Status of the S-band RF Power System for the FERMI@elettra Linac

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OUTLINE

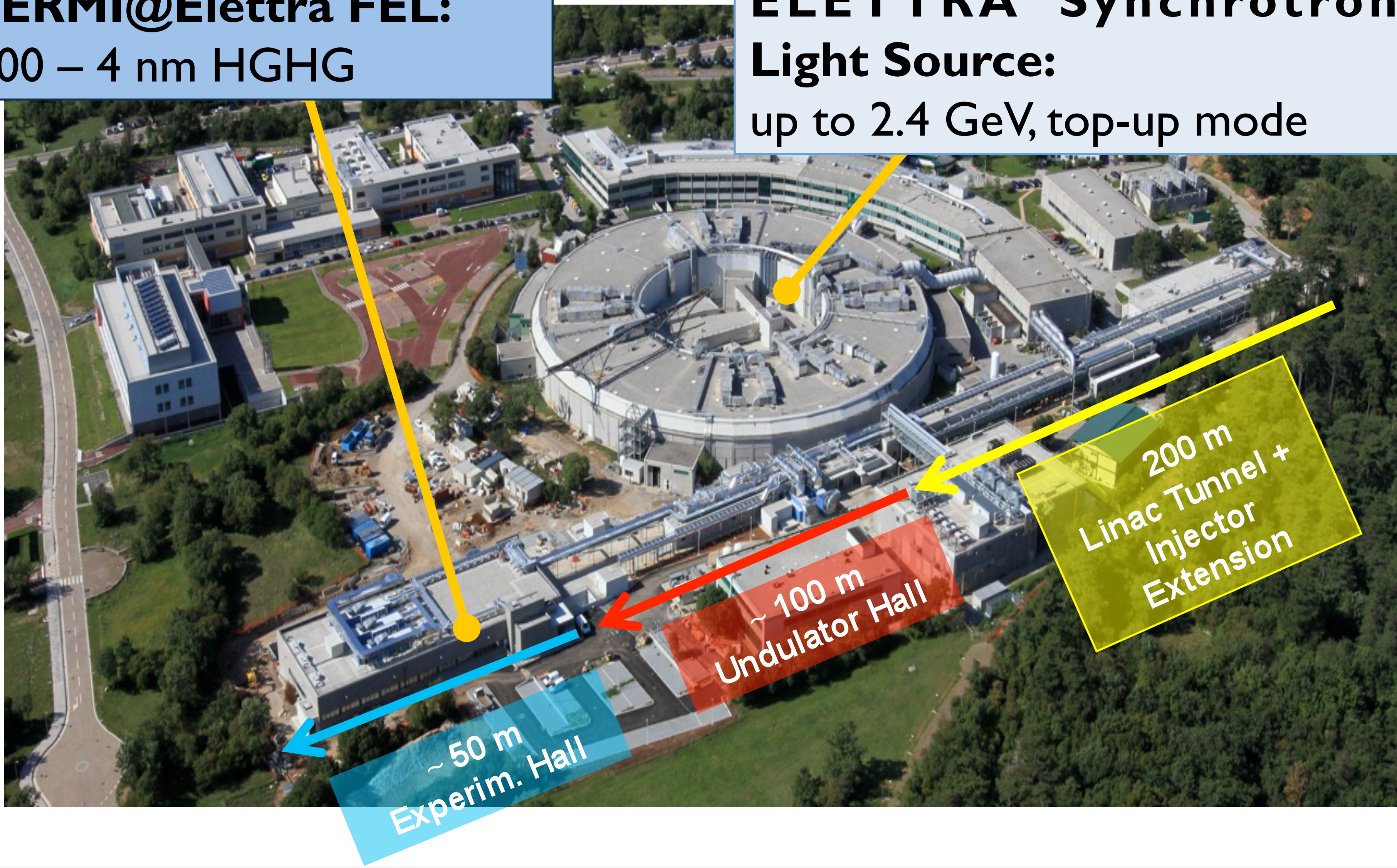
- FERMI@elettra overview
- S-band RF System
- RF power plants
- Outlook and conclusions

FERMI@elettra
OVERVIEW

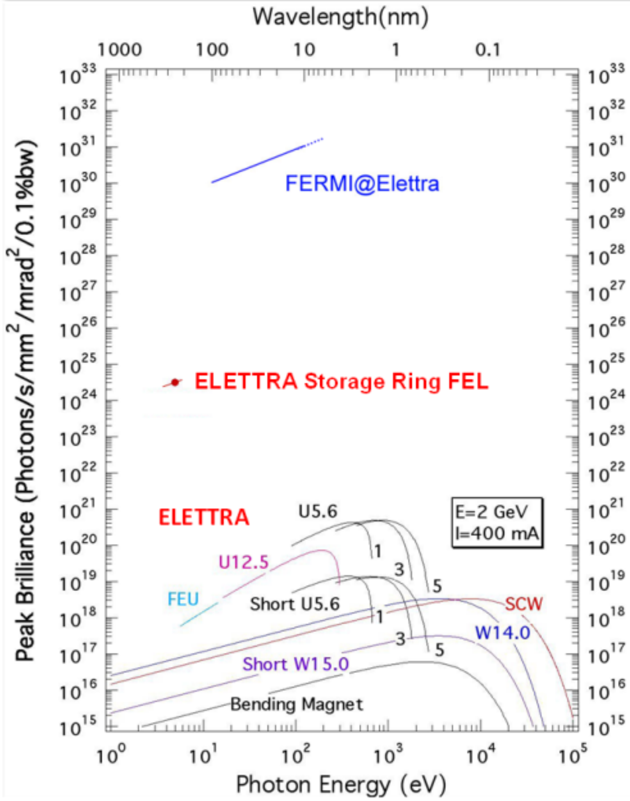
The ELETTRA LABORATORY

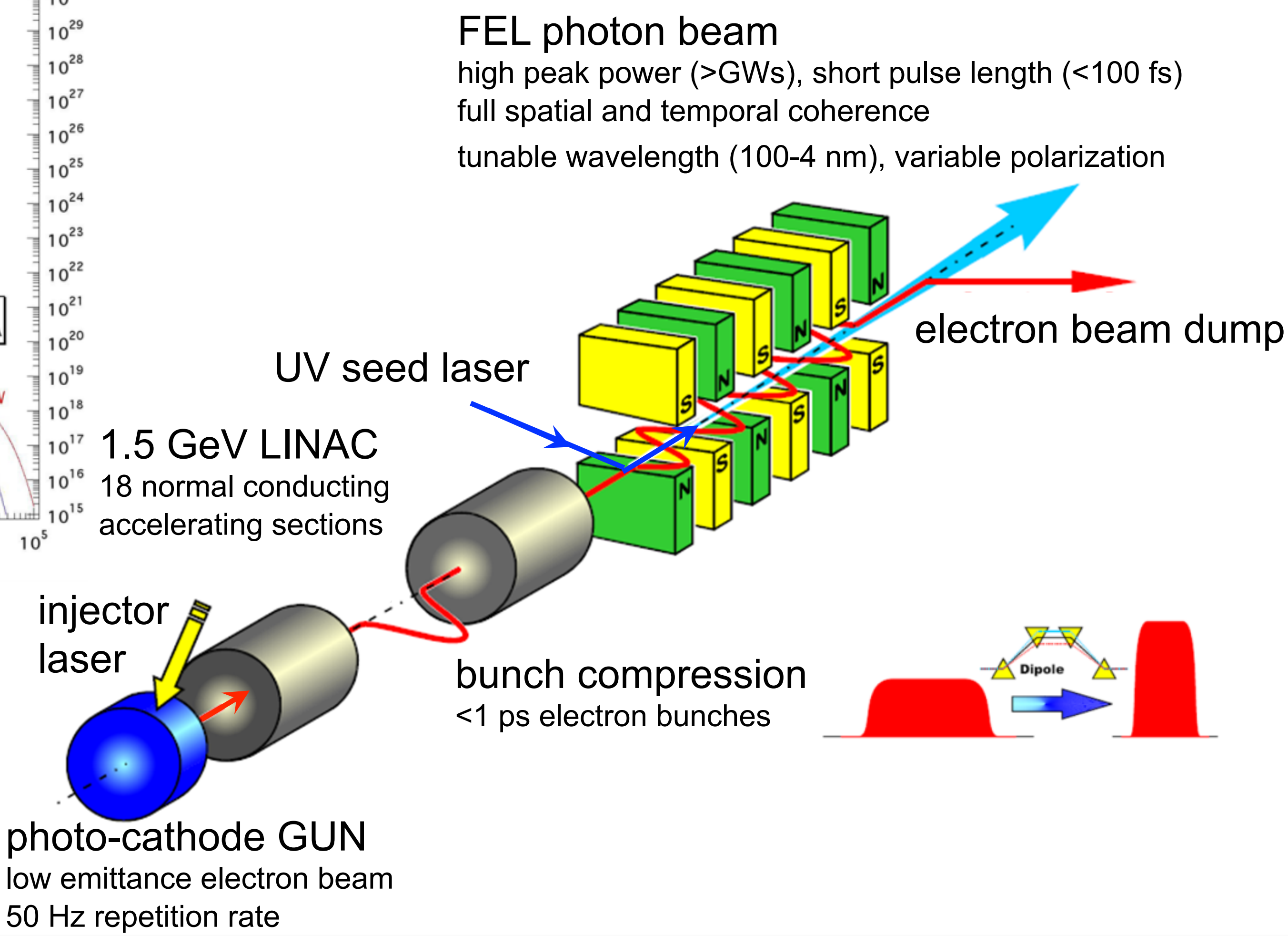
FERMI@Elettra FEL:
100 – 4 nm HGHG

ELETTRA Synchrotron Light Source:
up to 2.4 GeV, top-up mode



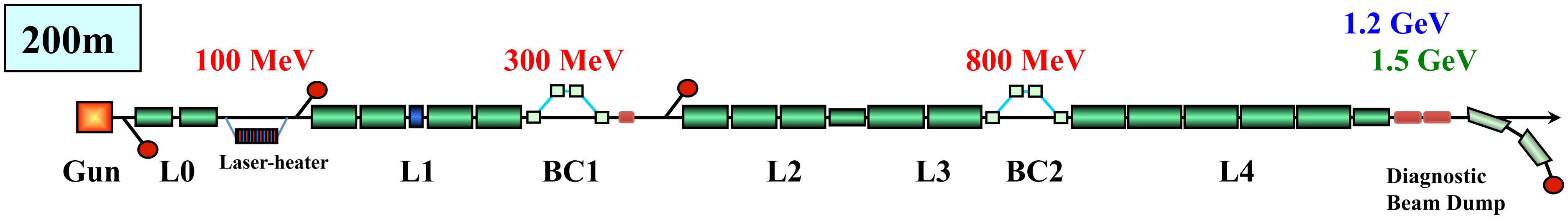
First seeded FEL, designed to produce fundamental output wavelengths down to 4 nm with **High Gain Harmonic Generation**



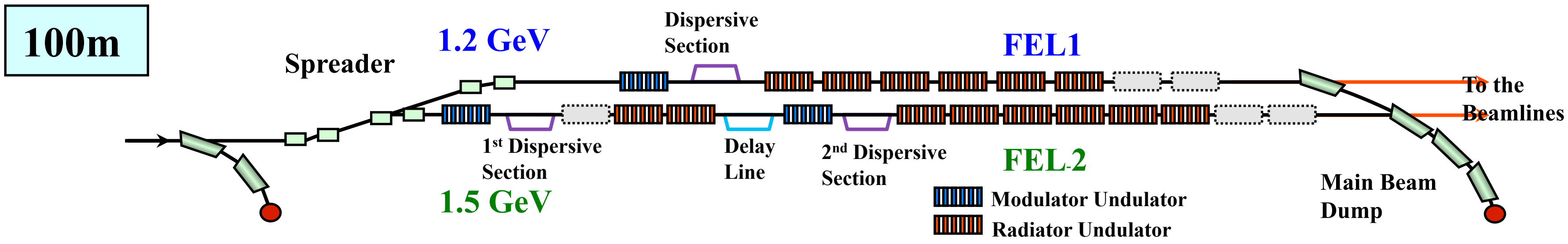


MACHINE LAYOUT

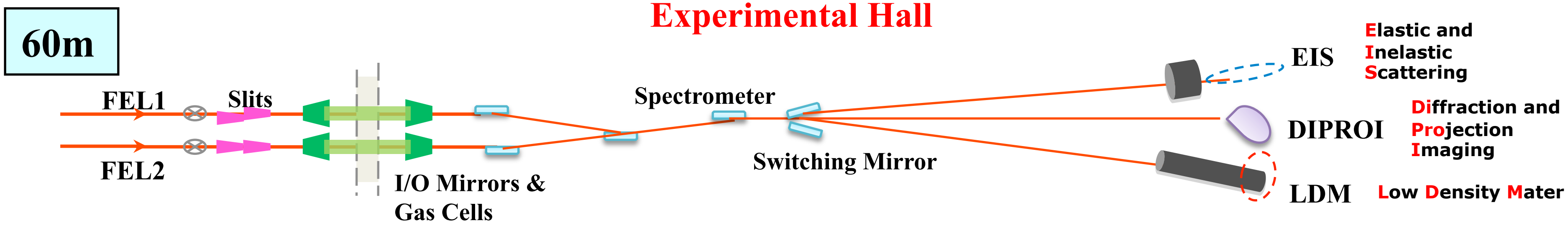
Linac



Undulator Hall



Experimental Hall



MACHINE PARAMETERS

Parameter	FEL- 1	FEL -2	Units
Wavelength	100-20	20-4	nm
Electron Beam Energy	1.2	1.5	GeV
Bunch Charge	0.8	1	nC
Peak Current	850	500	A
Bunch Length (FWHM)	400	600	fs
Norm. Emittance (slice)	0.8-1.2	1.0-2.0	mm mrad
Energy Spread (slice)	150-250	100-200	keV
Repetition rate	10-50	50	Hz

DESIGN GOALS & ACHIEVEMENTS

Parameter	Nominal	Units	Achieved To Date
Electron beam Energy	1.2	GeV	1.2
Bunch Charge	800	pC	500
Peak Current	850	A	≤350
Bunch Length (FWHM)	400	fs	≥400
Norm. Emittance (slice)	0.8-1.2	mm mrad	1.0 (estimated)
Energy Spread (slice)	150-250	keV	150
Wavelength	100 - 20	nm	65 - 20
Photon energy	12 - 62	eV	19 - 62
Tunability	continuous		continuous
Pulse Length (FWHM)	30 - 100	fs	< 150 (estimated)
Bandwidth	~ 20 - 40	meV	22 (rms, @ 32 nm)
Bandwidth ΔE/E	~ $5\ 10^{-4}$		$6\ 10^{-4}$ (rms, @ 32 nm)
Bandwidth fluctuations		rms	~3%
Polarization	variable		Circular and Linear
Repetition Rate	10 - 50	Hz	10
Energy/pulse	> 100	μJ	20 – 50
Peak Power	1 - 5	GW	0.1 - 0.5 (estimated)
Photons per pulse	$2 \cdot 10^{14}$ @ 100nm		~ 10^{13} @ 32 nm
FEL mode	TEM_{00}		TEM_{00}
Central Wavelength Fluctuation	within bandwidth		~ 1.1 meV

FUTURE ROAD MAP

- **FEL – 1**
  - FEL -1 optimization is expected to be concluded in 2012
  - Some important systems are now under commissioning, namely:
    - The linearizing cavity at the 4th harmonic (X-band system), which will allow us to increase the core peak current of the electron bunch.
    - The laser heater, which will allow us to cure the microbunching instabilities, observed at higher charge per bunch and stronger compression factors.
    - The Second Bunch Compressor, which will allow us to distribute the compression over two compressors (BC1 and BC2).
    - The High Energy RF Deflecting cavity, which will allow us to find the optimum e^- beam trajectory in the last part of the linac.
  - ***The Users' program starts in 2012.***
- **FEL – 2**
  - Prove HGHG with FEL – 2 (major goal for 2012)
  - Test experiments in 2013

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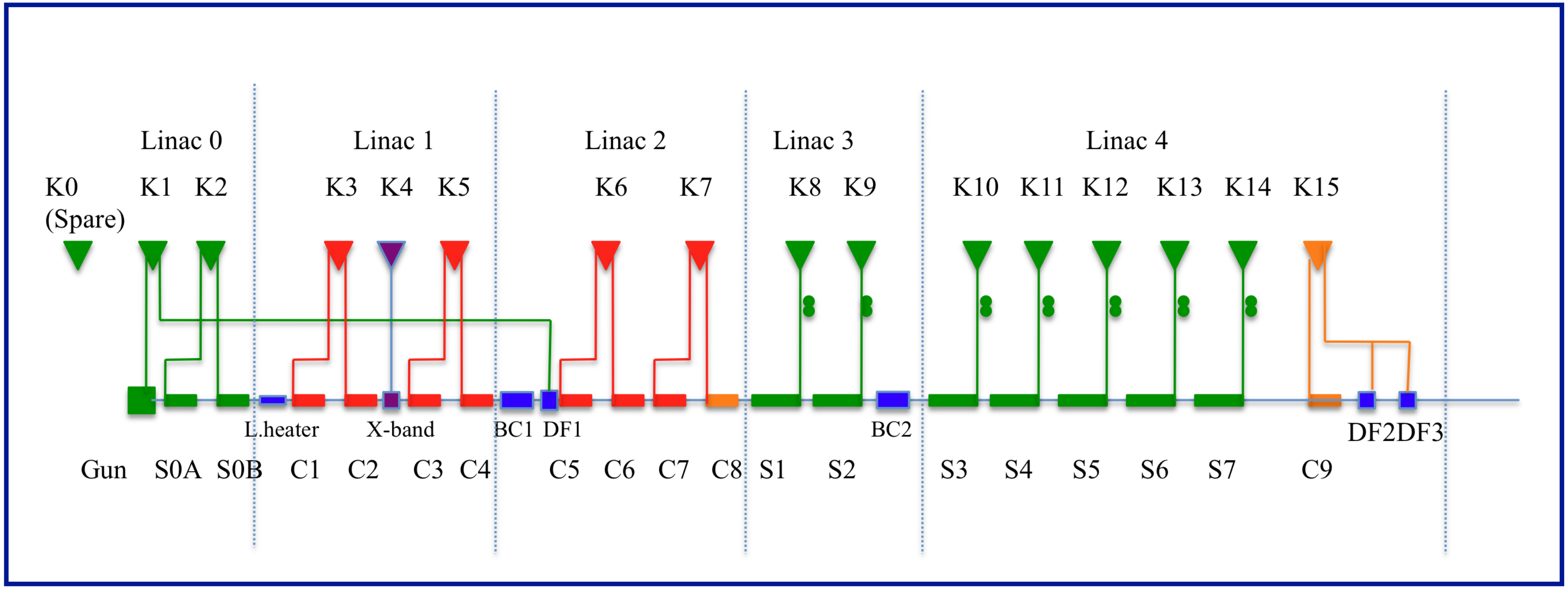
S-BAND RF SYSTEM

GENERAL

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



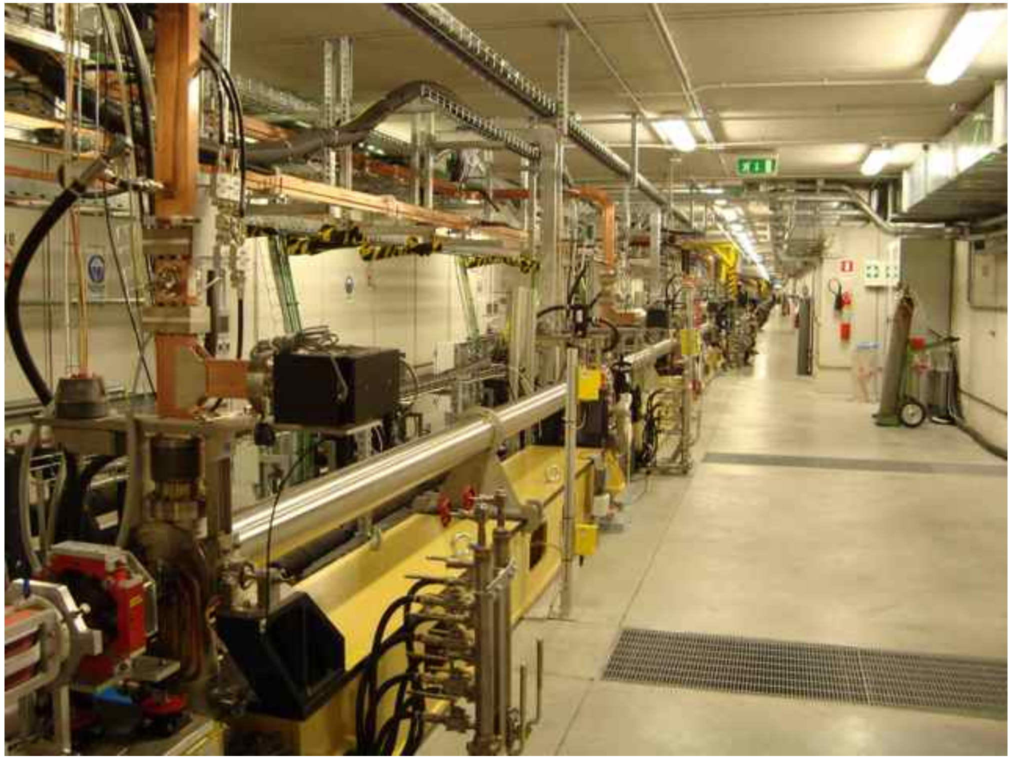
STATUS

- **RF TRANSMITTERS:**
  - Fifteen RF transmitters operational.
  - Transmitters operating at 10 Hz, upgrade to 50 Hz from 2012.
- **ACCELERATING STRUCTURES:**
  - Sixteen accelerating structures in operation.
  - Two to be acquired.
  - SLED systems operational.
- **LOW LEVEL RF:**
  - All plants equipped with intermediate LLRF.
  - Final system construction in progress.

RF POWER DISTRIBUTION

- Two main RF power distribution schemes are used:
  - One klystron feeding two structures.
  - One klystron feeding a single high gradient accelerating structures equipped with SLED system.

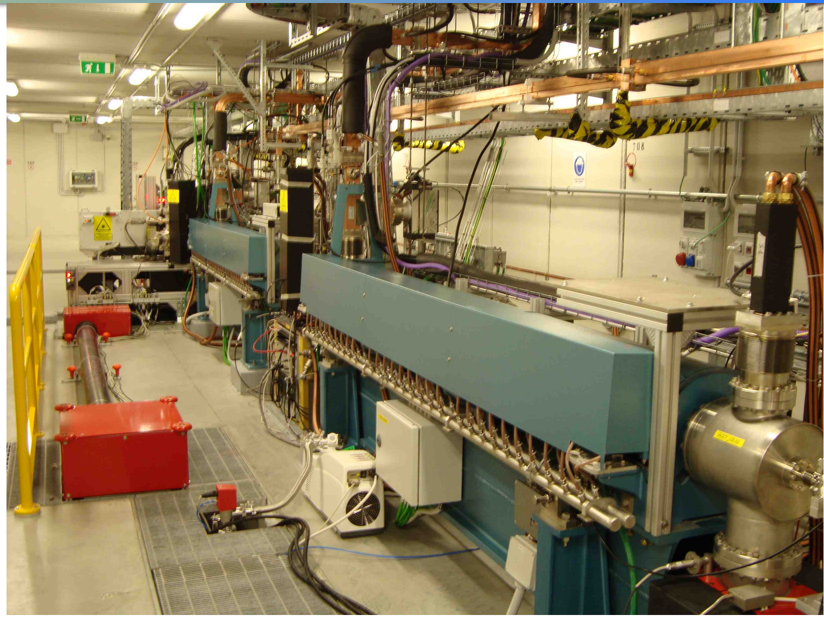
- OFHC WR284 waveguides working either under ultra high vacuum or under SF6 pressure.
- Waveguide attenuators and phase shifters are used to control in phase and amplitude the power in case of multiple users.
- An array of switches is used to connect the spare system in case of need to replace one of the first two klystrons.



ACCELERATING STRUCTURES (1)

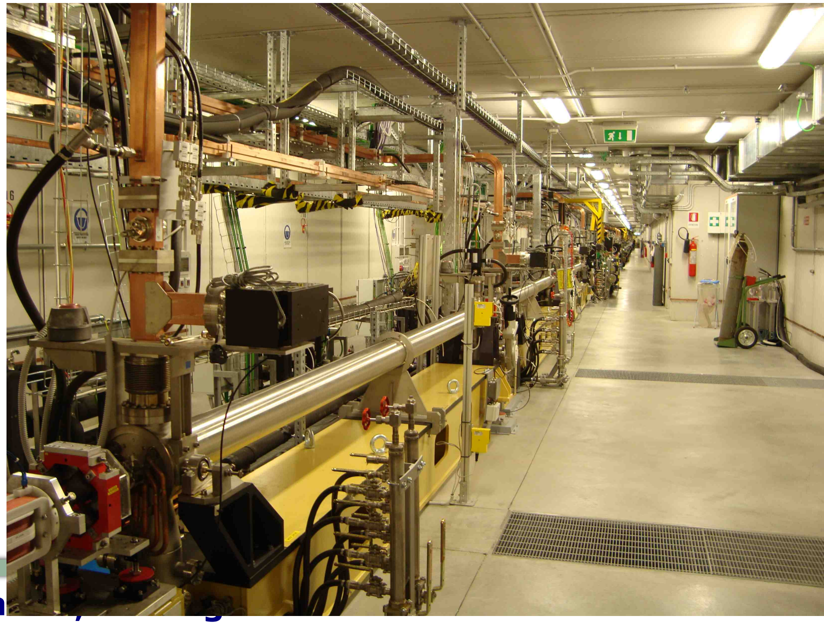
- **Linac 0: two sections**
- From old Elettra injector

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



- **Linac 1 : four sections**
- **Linac 2 : presently three section**
- Sections from CERN

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



ACCELERATING STRUCTURES (2)

- **Linac 3: two sections**
- **Linac 4: presently five sections**
- From old Elettra injector
- 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	0.603 μsec

- Two more structures to be acquired:
  - They will replace the first two sections (Linac 0) that will be eventually relocated along the machine (in linac 2 and 4 respectively).
  - The new structures will have to minimize phase and amplitude asymmetries in the coupler cells, to minimize the induced kick to the beam.

ACCELERATING STRUCTURES PERFORMANCES

- All available structures in operation.
- No new issue.
- SLED operational and implemented phase modulation.
- Energy gain per section:

Type	Number	1.2 GeV	1.5 GeV	1.5 GeV
Gun	1	5 MeV	5 MeV	5 MeV
S0a-S0b	2	47.8 MeV	47.8 MeV	47.8 MeV
C1-C7	7	57 MeV	57 MeV	57 MeV
S1-S7	7	110 MeV	150MeV	136 MeV
New sections	2	//	//	50 MeV
Total Energy		*1270 MeV*	*1550 MeV*	*1552 MeV*

- Typical power from the klystron will not exceed 35 MW.
- **The energy required for FEL-2, i.e. 1.5 GeV, should be attained with a reasonable margin for availability and reliability.**

LOW LEVEL RF

- Specification on amplitude and phase stability: 0.1% and 0.1° at 3 GHz.
- The LLRF is an all-digital system, specifically developed for FERMI.
- System developed in the frame of a collaboration agreement between Sincrotrone Trieste and Lawrence Berkeley National Lab.
- Intermediate system performance:
  - Commercial processing board (LLRF4).
  - All loops needed have been implemented on the intermediate system:
    - Loops: amplitude, phase, cable calibration and phase locking loop.
    - SLED: phase reversal and phase modulation.
  - The system is very crucial for the reaching of the performance of the beam needed for the FEL.
- Final system:
  - Prototype processing board fully tested on bench and on the machine with beam.
  - Firmware ported from LLRF4 board to the final board.
  - Boards in construction.
  - It will allow further firmware developments (for example intra-pulse feedback, real time communications between LLRF units, etc.).

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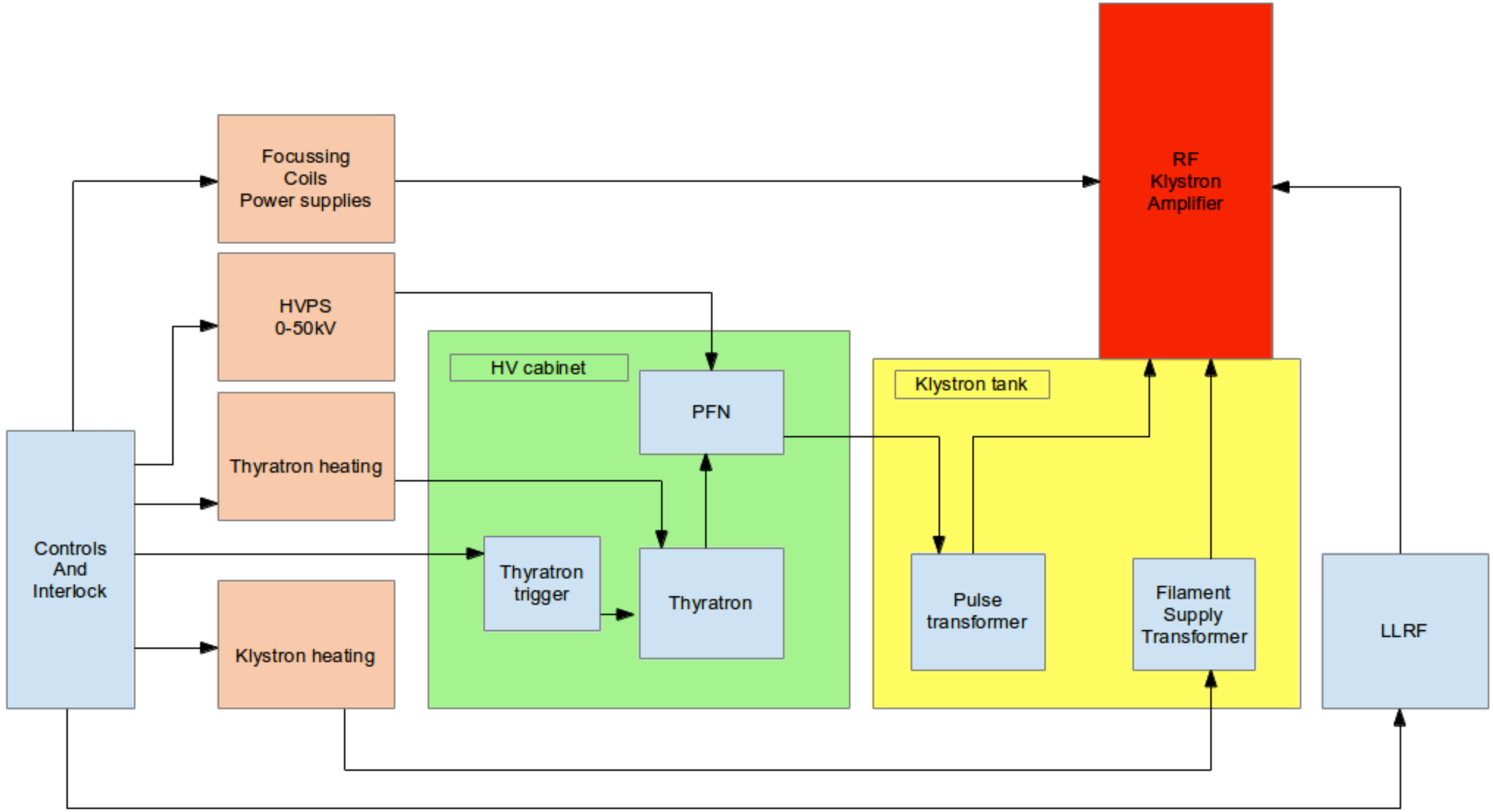
RF POWER PLANTS

RF TRANSMITTERS

- Fifteen identical power plants : fourteen + one spare
- PFN modulators assembled by local companies under our specification.

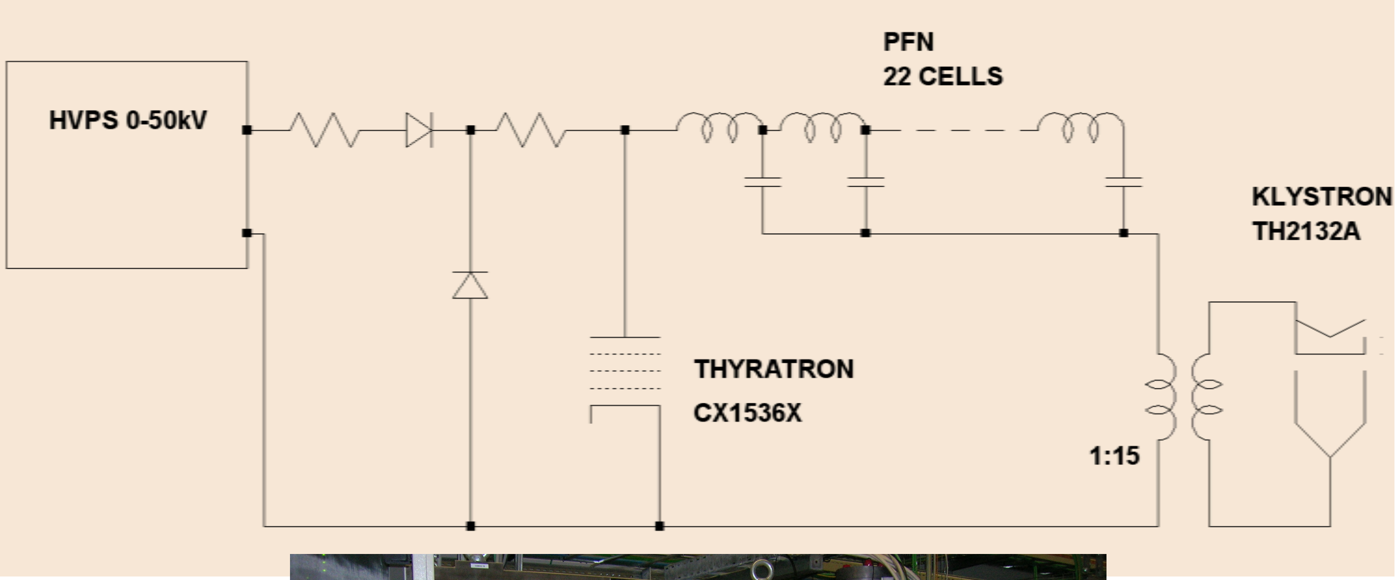
RF TRANSMITTERS



KLYSTRONS

Klystron Thales TH 2132A-typical parameters	
Frequency	2998 MHz
Peak RF power	45 MW
RF pulse width	4.5 μsec
Pulse repetition frequency	10-50 Hz
Gain at full output power	≥ 53 dB
Efficiency in saturation condition	≥ 43%
Beam cathode voltage (typical)	310 kV
Peak cathode current	350 A

Klystron output power	
K1	21 MW
K2	33 MW
K3 to K7 (typ)	33 MW
K8 to K14 (typ)	24 MW

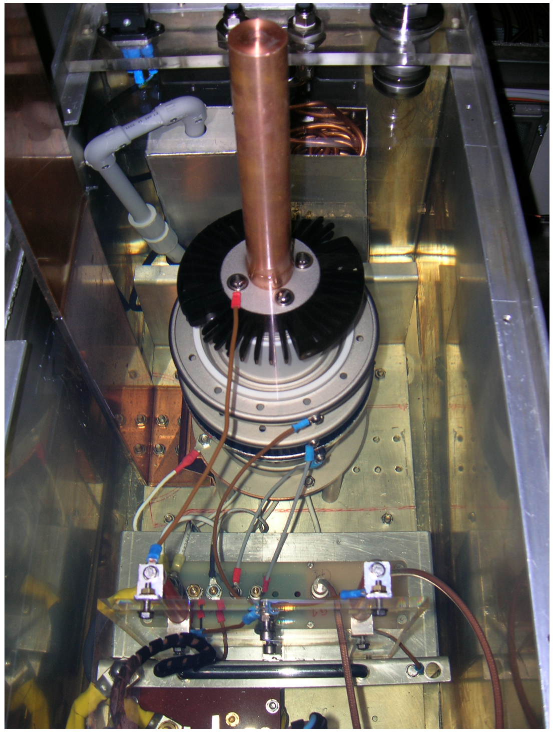

PFN
22 CELLS
HVPS 0-50kV
KLYSTRON
TH2132A
THYRATRON
CX1536X
1:15

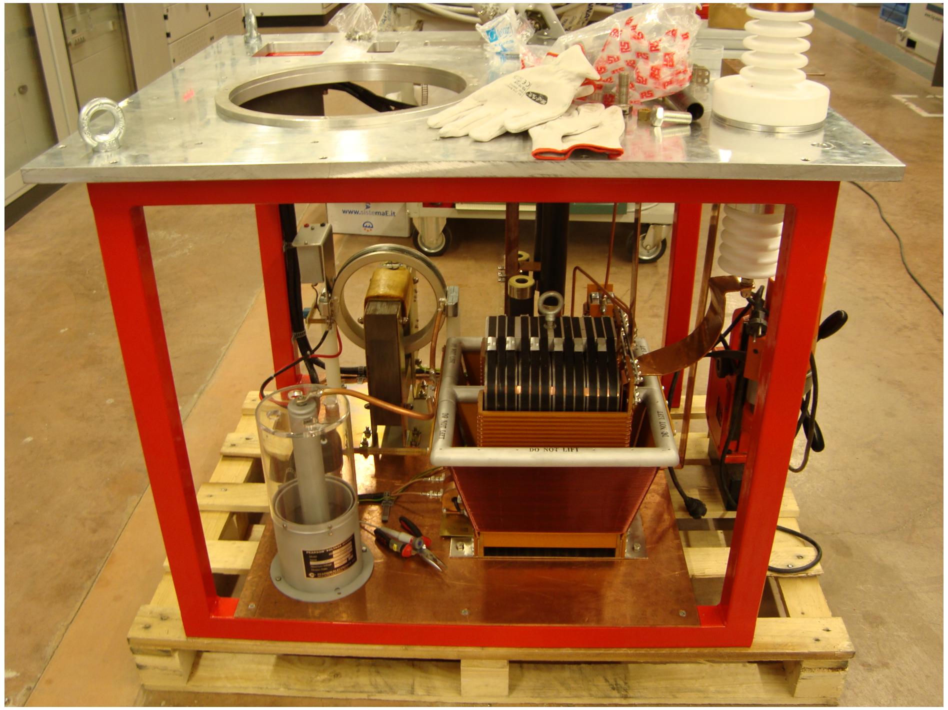
MAIN SUB-COMPONENTS

- FUG Power supply
  - Capacitor charging p.s: 0-50 kV, 0-2 A
  - Pulse to pulse repetition accuracy < ±1*10e-4 at 50 Hz

- TPC pulse forming network
  - Charging voltage: 46 kV
  - Characteristic impedance : 4.7 Ω

MAIN SUB-COMPONENTS



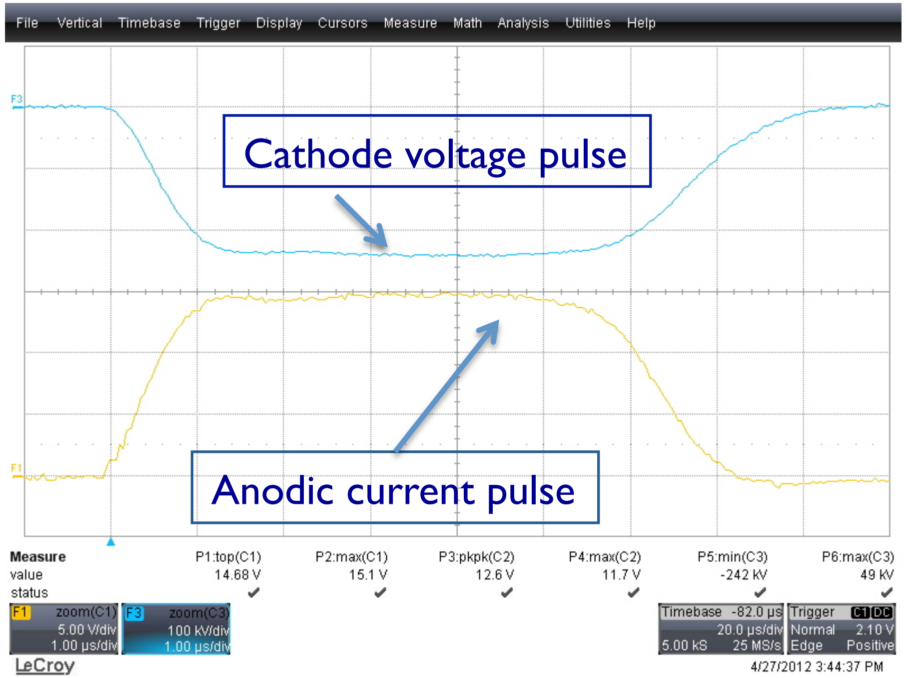


- Thyratron E2V CX1536X

- Klystron tank electronics
- Stangenes pulse trasformer

RF TRANSMITTERS

PFN Modulators – typical parameters	
Maximum output voltage	320 kV
Maximum delivered current	350 A
Repetition frequency	10-50 Hz
RF pulse width	4.5 μsec
Risetime / falltime	< 2 μsec
Pulse flatness	< ± 1%
Stability	< 100 ppm



Klystron	Beam current (% of I max)	RF power
K1	61 %	21 MW
K2	83 %	33 MW
K3 to K7 (typ)	81 %	33 MW
K8 to K14 (typ)	66 %	24 MW

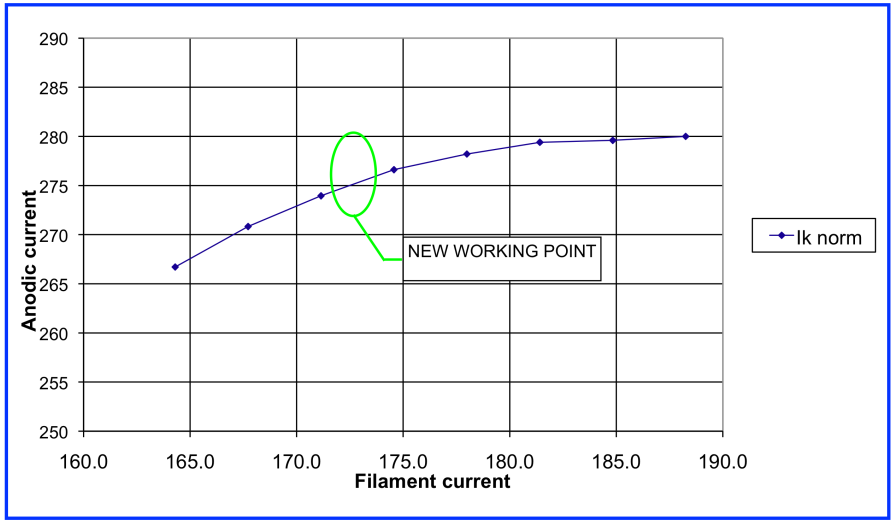
PERFORMANCE (1)

- Power plants are in operation on a 24 hours/day basis.
- Typical operating hours are more than 6000 hours/year.
- Uptime of the RF system overall is 93 %.
- The main contribution to the downtime is what we call "peak I faults", i.e. an anomalous increase in the klystron current:
  - They account for more than 90% of the total faults on the S-band System.
  - They are generally random distributed and resettable.
  - They are power dependent.

- **Specific actions taken to assure the operability and maintenance strategy:**
  - Studies on peak current threshold definition.
  - Regular check of dielectric oil characteristic during shutdowns.
  - Regular check of thyratron pulse.
  - Perform HV conditioning during shutdowns or in case of fault rate increase.
  - Optimization of klystron parameters.
  - Routinely perform klystron heating curve optimization.

PERFORMANCE (2)

- KLYSTRON FILAMENT HEATING CURVE OPTIMIZATION:
  - Done on all the klystrons.
  - According to Klystron manufacturer, to be done:
    - between the first 500 and 1000 hours of operation and then at least once a year,
    - or when the current operating point is changed (working point optimized for nominal V_{cath} , I_{cath} settings).
  - Criterion $\Delta I_{cath}/I_{cath}$ comprised between -3 % and 0%.



- Excessive cathode heating ➔ premature depletion of the cathode emission surface ➔ dc and rf problems (breakdowns).
- Low cathode heating ➔ hamper cathode emission ➔ degrade operation at higher power levels and possible dc arcing in the gun area.

PERFORMANCE (3)

- The present uptime is acceptable, especially since we are in a commissioning period, nevertheless we are working to improve it.
- Until now the main effort has been put on installation and machine commissioning, so little time was allowed to the modulator test.
- During shutdowns we can switch on the klystrons only in diode mode.
- The completion of the spare modulator will allow to start a testing program to analyze modulator performance to look if there is any other part of the system which could affect the arc rate.

50 Hz OPERATION

- Present operation of the machine is at 10 Hz.

- Operation of the linac to 50 Hz is required in 2013, after the installation in the machine of the new RF gun (which will be previously tested using the spare plant).

- The first six plants were built re-using the components of the old Elettra injector and therefore are limited by the hardware to 10 Hz.

- Operation at 50 Hz implies upgrade of the presently working modulators.

- Boundary condition: upgrade must not affect the commissioning calendar and upgrade can be generally done only in the already planned shutdowns.

- Due to the machine calendar and available manpower, this process will be completed in January 2013, without affecting the availability of the plants for the machine runs and for the testing of the new gun.

OUTLOOK AND CONCLUSIONS

SUMMARY

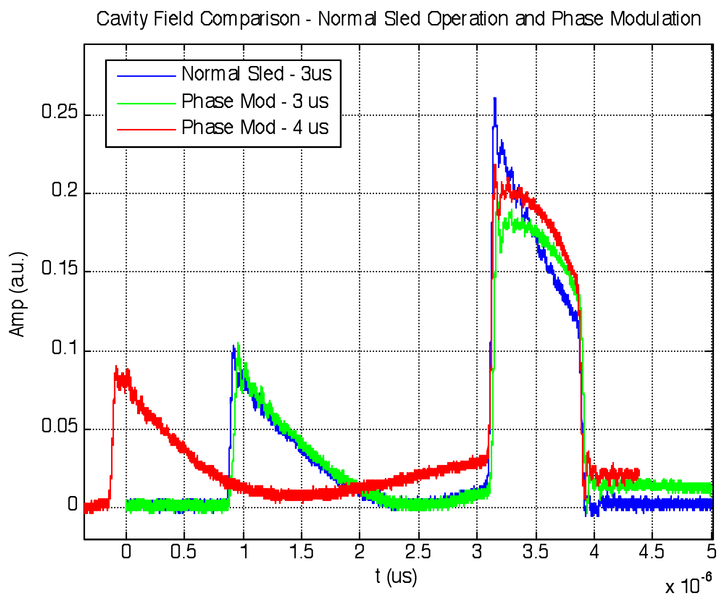
- The S-band RF system of the FERMI@Elettra linac has been gradually set into operation from the first installation of the plant for the gun in the second half of 2009.

- 15 power plants and 16 accelerating sections are in operation.

- LLRF intermediate system is performing according to specifications.

- Phase modulation of the SLEDS has been tested and implemented.

- On the section used for the tests this has allow to reach an energy gain of 165 MeV, corresponding to an accelerating gradient of 27 MV/m.



NEXT STEPS

- Raise machine energy to 1.5 GeV in 2012 for FEL-2.
  - Complete conditioning of all BTW structure to maximum power.
- Accelerating Structures:
  - Complete conditioning.
  - Procurement of the two additional structures.
- LLRF:
  - Complete AD boards construction.
  - Upgrade chassis to final systems.
  - Firmware development.
- RF power plants:
  - Upgrade plants to 50 Hz operation.
- ***Investigate upgrade path for the system both in terms of power increase and reliability aspects.***

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- The FERMI Commissioning Team and all the people involved in the commissioning of FERMI for the results on the machine.

THANK YOU FOR YOUR ATTENTION