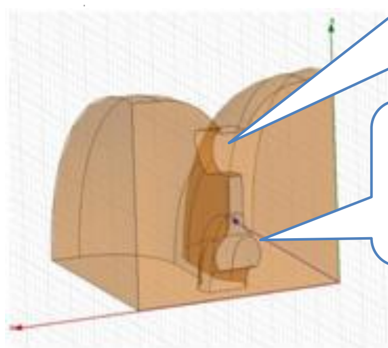
- **Power Sources**: 45 MW peak power, 4.5 μs pulse width, Klystron
- **Linac 1 & Linac 2**: one klystron feeds two FTW accelerating structures
- **Linac 3 & Linac 4**: one klystron feeds one BTW accelerating structure

In order to reach a beam energy of **1.5 GeV**, all the BTW structures must be operated at an operating gradient of nearly **24 MV/m**

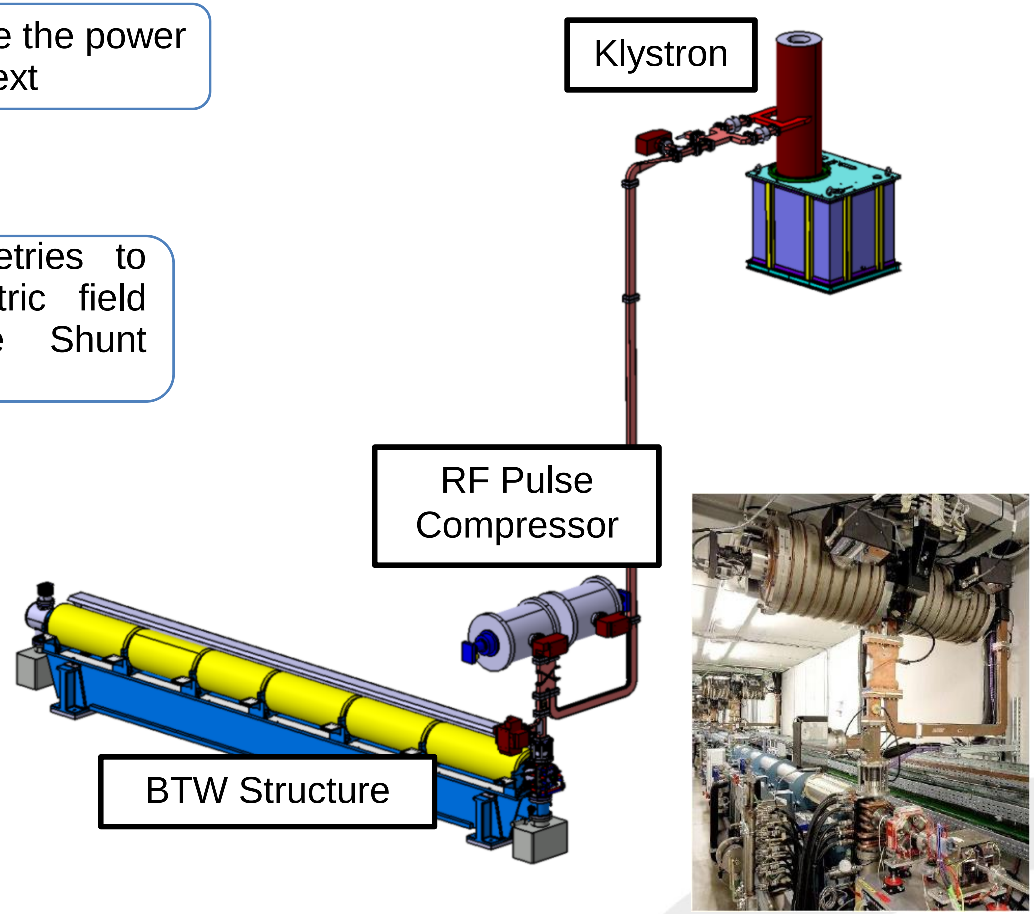
THE FERMI BTW STRUCTURES

The Backward Traveling Wave (**BTW)** accelerating sections are 6.2 meters long, made up of 160 cells, magnetically coupled.





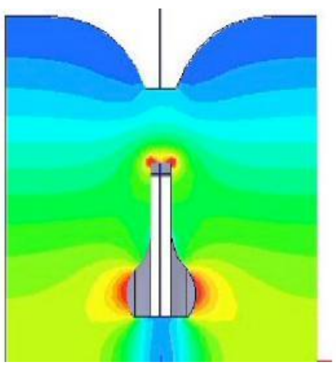
In order to increase the achievable accelerating gradient, each power plant is equipped with a **SLED-type RF pulse compressor**.



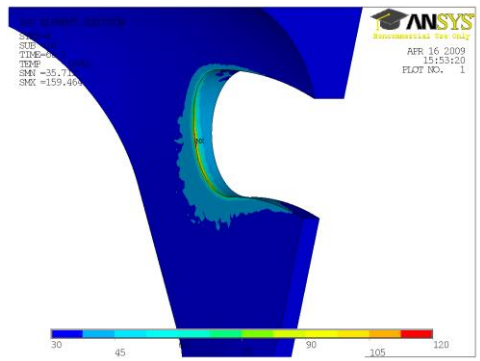
LIMITS OF THE FERMI BTW STRUCTURES

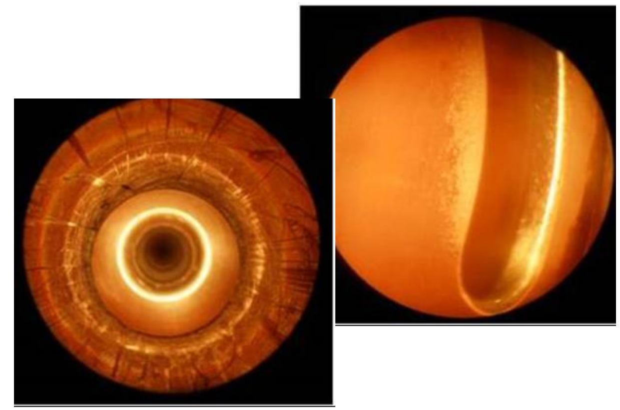
- BTW accelerating structures suffered heavy breakdown phenomena when pushed to **24 MV/m** at a repetition rate of **50 Hz**.

Peak surface electric field



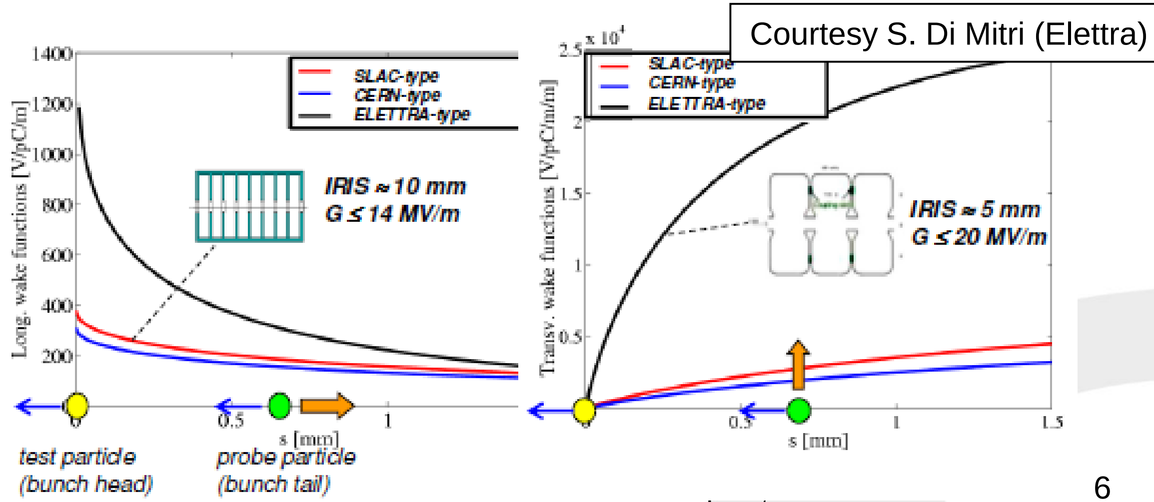
Temperature increase due to RF pulse heating





Inner surfaces of a regular cell of the FERMI BTW. Pictures are taken with an endoscope and clearly show sign of breakdowns on the surfaces

- Small beam aperture (i.e. **5 mm iris radius**) of the BTW structures has a huge impact on beam dynamics in terms of longitudinal and transverse wakefields.



Courtesy S. Di Mitri (Elettra)

THE FERMI UPGRADE PROPOSAL

TO EXTEND THE RANGE TO SHORTER WAVELENGTH UP TO 2 NM

ACTUAL LINAC ENERGY

1.5 GeV @ 10 Hz

TARGET LINAC ENERGY

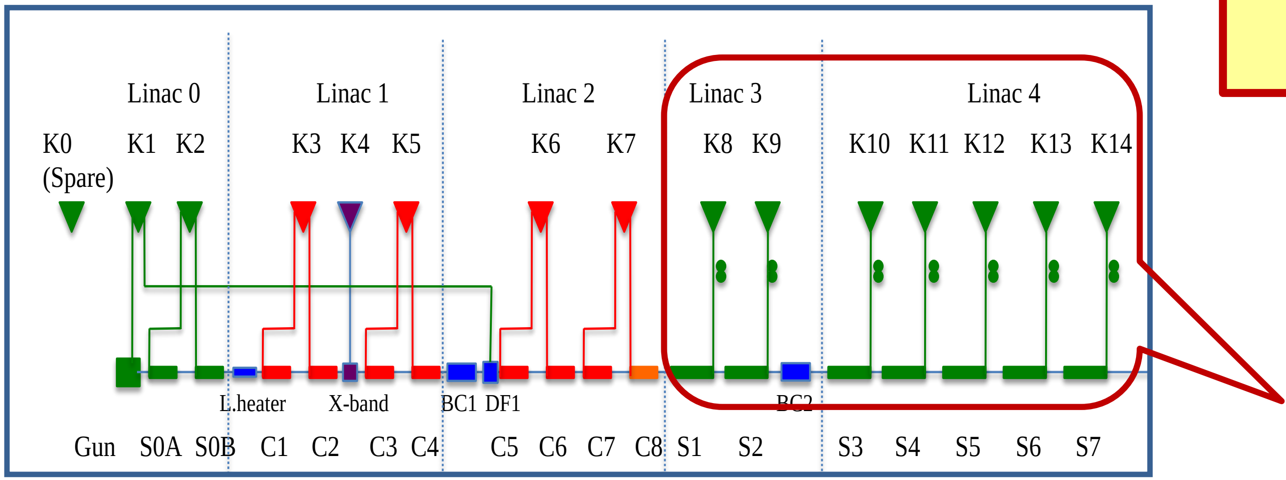
1.8 GeV @ 50 Hz

The actual Linac energy is limited by the **breakdown rate** of the **BTW structures**.

PROBLEMS/REQUIREMENTS

- Very stringent space constraints
- Active length for acceleration is assigned
- Available RF power is assigned

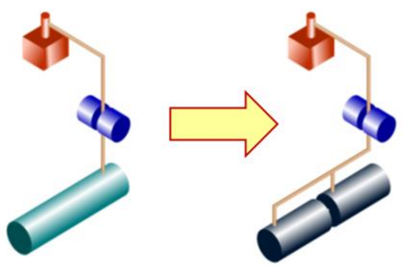
THE FERMI UPGRADE PROPOSAL



SOLUTION

HIGH GRADIENT → 30 MV/m

Replace the 7 BTW with high gradient, accelerating modules

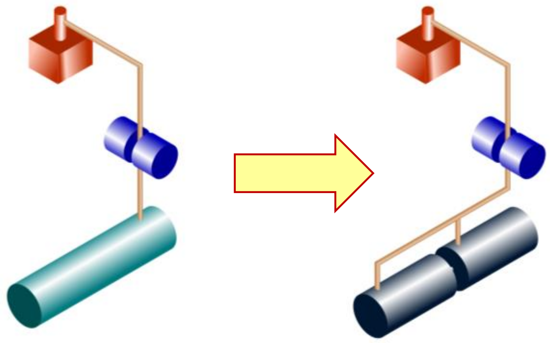


$$BDR \propto E_a^{30} \cdot t^5$$

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

NEW ACCELERATING MODULE
RF PARAMETERS

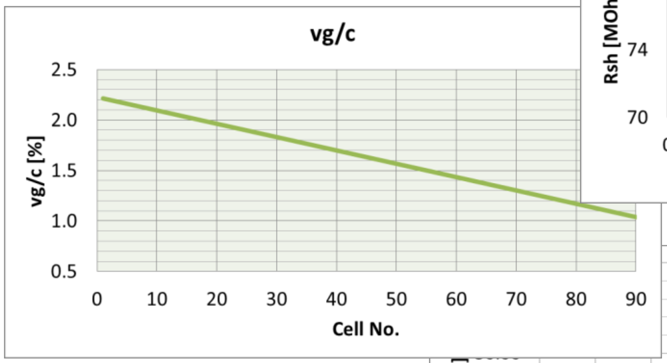
- The new accelerating module will be comprised of two 3.2-m long accelerating structures .
- Each structure will be of the **constant-gradient type**.

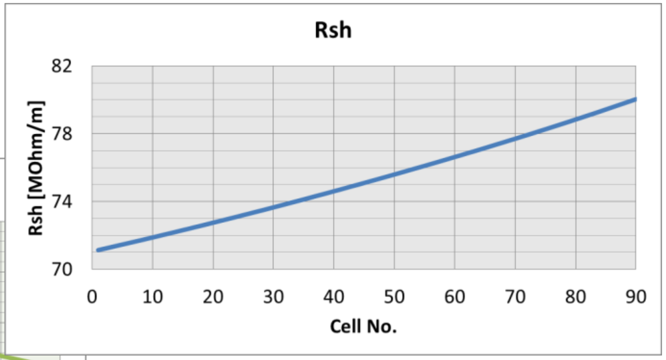


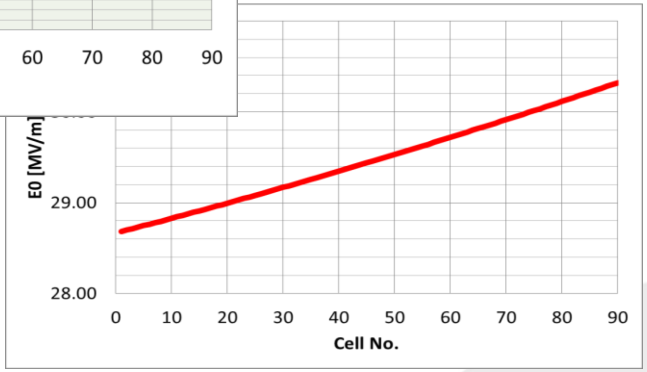
Structure RF parameters

L	3175	mm
Ncells	90	
a	11.4 → 9	mm
Q_0	15800	
R_{sh}	71 → 80	MΩ/m
Attenuation	0.38	Neper
Filling Time	650	ns

Optimal filling time for the power plant RF parameters







ACCELERATING CELLS' DESIGN

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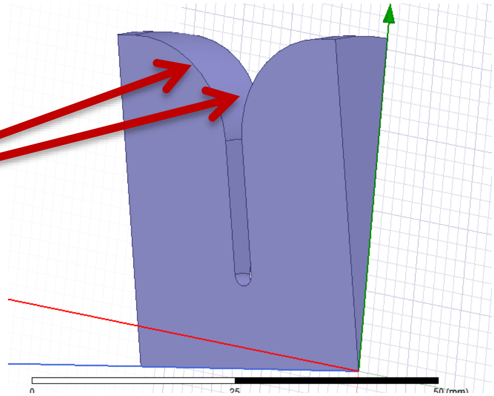
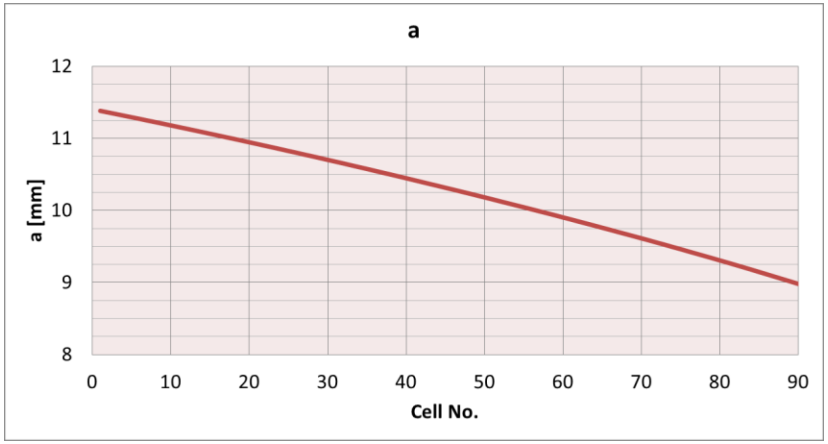
- Double roundings have been introduced to reduce ohmic losses and increase the ***Quality Factor***

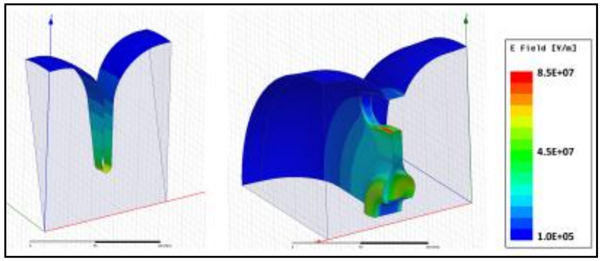


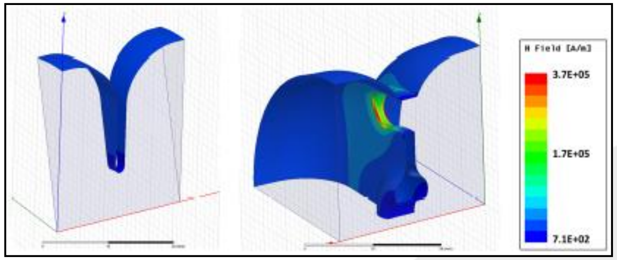
Sketch of a regular cell



- Beam aperture diameters are tapered to guarantee a **constant-gradient** profile

- HFSS simulations have been performed to maximize the acceleration efficiency while minimizing electric and magnetic surface fields for the regular cells

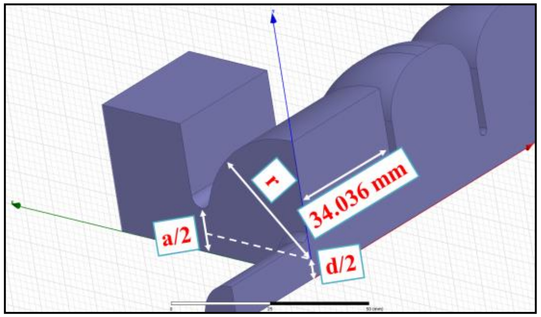




Electric and magnetic surface fields for a regular cell and comparison with a BTW cell

RF Couplers' Design

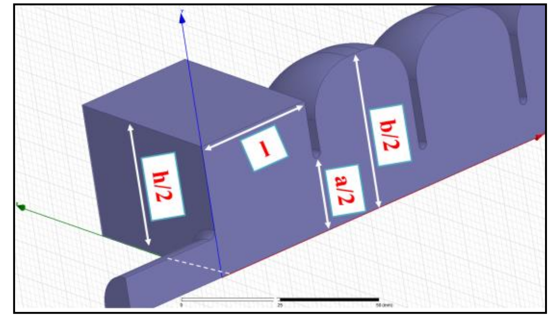
Magnetic Coupled	***vs***	***Electric Coupled***

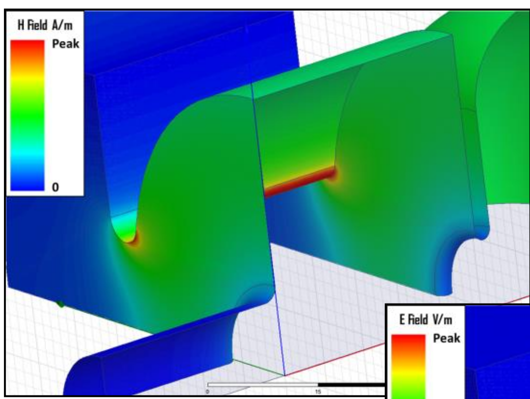


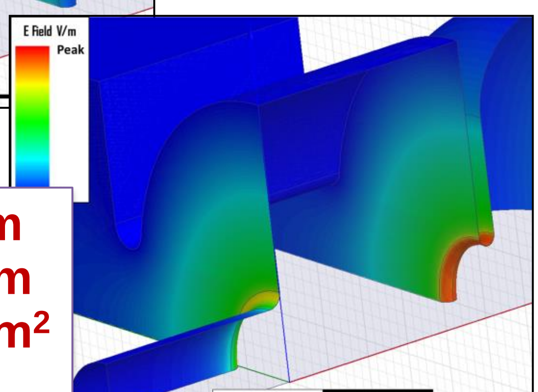
Working Point

V_0 = 30 MV/m

ΔT = 700 ns

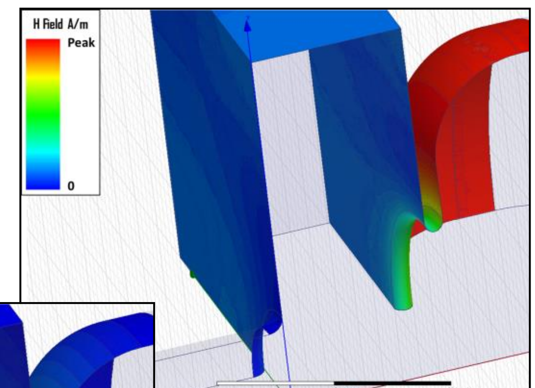


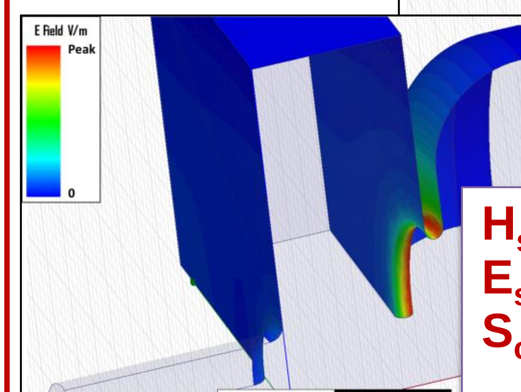




$H_{surf\ max}$ = 175 kA/m
$E_{surf\ max}$ = 93 MV/m
$S_{c\ max}$ = 0.7 W/μm²

BDR = 10^{-12} bpp/m



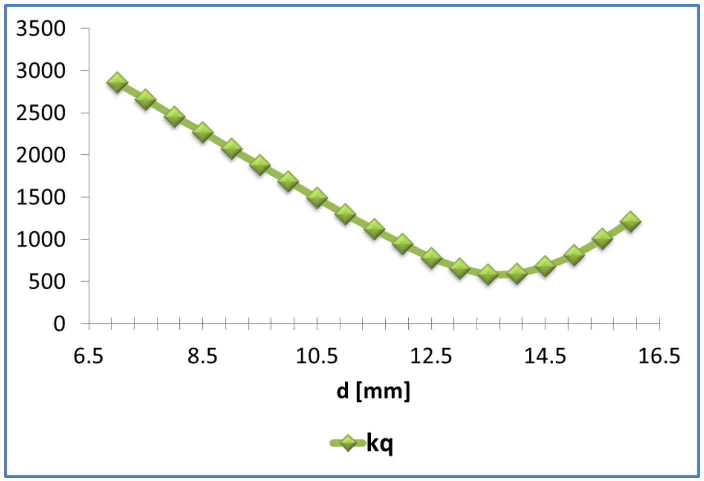


$H_{surf\ max}$ = 78 kA/m
$E_{surf\ max}$ = 81 MV/m
$S_{c\ max}$ = 0.57 W/μm²

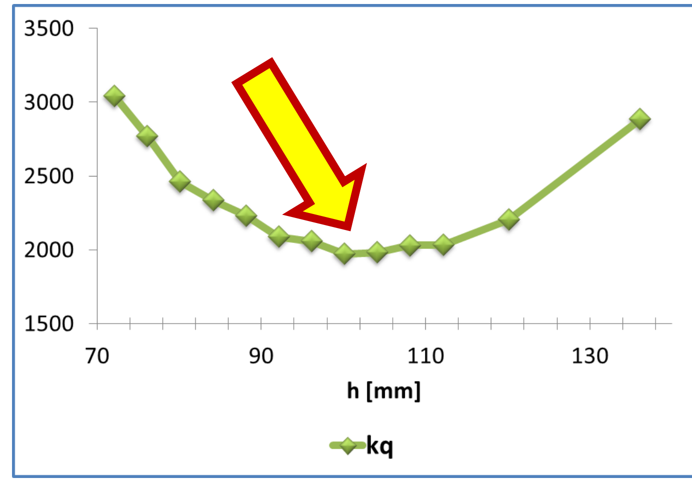
BDR = 10^{-12} bpp/m

RF COUPLERS' DESIGN

Magnetic Coupled ***vs*** ***Electric Coupled***



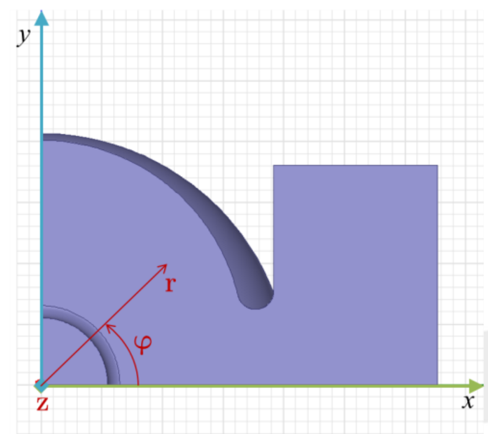
Integration is limited to the input coupler region



MINIMIZATION OF THE RESIDUAL QUADRUPOLE COMPONENT

$$F_\varphi(z) = \left[F_x(r = 5\,mm, \varphi = 45°, z) - F_y(r = 5\,mm, \varphi = 45°, z)\right]$$

$$k_q = \frac{1}{qr}\left|\int_0^L F_\varphi(z) e^{\pm j \frac{\omega}{c} z} dz\right|$$



- **EC coupler – Pros**: E-field and H-field are lower for the EC.
- **EC coupler – Cons**: residual quadrupole component is bigger for the EC coupler.

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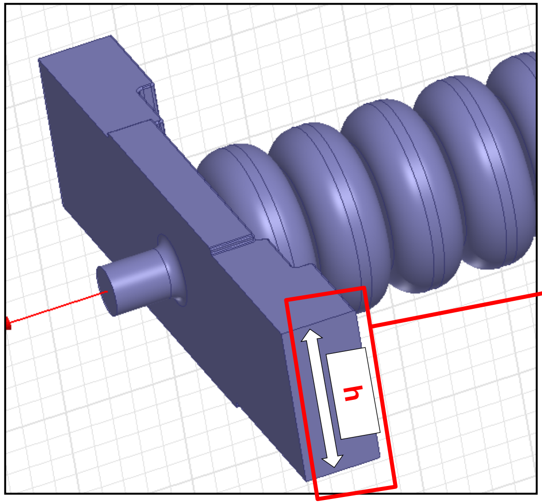
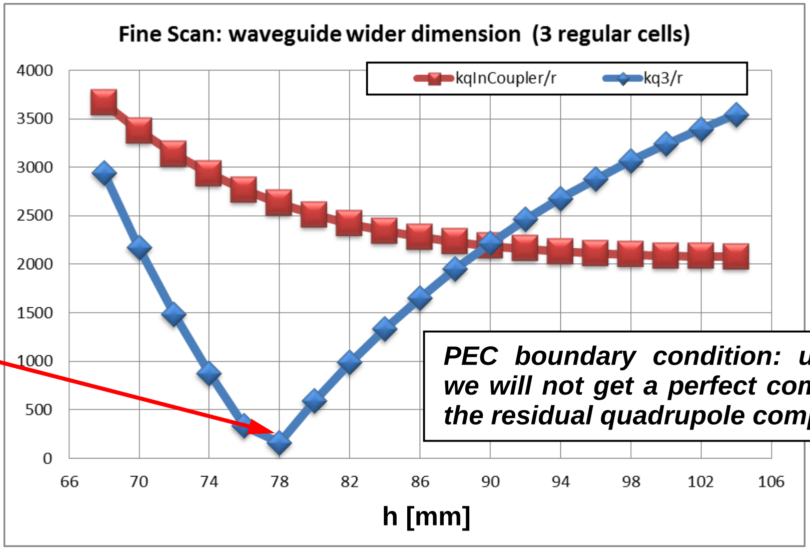
RF COUPLERS' DESIGN

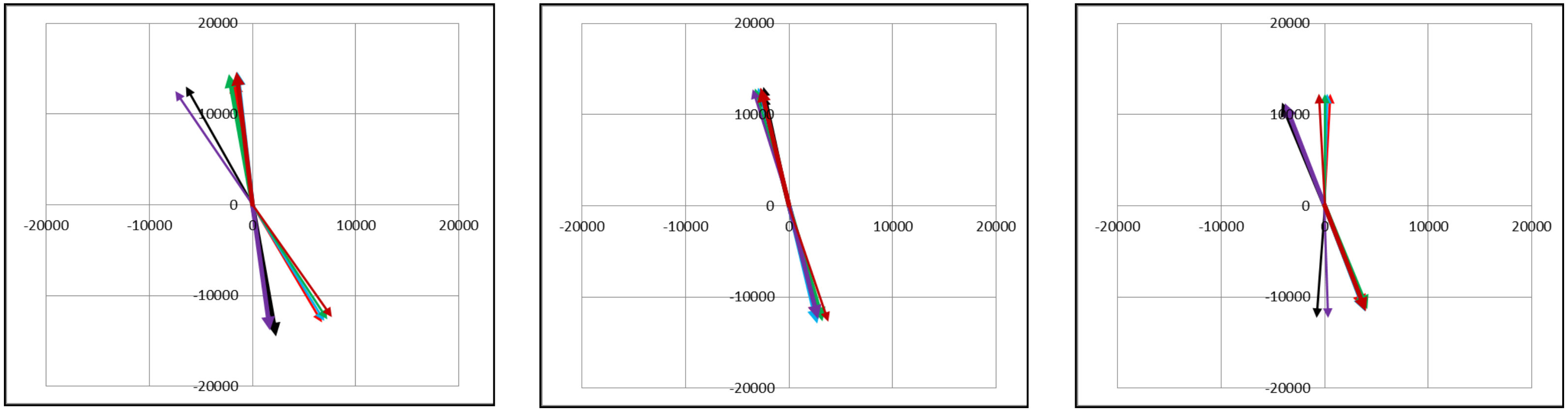
By adjusting the relative phase of the fields at the input and output couplers, it is possible to further minimize the overall residual quadrupole component





PEC boundary condition: using copper, we will not get a perfect compensation of the residual quadrupole component.

WG WIDER DIMENSION: 74MM | **WG WIDER DIMENSION: 78MM** | **WG WIDER DIMENSION: 82MM**



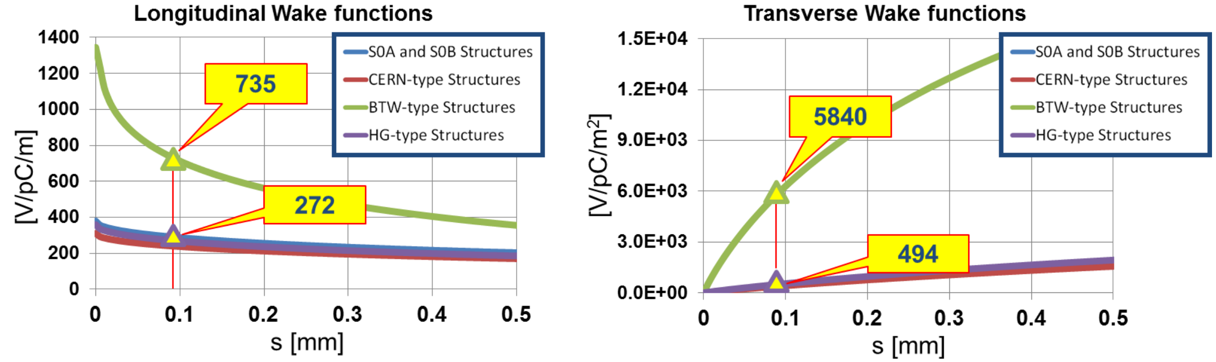
- KqInCoupler_3Cells
- KqOutCoupler_3Cells
- KqInCoupler_4Cells
- KqOutCoupler_4Cells
- KqInCoupler_5Cells
- KqOutCoupler_5Cells
- KqInCoupler_6Cells
- KqOutCoupler_6Cells
- KqInCoupler_7Cells
- KqOutCoupler_7Cells
- KqInCoupler_8Cells
- KqOutCoupler_8Cells

Electric-Coupled RF Coupler has been adopted

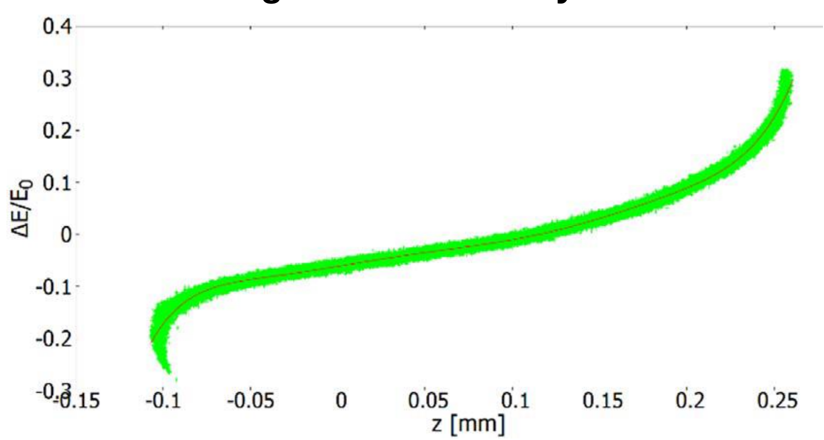
BEAM DYNAMICS

SHORT RANGE WAKEFIELDS

A bigger beam aperture leads to a weaker wakefield contribution, which has to be carefully evaluated.

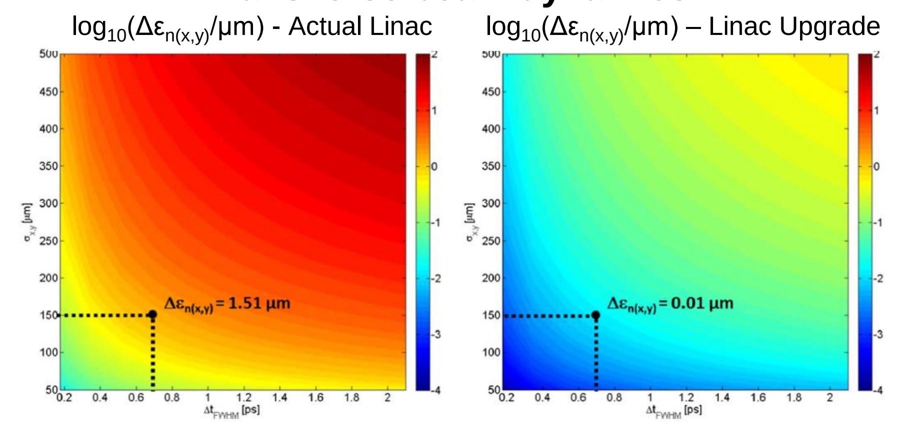


Longitudinal beam dynamics



Longitudinal phase space at 1.8 GeV (LiTrack result)

Transverse beam dynamics



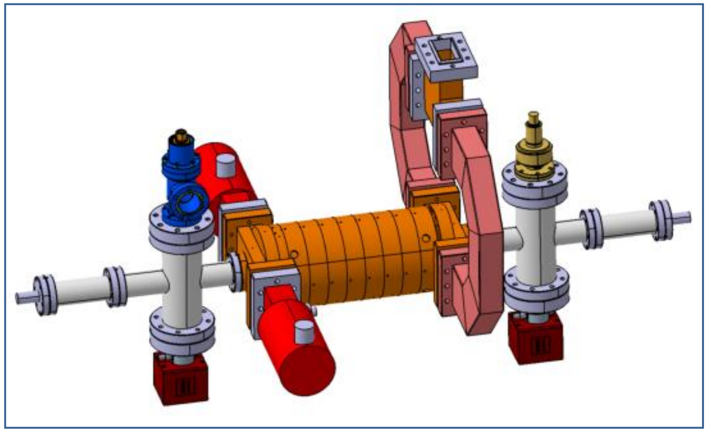
Transverse normalized emittance growth through L3 and L4 as a function of the bunch duration (fwhm) and of the linac-to-beam relative misalignment (rms)

- The relative energy spread is lowered to <0.1% with L4 run 10 deg off-crest, and 1% final beam energy loss.
- The transverse emittance growth is lowered by two orders of magnitude w.r.t. present.

PSI PROTOTYPE

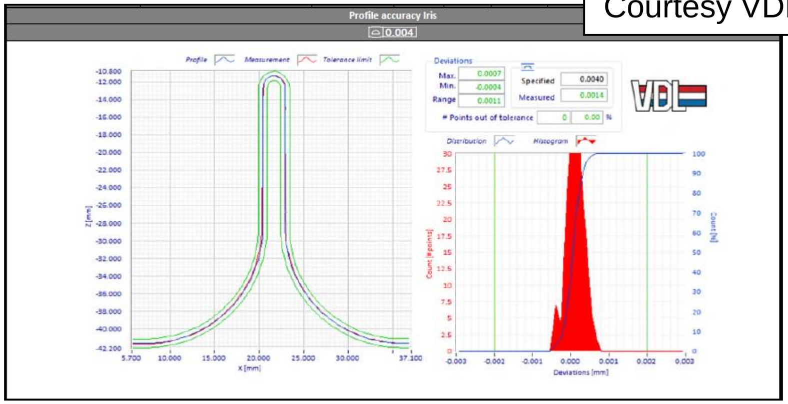
To prove the **reliability** and the **feasibility** of the upgrade proposal at an accelerating gradient of 30 MV/m, a **first (short) prototype** has been built in collaboration with Paul Scherrer Institut (PSI, Switzerland), using the same structure technology as developed for SwissFEL.

PROTOTYPE



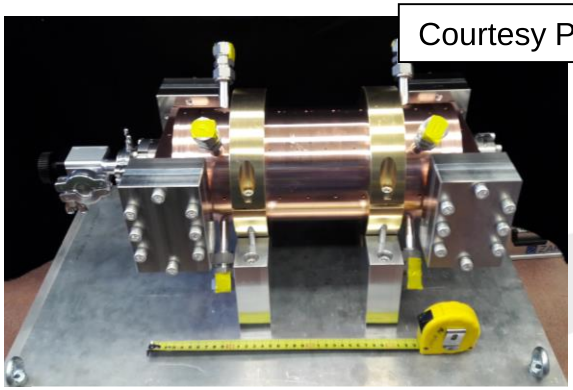
- The prototype is made by 7 regular cells and 2 EC-couplers.
- Cells and couplers are realized with Ultra-high precision machining (tolerances of +/- 4 μm).
- Prototype is machined on tune.

Courtesy VDL



Prototype ready for Vacuum Brazing

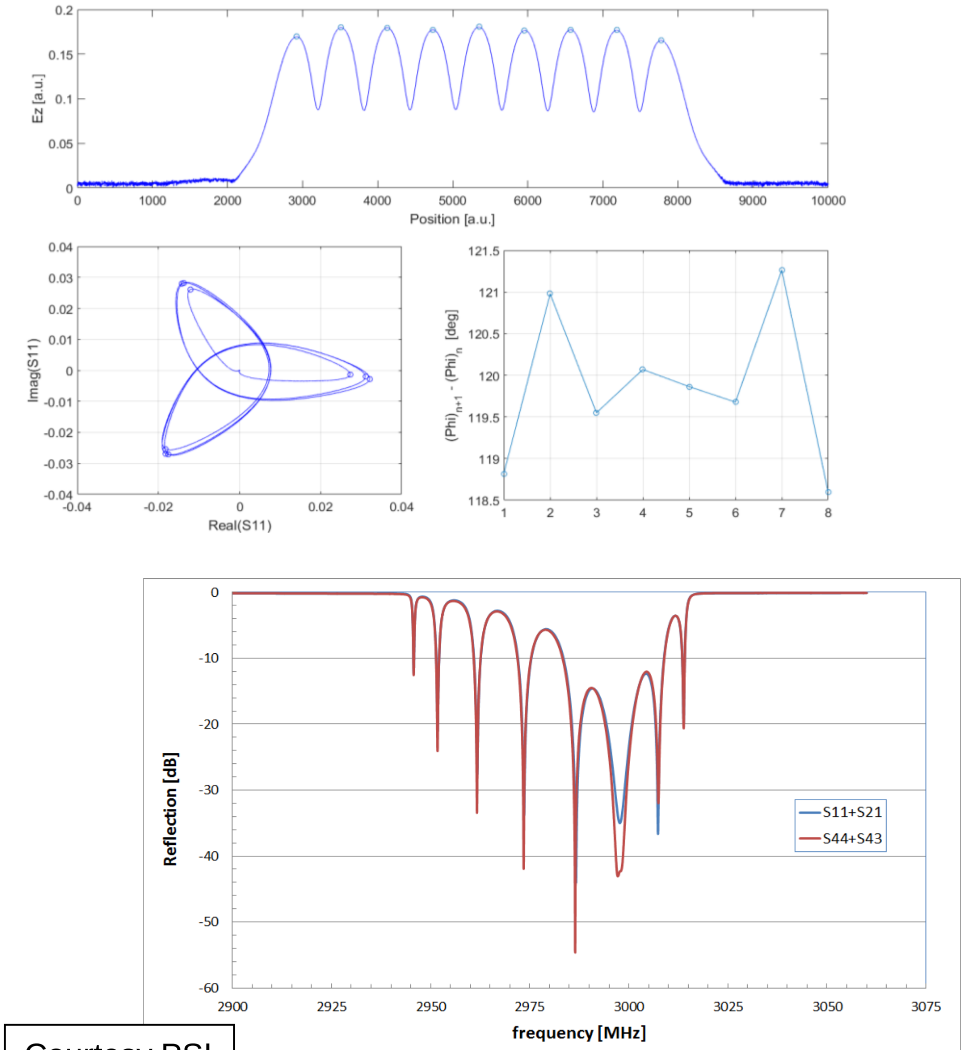
Courtesy PSI



Prototype after brazing

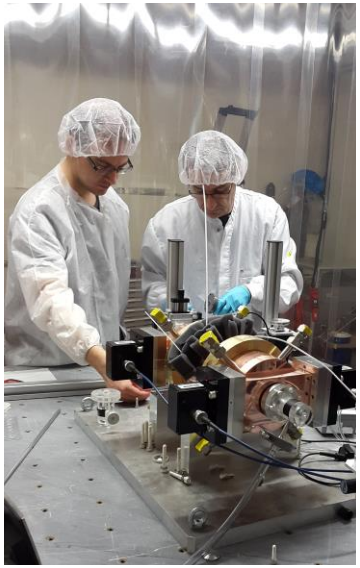
FACTORY ACCEPTANCE TEST

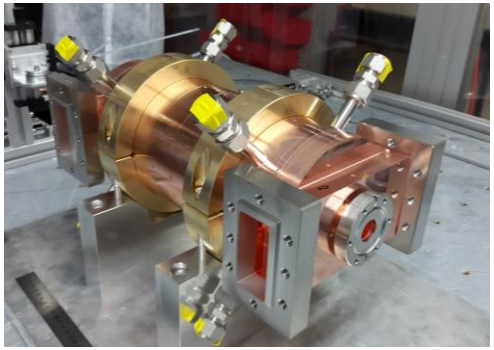
RF measurements and bead-pull at PSI



Courtesy PSI

- ❑ Very good field flatness
- ❑ Optimal phase advance
- ❑ Reflection paramenter: - 35 dB @ f_0

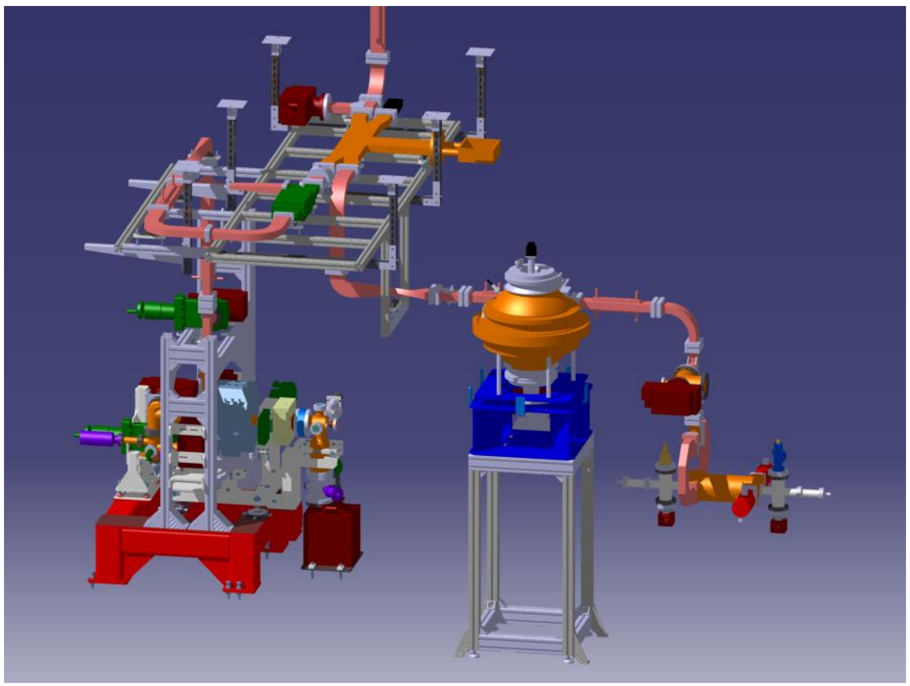




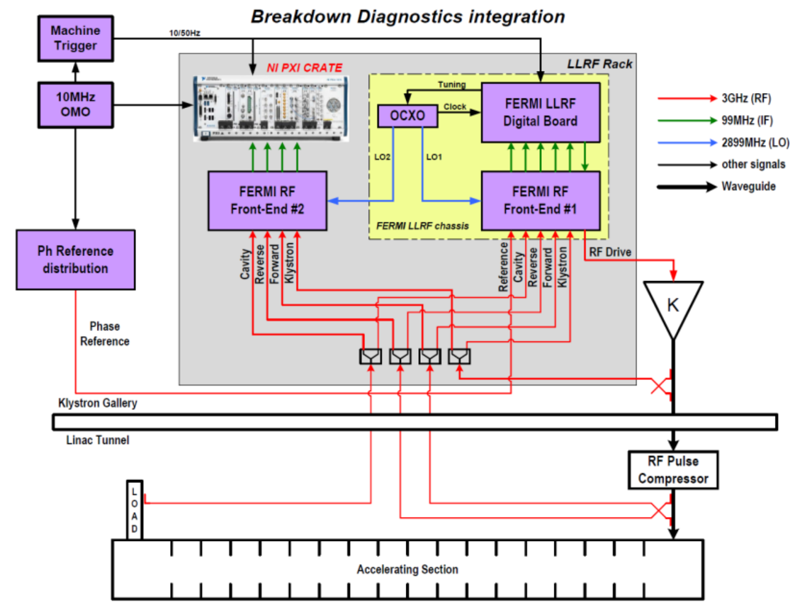
FERMI TEST FACILITY

In order to perform high power tests, a multi-purpose Test Facility has been built at Elettra, in the FERMI tunnel.

TEST FACILITY @ ELETTRA



TEST FACILITY DIAGNOSTIC



CERN-like breakdown diagnostic is being developed at Elettra.

- Test of Standing Wave structures/RF Guns up to 25 MW peak power.
- Test of Traveling Wave structures and RF components up to 150 MW peak power.
- Breakdown rate measurements and breakdown localization

Target Gradient and BDR

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Present operational parameters of the Backward Traveling Wave structures at **1.5 GeV** beam energy and **10 Hz** repetition rate

	Energy Gain [MeV]	Gradient [MV/m]	Rep Rate [Hz]	BDR [bpp]
K8	145	23.9	10	6.6e-8
K9	146.4	24.1	10	**5.8e-7**
K10	145.2	23.9	10	3.3e-8
K11	142.9	23.5	10	**5.5e-7**
K12	133	**21.9**	10	**1.5e-7**
K13	132	**21.7**	10	**3.1e-7**
K14	134.9	**22.2**	10	**1.8e-7**

5 structures present a breakdown rate quite high

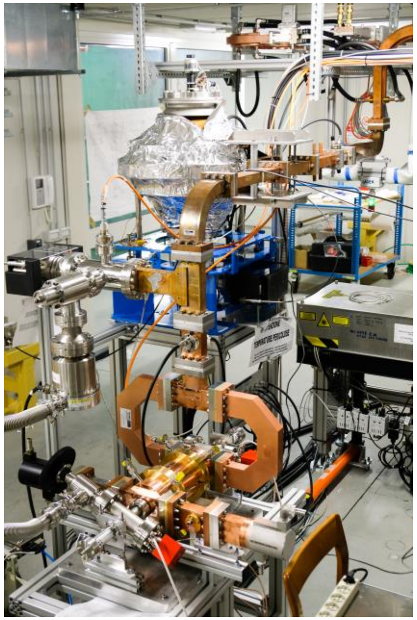
3 structures are operated at nearly 22 MV/m and cannot be pushed at higher values.

None of the structures can be operated at the previous values if the repetition rate is 50 Hz. The resulting downtime is too high to be tolerated for User Operation!

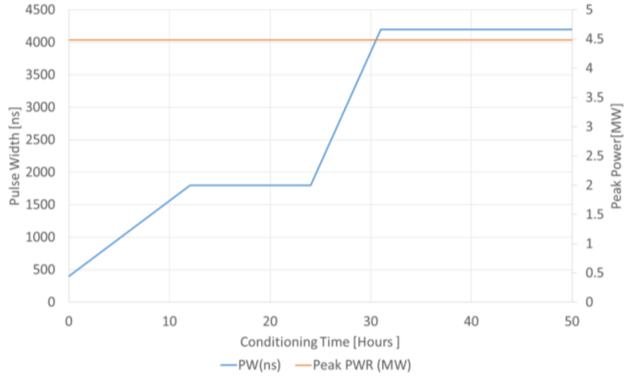
Target Breakdown Rate for the new structure at **1.8 GeV** beam energy (30 MV/m accelerating gradient) and **50 Hz** repetition rate is **3e-8 bpp**

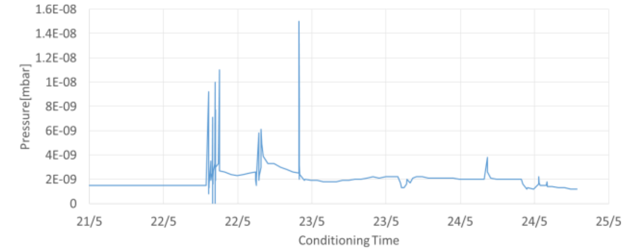
Prototype Installation and Preliminary Power Tests

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



Preliminary Power Tests





Constant peak power to the structure (5 MW), increasing the pulse width.

Once all the diagnostic was properly set up (power calibration, etc.), we turned the Pulse Compressor on and were ready to start increasing the peak power, but....

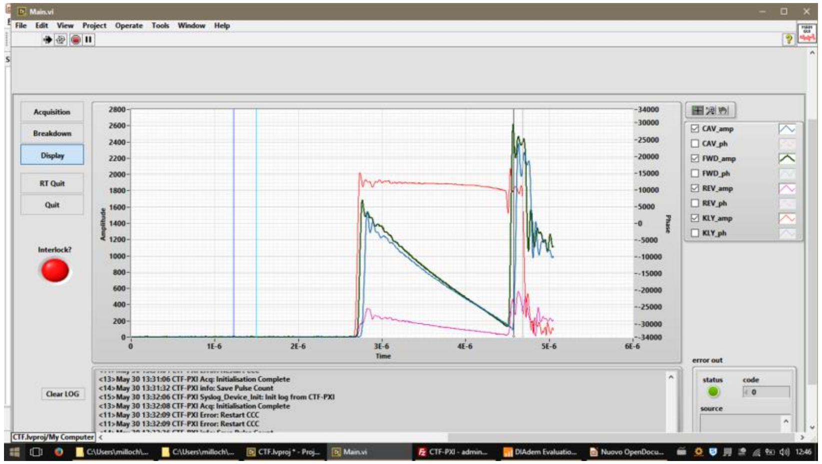
Cooling System Issue!

Finally, on **May 30** we were able to start the proper RF conditioning of the prototype

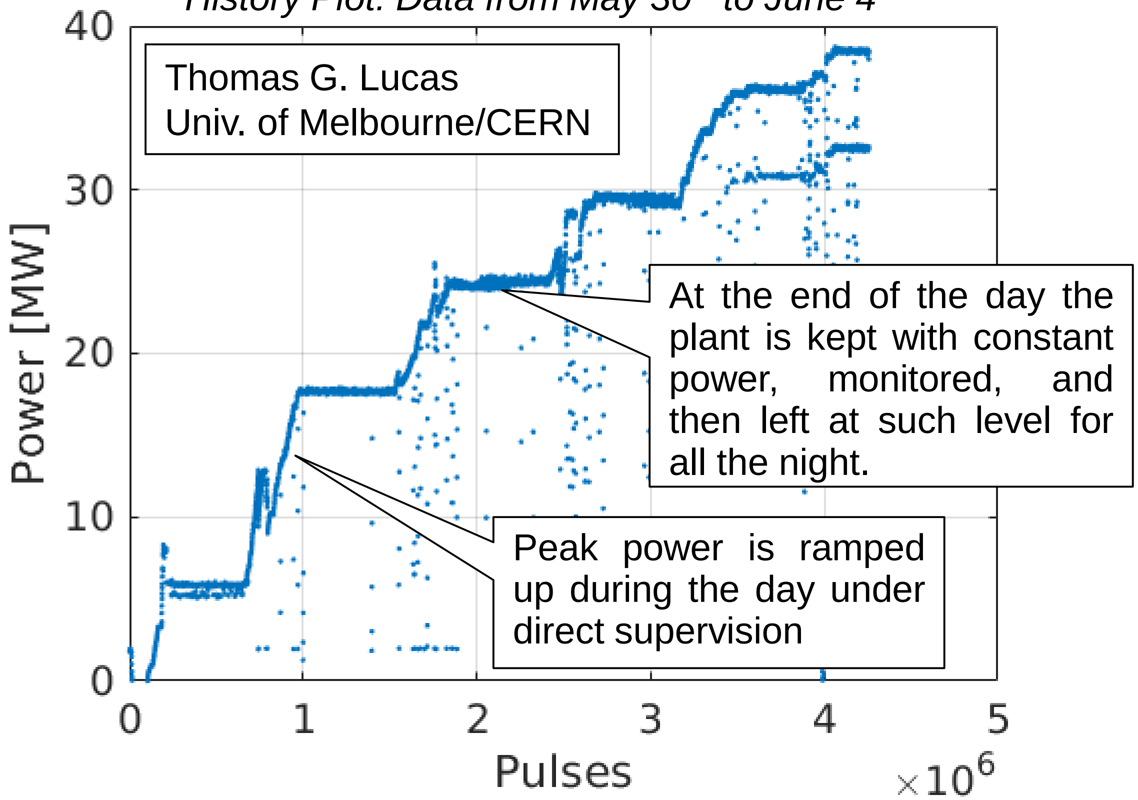
RF CONDITIONING

So far....

- 2 μs pulse from the klystron
- **200 ns** RF pulse after Pulse Compressor
- Final Goal: **75 MW** and **650 ns**



History Plot: Data from May 30th to June 4rd

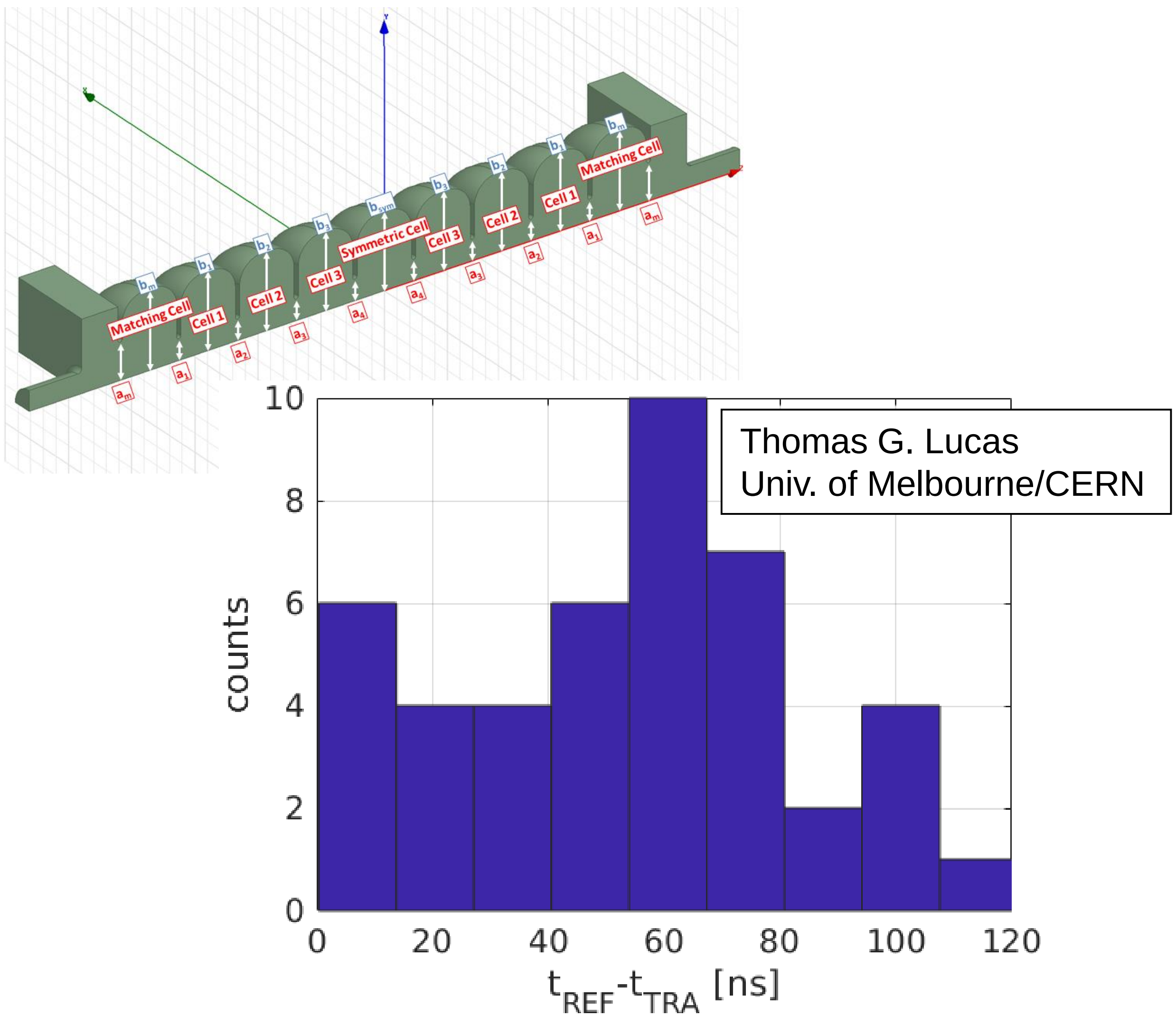


- During the last 2 days, we had just few hours of effective RF conditioning due to planned maintenance activities in the Linac tunnel.
- Even if not pushing during the nights, in 6 days we reached **39 MW** to the structure (almost **21 MV/m**)

RF Conditioning

Breakdown Location

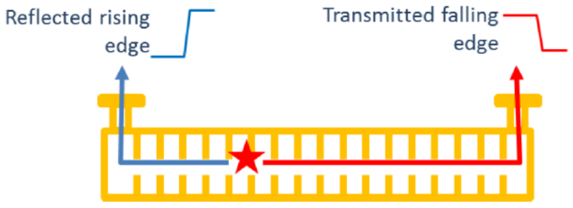
- Prototype filling time: $t_f \approx 60$ ns
- Breakdown Location is measured in TOF units, between 0 and 2^*t_f



- Number of events is still small to get a full statistics (44 events over 4.3 M pulses).
- So far, a slightly higher number of events have been observed in the central cell (i.e. the symmetric one).
- **Accelerating gradient is already close to the operating point of the BTW structures.**

CONCLUSION, NEXT STEPS AND TIME SCHEDULE

- ❑ Conditioning is progressing quite fast. So far, no clear indication of hot cells.
- ❑ Prove the **reliability** of operating at **30 MV/m** with a **50 Hz** repetition rate: experimental data will be collected and will be analyzed in collaboration with CERN.



- ❑ Address all the technical issues related to the production/brazing of a 3 meter long accelerating structure and eventually plan the construction of the first module.

- ❑ **By the end of 2018** we expect to have a set of data from the ongoing tests and experiments which will allow us to draft a detailed and complete upgrade proposal.

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Thank you!

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