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Update on the FERMI Linac S-band RF System

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on behalf of the S-band team
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September 18-19, 2013

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Outline

- FERMI overview
- S-band RF System overview
- S-band RF System operations and upgrades
- Outlook and conclusions

This presentation reports the work of the people working on the FERMI S-band RF Systems :

A. Fabris, Delgiusto, P. Delgiusto, F. Gelmetti, M. Milloch, A. Milocco, M. Predonzani, F. Pribaz, C. Serpico, N. Sodomaco, R. Umer, L. Veljak

Thanks to L. Giannessi and the FCT for the slides on the progress of the machine

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FERMI OVERVIEW

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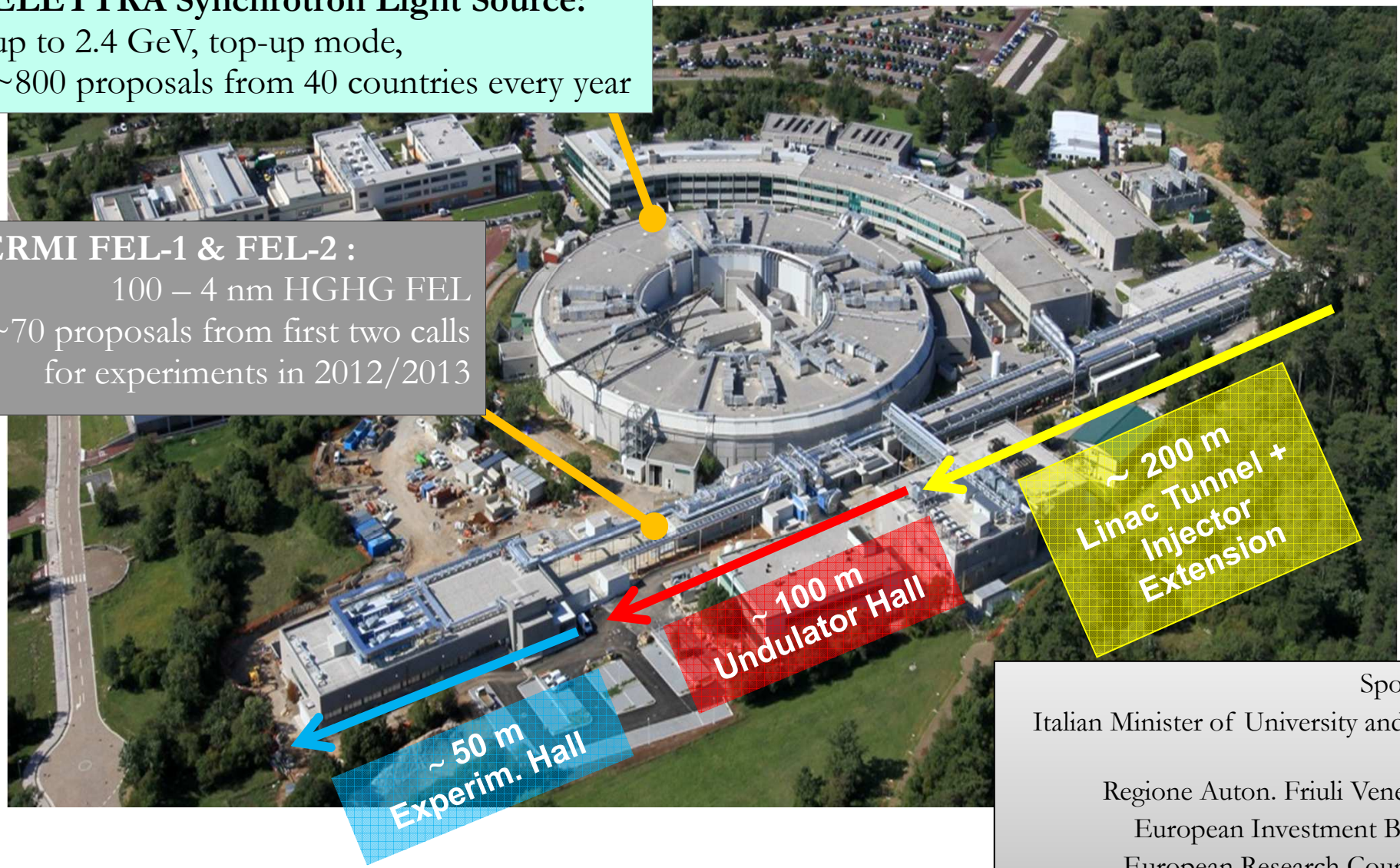
ELETTRA LABORATORY

ELETTRA Synchrotron Light Source:
up to 2.4 GeV, top-up mode,
~800 proposals from 40 countries every year

FERMI FEL-1 & FEL-2 :
100 – 4 nm HGHG FEL
~70 proposals from first two calls
for experiments in 2012/2013



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FERMI PARAMETERS

- FERMI@Elettra: first single-pass FEL seeded user-facility, based on the High Gain Harmonic Generation (HGHG) scheme.
- Two separate FEL amplifiers cover the spectral range from 100 nm (12eV) to 4 nm (320 eV) providing photon pulses with unique characteristics.

❑ high peak power:	0.3 – GW's range
❑ short temporal structure:	sub-ps to 10s fs time scale
❑ tunable wavelength:	APPLE II-type variable gap undulators
❑ variable polarization:	horizontal/circular/vertical
❑ seeded FEL cascade:	longitudinal and transverse coherence

- Photon parameters are achieved using the coherent emission from high brightness and high energy electron beams .
- FERMI electron beam main parameters are:

Q = 500 pC ; ε_n~1 mm mrad ; Energy= 1.2-1.5 GeV

Courtesy of the FERMI Commissioning Team

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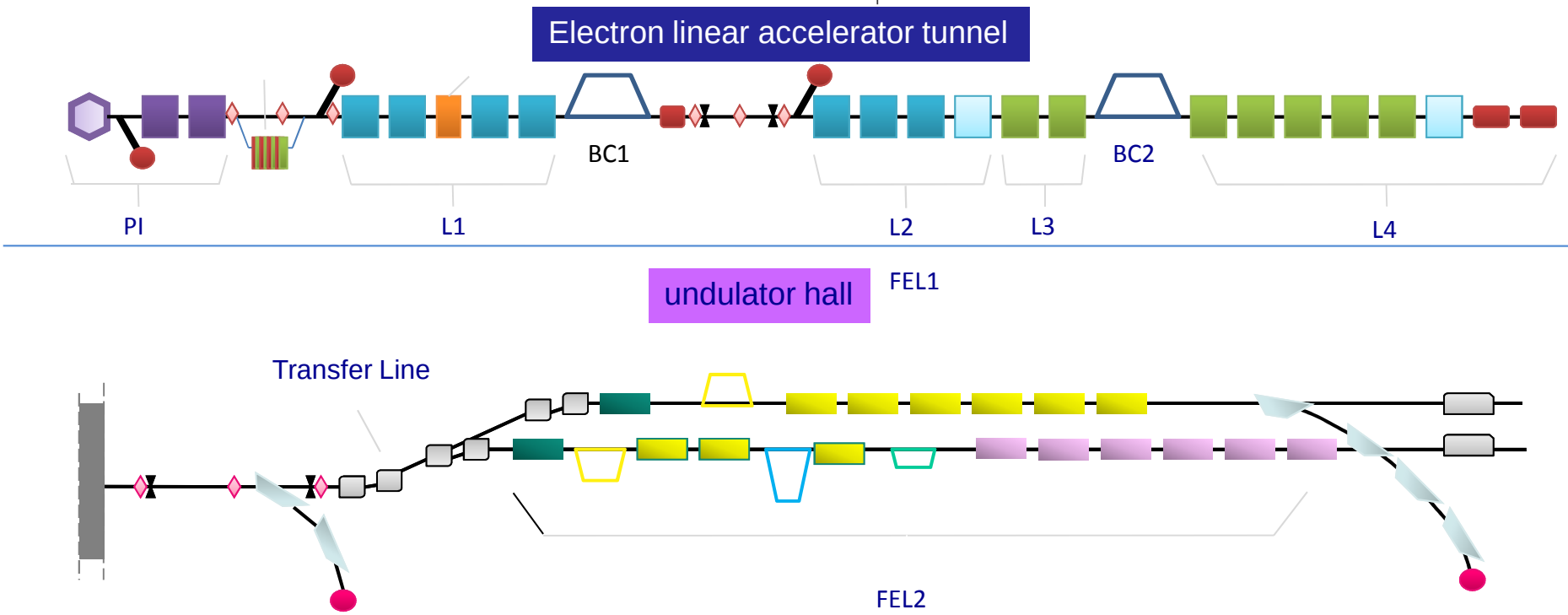
FERMI LAYOUT



Courtesy of the FERMI Commissioning Team

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FEL1 & FEL 2 STATUS

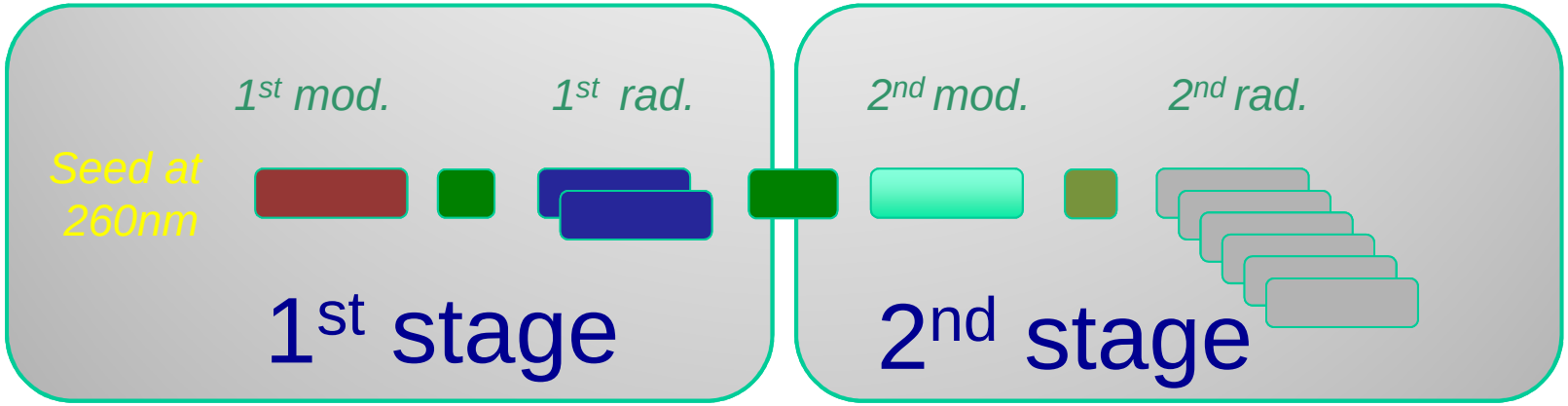
- FEL-1: single stage cascaded FEL, full specifications achieved in 2012, now dedicated to user experiments.
  - Continuously tuneable in the wavelength range 20-65 nm (up to 100 nm possible with specific machine setup).
  - Bandwidth (best) 5x10-4 @32 nm
  - Energy per pulse 30-100 μJ (depending on wavelength setting - up to a factor 2-3 more relaxing the spectral purity range).
- FEL-2: double stage, fresh bunch, cascade FEL, in commissioning.
  - October 2012 commissioning @ 1.0 GeV, 14.4 nm & 10.8 nm ≈50 uJ @10.8 nm
  - Extended wavelength range down to 8 nm in March 2013 (@1.23 GeV) commissioning
  - Down to 5 nm in June 2013 (@1.4 GeV)

Courtesy of the FERMI Commissioning Team

FEL 2 COMMISSIONING

THE FRESH BUNCH INJECTION TECHNIQUE

**L. H. Yu, I. Ben-Zvi, NIM-A 1993*



- Two HGHG FELs stages (equivalent to FEL-1)
  - The first stage is seeded by the Ti:Sa 3rd harmonic
  - The second stage is seeded by the first stage FEL
  - The two FELs operate with the same e-beam

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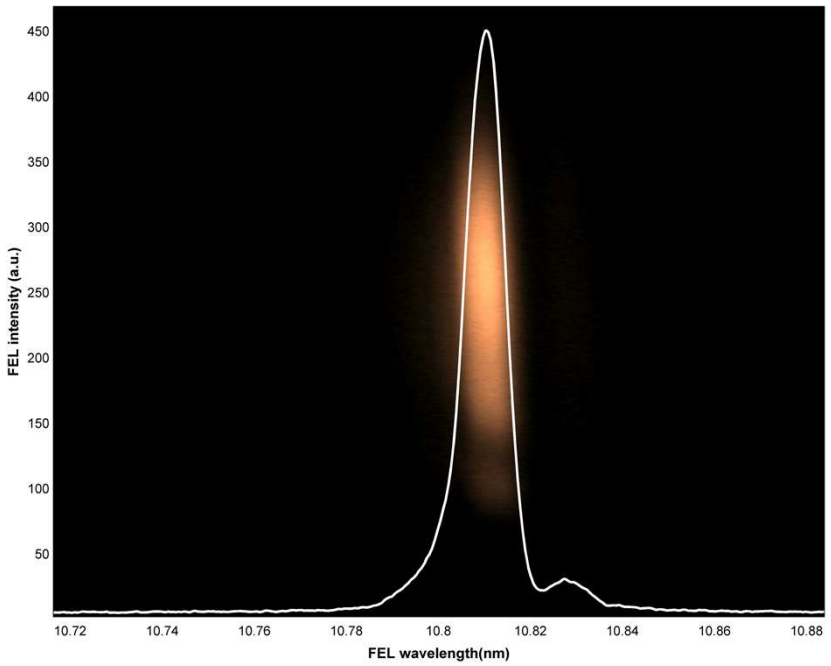
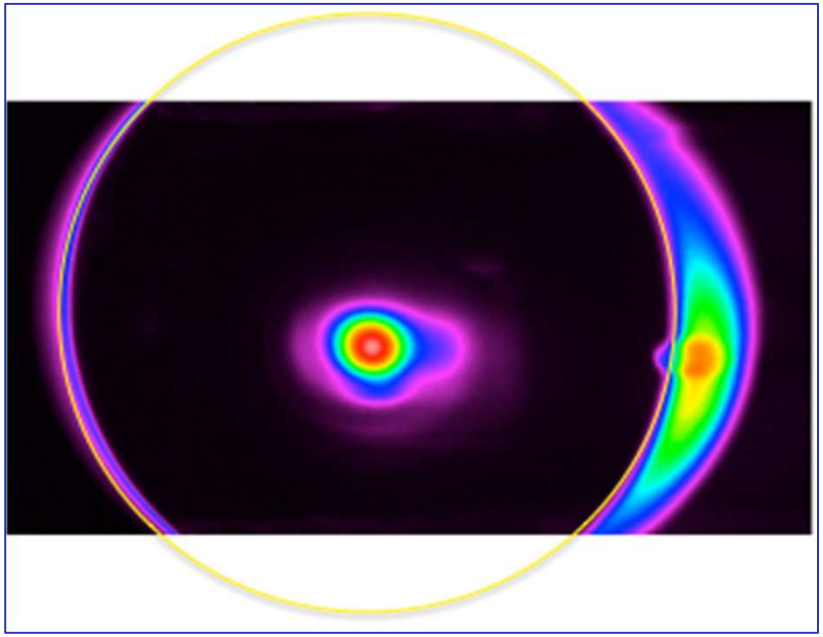
FEL-2 FIRST COMMISSIONING*



Wavelength 10.8 nm



Narrow linewidth, single mode spectrum

Gaussian like transverse mode

** submitted to Nature Photonics*

Courtesy of the FERMI Commissioning Team

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S-BAND RF SYSTEM OVERVIEW

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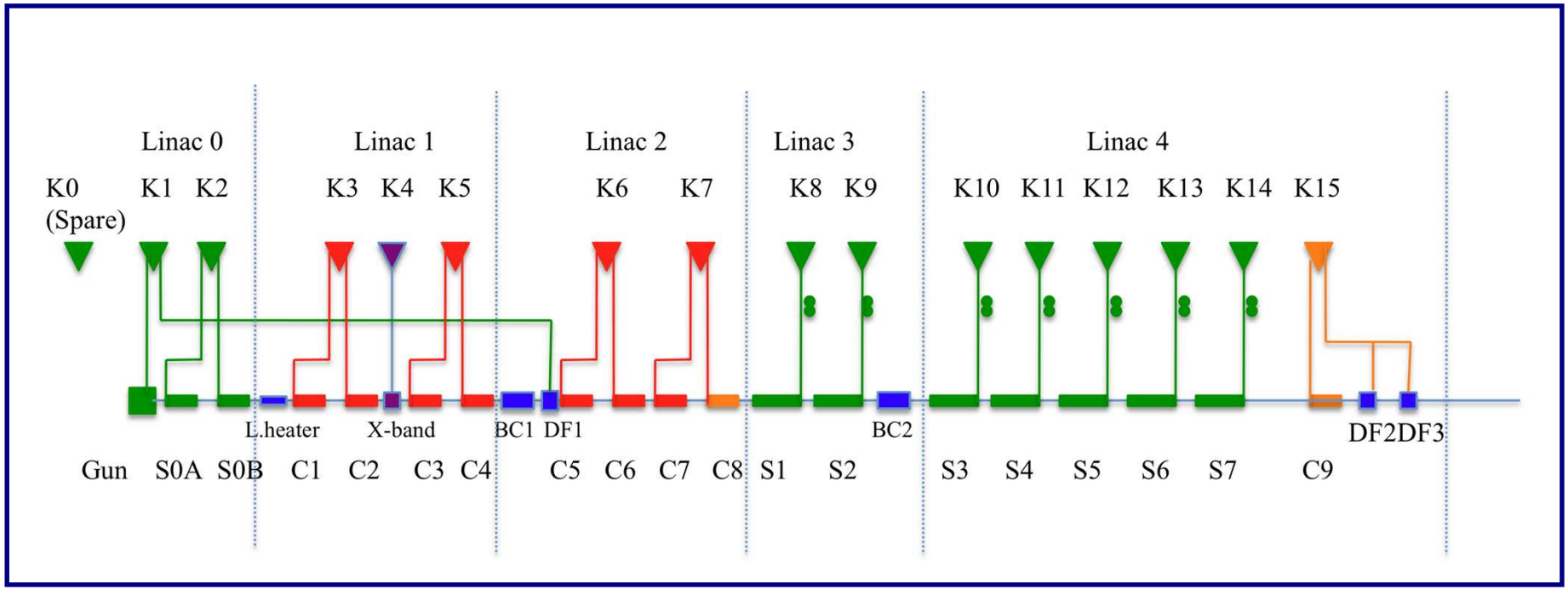
LAYOUT



- Fifteen RF plants (fourteen plus a spare one).
- Eighteen accelerating structures (presently sixteen installed).
- Waveguide system to provide power to the structures, RF gun and deflectors.
- Low Level RF for all the plants.

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POWER PLANTS

- **pfn modulators assembled by local companies under Elettra supervision.**
- **45 MW klystrons (TH2132A).**

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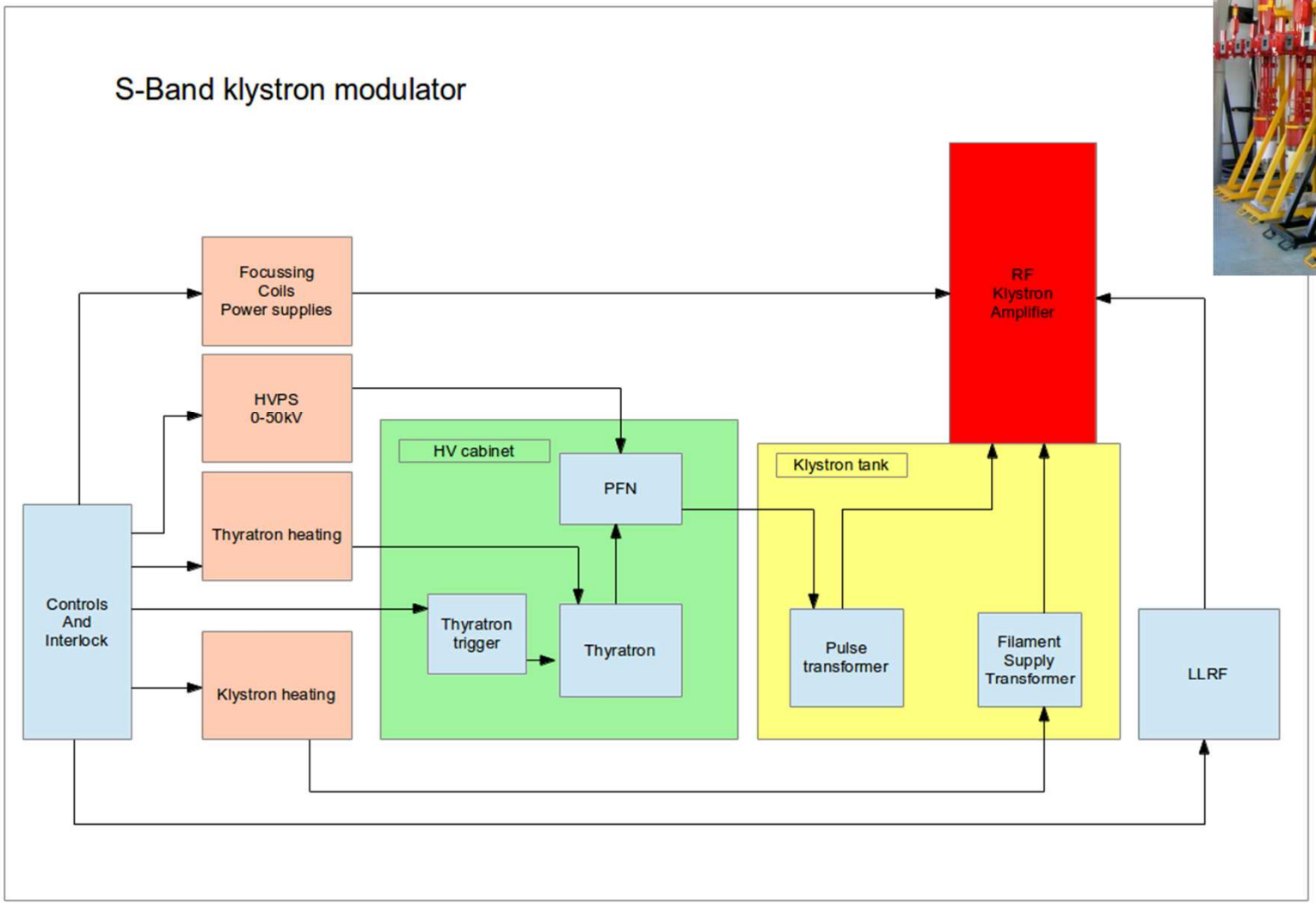
MODULATORS



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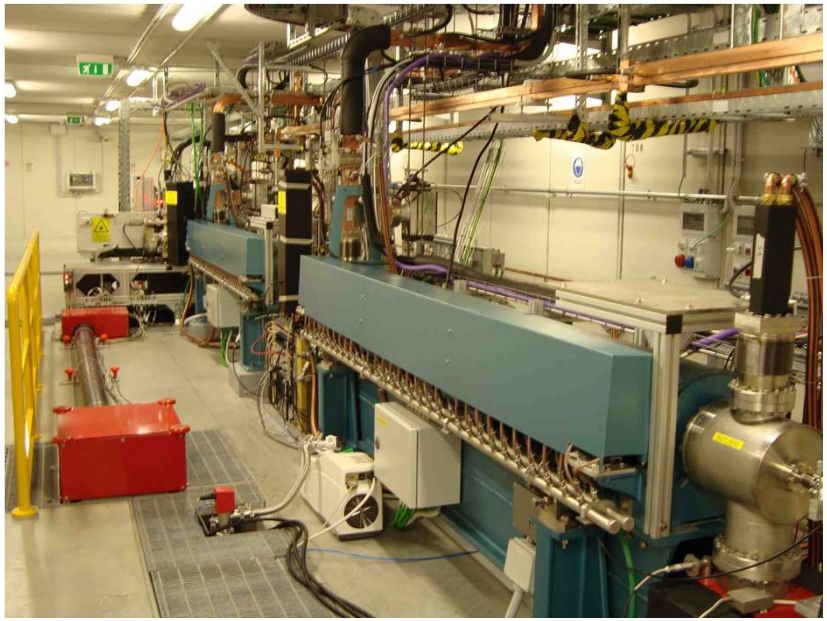
ACCELERATING STRUCTURES

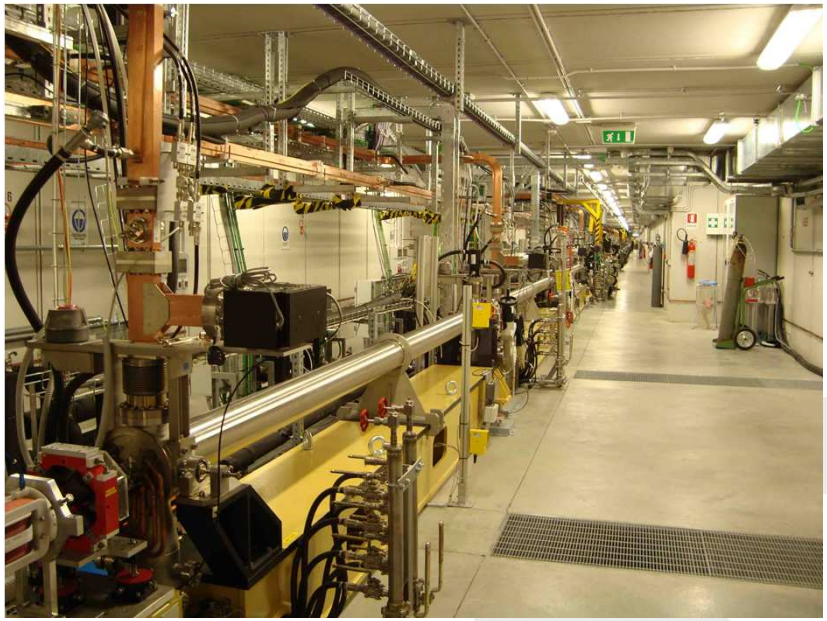
- Two structures from old Elettra injector(linac0).

Mode	2π/3 TW on axis coupled
Type	Const. grad
Frequency	2998.010 MHz
Eff. length	3.166 m
Q	14000
Rs	67 MΩ/m
Filling time	0.903 µsec

- Seven structures from CERN (linac1 and linac2)

Mode	2π/3 TW on axis coupled
Type	Const. grad
Frequency	2998.010 MHz
Eff. length	4.565 m
Q	14000
Rs	69 MΩ/m
Filling time	1.5 µsec





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ACCELERATING STRUCTURES

- Seven structures from old Elettra injector (linac3 and linac4).
- Equipped with SLED

Mode	3π/4 BTW magnet. coupled
Type	Const. grad
Frequency	2998.010 MHz
Eff. length	6.150 m
Q	11700
Rs	71-73 MΩ/m
Filling time	0.75 µsec

- Two more structures to be acquired:
  - They will replace the first two sections (Linac 0) that will eventually be relocated along the machine.
  - The new structures will have to minimize phase and amplitude asymmetries in the coupler cells, to minimize the induced kick to the beam.

LOW LEVEL RF

- Specification on amplitude and phase stability: 0.1% and 0.1° at 3 GHz.
- All-digital system, specifically developed for FERMI.
- System developed in the frame of a collaboration agreement between Elettra - Sincrotrone Trieste and Lawrence Berkeley National Lab.
- Intermediate system :
  - Commercial processing board (LLRF4).
  - All basic loops needed have been implemented :
    - Loops: amplitude, phase, cable calibration and phase locking loop.
    - SLED: phase reversal and phase modulation.
- Final system:
  - Processing board specifically designed for FERMI.
  - First two units in operation on the machine.
  - Firmware ported from LLRF4 board to the final board.
  - It will allow further firmware developments of the system.

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S-BAND RF SYSTEM OPERATION AND UPGRADES

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OPERATING PARAMETERS

MAY 2013

Klystron	Section	Energy gain (MeV)
K1	GUN	4.8
K2	L0_1	47
K2	L0_2	47
K3	L1.1	55.2
K3	L1.2	55.2
K4	L1_X	-20
K5	L1_3	55.2
K5	L1_4	55.2
K6	L2_1	57.5
K6	L2_2	57.5
K7	L2_3	52
K8	L3_1	118
K9	L3_2	127
K10	L4_1	116
K11	L4_2	119
K12	L4_3	119
K13	L4_4	117

- For FEL-1 the linac is typically operated at 1.27 GeV, 10 Hz.
- The gain in the BTW structures is typically around 120 MeV/section.
- SLED phase modulation applied on all the BTW structures.
- Klystron typical output:
  - K2 to K7: 32 MW @ 2µsec
  - K8 to K14: ~22 MW @ 3 µsec.
- The power plants are in operation on a 24 hours/day basis. Operating hours are higher than 6000/year.
- From May 2013, after the installation of the new gun, the upgrade in repetition rate and energy of the machine is taking place.

REPETITION RATE UPGRADE

- The first six modulators were assembled re-using the components of the old Elettra hardware, and therefore were limited to 10 Hz by the hardware. The remaining modulators only required minor modifications.
- The upgrade gave also the opportunity to implement a circuit revision to optimize the 50 Hz repetition rate operation and the klystron anodic voltage stability.
- Some of the changes:
  - Direct charging of the pfn instead of a resonant circuit system
  - New HV power supply (higher range and better voltage stability)
  - New pfn (water cooled, better pulse flatness)
  - New pulse transformer
  - Additional klystron lead shielding

- Boundary condition for the activities was that the upgrade should not affect the commissioning calendar, i.e. only in the already planned shutdowns.
- This process was completed in January 2013, in time, without affecting the availability of the plants for the machine runs.

ENERGY UPGRADE

- For FEL-2, which reaches the lower wavelength range, the energy of the beam should be increased to 1.5 GeV .
- The energy gain of the seven BTW accelerating structures (equipped with SLEDs) should be pushed in the 150 MeV/range.
- The energy gain of the TW section was kept unchanged.

- In the operation as part of the old Elettra injector the BTW structures suffered of heavy breakdown phenomena when pushed to high gradient.
- Phase modulation was adopted to overcome this limitations.

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50 Hz AND RF CONDITIONING

- Allocated periods:
  - May 2013 (four weeks): both frequency and energy upgrade.
  - August 2013 (one week): only energy upgrade at 10 Hz.
- TW Structures:
  - Only 50 Hz conditioning.
  - Same peak RF power and pulse length.
  - Target operating parameters reached in 4 days.
- BTW structures:
  - Klystron Output Power increased up to 32 MW (from the past 22 MW operation).
  - Pulse Length up to 3.0 µs at 50 Hz in May.
  - Pulse Length up to 3.5 µs at 10 Hz in August.

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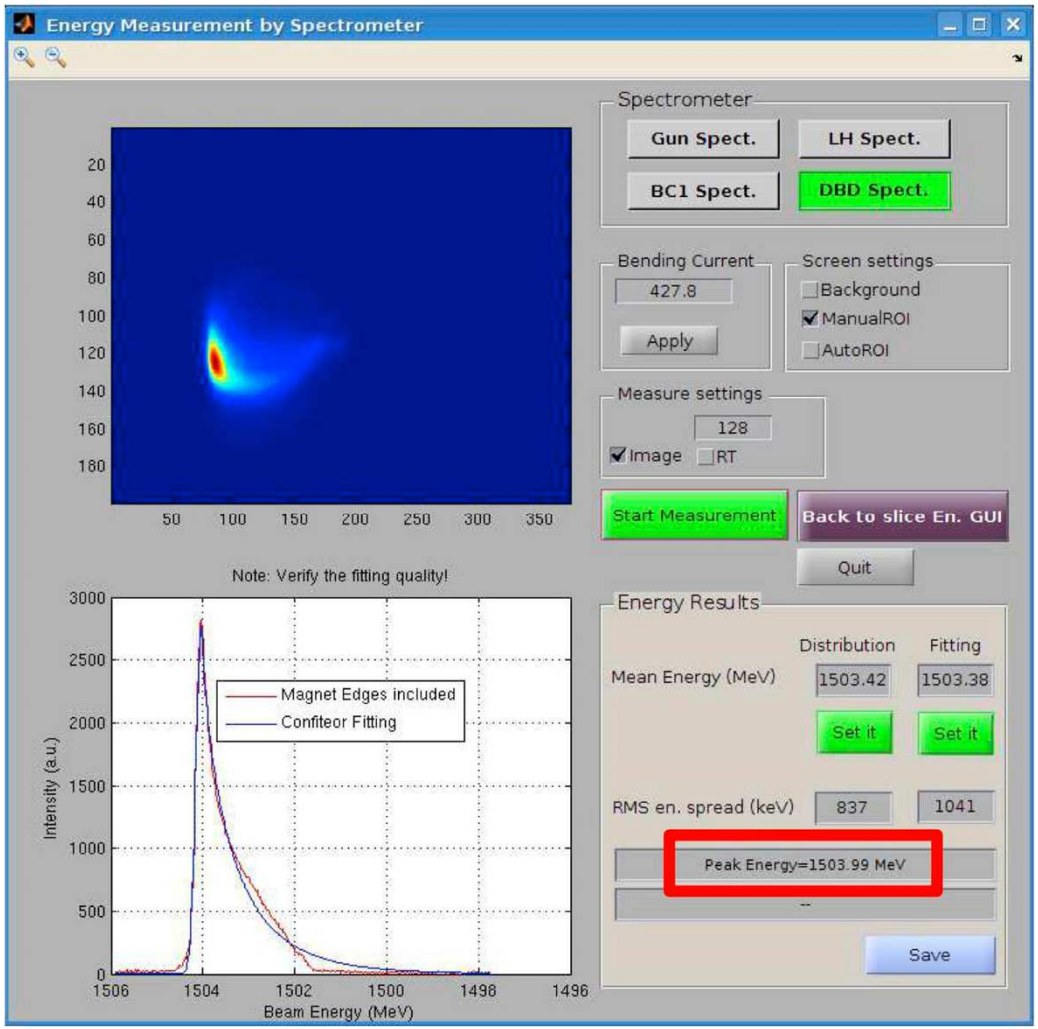
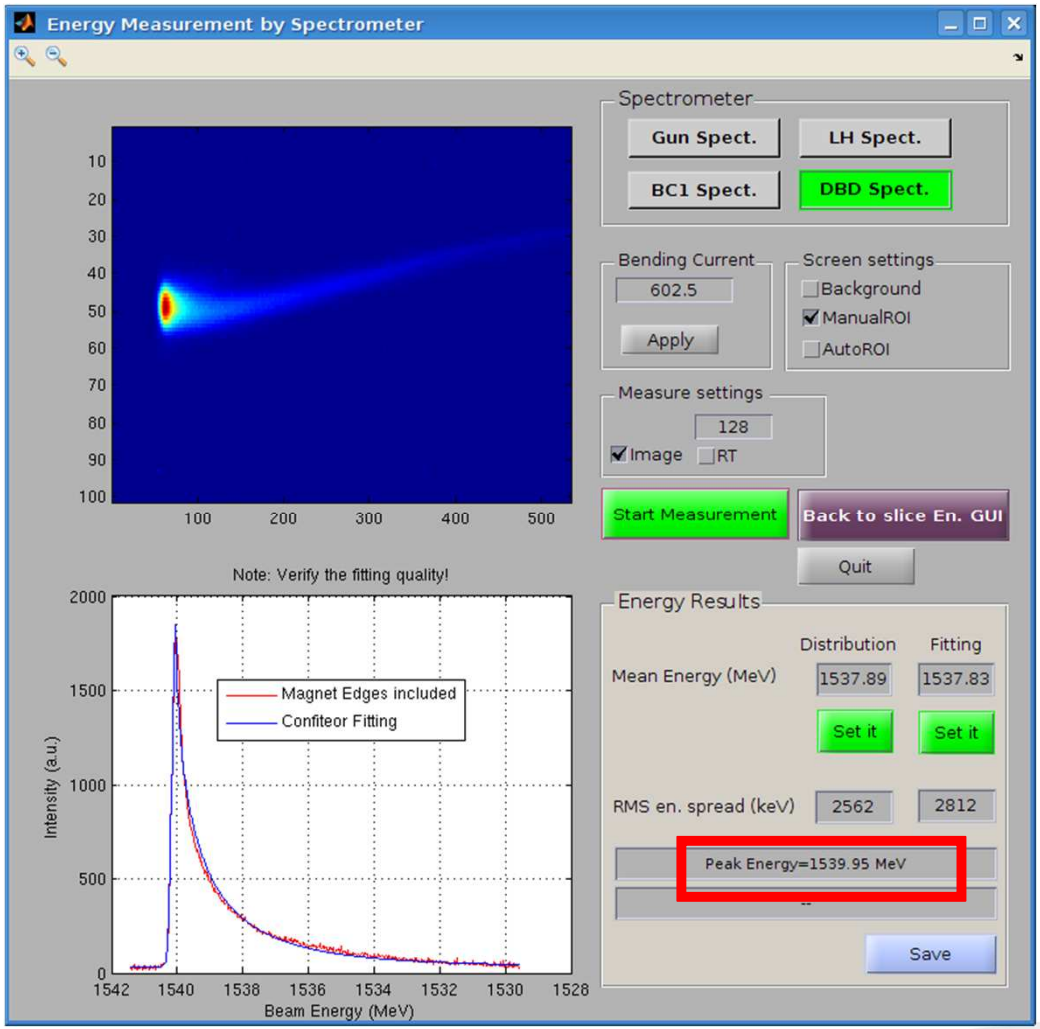
RESULTS



May 31: 1.503 GeV (on crest) at 50 Hz



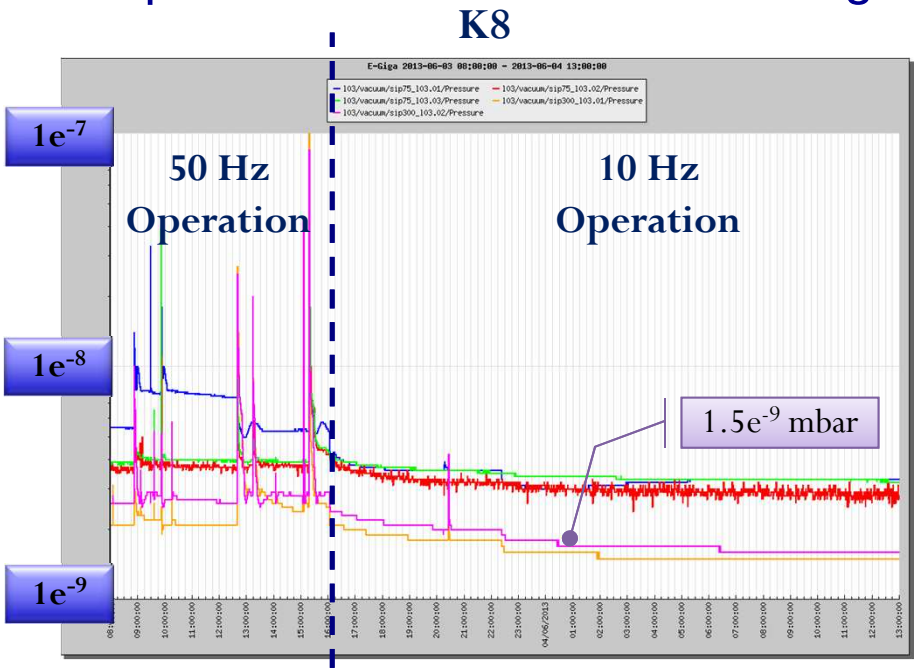
Sept. 4: 1.538 GeV (on crest) at 10 Hz

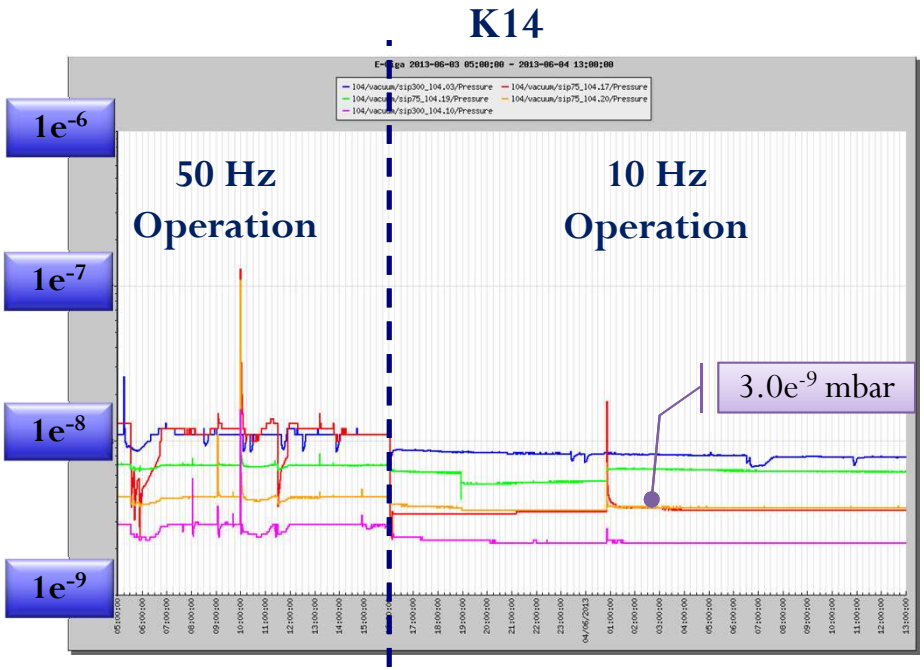
50 Hz TESTS AND RF CONDITIONING - NOTES

- Power plants.
  - Increase to higher frequency rate was achieved without any issue.
  - No change in the power plants fault rate.
- Structures
  - May conditioning
    - TW structures: only increase in repetition rate. No increase in gradient. No particular issues.
    - BTW structures: reached the gradient for 1.5 GeV (on crest) 50 Hz, however with still a too high breakdown rate.
  - Since the machine was expected to work at 10 Hz in the following run, decided to set the working energy (on crest) of the machine to 1.46 GeV, 10 Hz.
  - August
    - One week to increase to 1.538 MeV 10 Hz, working point. Result limited by the time allocated.

50 Hz TESTS AND RF CONDITIONING - ISSUESS

- Example of vacuum trends switching from 50 Hz to 10 HZ.





- Most of the vacuum spikes have been detected by ion pumps closer to the structures input: this suggests that breakdown events take place in structures input couplers and structures cells.
- The main hardware issue at 50 Hz was due to three breakdowns in the directional couplers between SLED and accelerating structures input.

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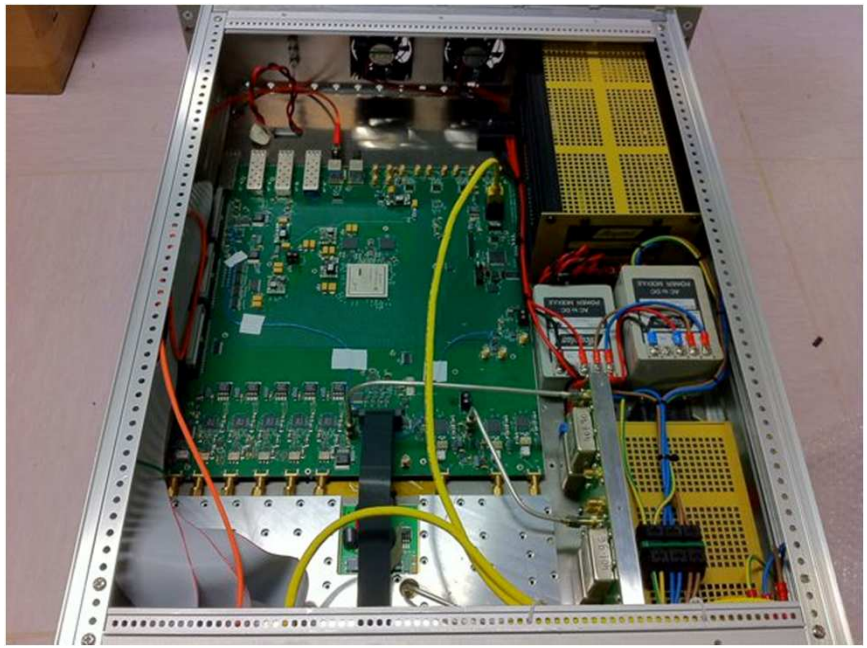
OPERABILITY

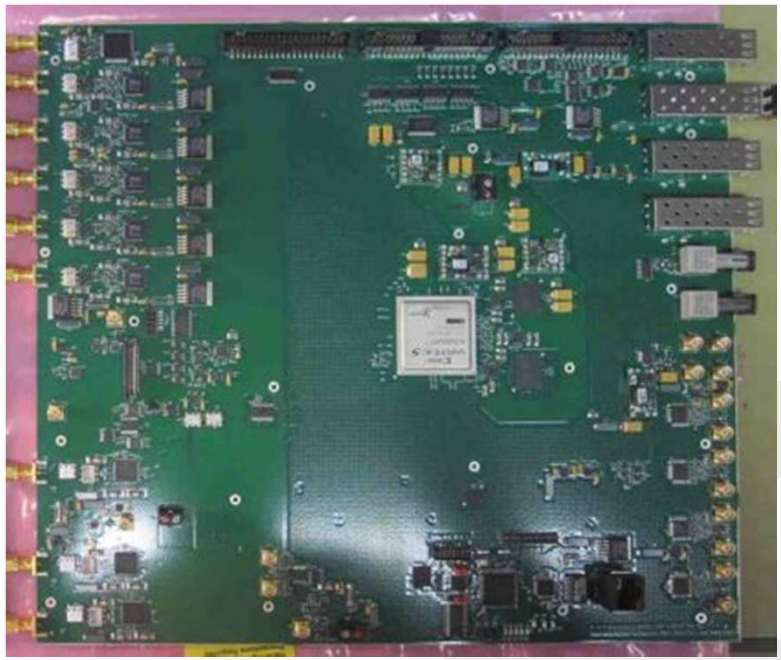
- Working points of the structures has been established according to the needs of machine operation.
- 50 Hz operation is required in Autumn 2014.
- The structures are set to the maximum gradient reached. When less beam energy is required, one or two sections are set off line. On these structures we can continue to work conditioning without the need of dedicated time.
- For the 50 Hz case and BTW structures:
  - We are changing the design of the directional couplers:
    - Reduce coupling, by reducing the coupling hole diameter.
  - We are adding further interlocks and diagnostics on the reflected power from the structure (similar to the one which protects the klystron).
- Other operational margin (100 MeV) will be available when the two structures still missing will be available.

LLRF

- Replacement of the intermediate LLRF chassis with the ones with the final board is started.
- First two chassis in operation since August without problems (fimware operating on the intermediate ported to the new board).
- Plan to complete replacements by 2014.



- Main features of the board:
  - More ADC channels.
  - Input channels isolation >95 dB.
  - Output channel isolation > 75 dB.
  - Digital acquisition accuracy 0.017° and 0.029 %.
  - DAC output: 0.018° , 0.032 % noise RMS @99 MHz.



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OUTLOOK AND CONCLUSIONS

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OUTLOOK

- Energy and repetition rate
  - Conditioning of the structures will continue according to the available time to increase operating margins and establish 50 Hz operation.
- Power plants
  - Study on reduction of the impact of klystron discharges on machine uptime is in course.
  - Fully characterize performance and study improvements to serviceability and maintainability (additional spare plants, spares management, etc.).
- Structures
  - The procedure for acquiring the two accelerating structures, foreseen in the machine layout, is in course.
  - We are looking on the possibility of sledding the TW structures from CERN (as suggested by the MAC meeting).
    - Due to the filling time, efficiency will not be maximized, but it could allow us a further increase in the energy budget at a moderate cost.
    - Checks on constraints on beam energy in fixed points along the linac.

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OUTLOOK

- SLED phase modulation
  - Up to now we have implemented a simple linear phase modulation.
  - We are now studying the optimization of the phase modulation parameters introducing a non linear phase modulation in order to have a flatter pulse, a lower peak field in the accelerating structure while keeping the energy gain.
- LLRF
  - The new board will allow introducing new functionalities, such as:
    - real time communication between LLRF units;
    - enlarging of average time of calibration and phase reference signals (increase in the signal to noise ratio of the measurements);
    - intra-pulse feedback (measure and apply correction in the same pulse in particular to correct jitter contributions);
    - reflected power interlocks implemented in the LLRF;
    - investigate iterative learning (to remove periodical known errors).

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CONCLUSIONS

- FERMI- FEL 1 is now open to users.
- FERMI – FEL 2 commissioning is advancing .
- The S-band RF system is in routine operation.

- Upgrade of power plants to the final repetition rate is completed.
- Establishing of higher beam energy operation is progressing according to the allocated machine time.
- The installation of the FERMI AD boards will allow to enlarge the features of the LLRF system.
- ***Studies on upgrade paths for the system both in terms of reliability and functionalities are in course.***

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REMINDER

- ***The next CWRF workshop will be held in Trieste.***
- *Please save the date on your agenda:* ***May 13-16, 2014*** .
- ***More information soon.***

THANK YOU FOR YOUR ATTENTION