ELECTRON LINACS

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39th International Nathiagali Summer College
4th – 9th August 2014

OVERVIEW

- ✓ Introduction
- ✓ Travelling wave structures
- ✓ Standing wave structures
- ✓ Building blocks
- ✓ FERMI linac
- ✓ Elettra pre-injector
- ✓ Summary
- ✓ Bibliography

INTRODUCTION

INTRODUCTION

- ✓ In a linac the beam is accelerated along a almost linear orbit.
- ✓ Linacs strongly rely on radiofrequency fields to produce the required electric field.
- ✓ Electron linacs are used for different applications:
    - Injection in circular machines
    - Advanced light sources (FEL, ERL,…)
    - Linear colliders
    - Medical applications (radiotherapy, production of industrial isotopes)
    - Industrial irradiation for various materials and products.

- ✓ **NB. This presentation will cover mainly travelling wave linacs and the technological aspect. It will not discuss the beam dynamics issues.**
- ✓ **Reference is made to the electron linacs in operation in FERMI and as pre-injector for the Elettra booster**

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INTRODUCTION

- ✓ Electrons are highly relativistic already at few MeVs.
- ✓ This means:
    - *The word accelerator has to be interpreted relativistically*
    - *Accelerating structures can be made at constant velocity v=c above 1 MeV*
    - *After the bunch of electron has been formed, its distribution is frozen. Above about 1 MeV, special bunch compressors have to be used to change it.*
    - *Space charge effects are generally negligible except for high current at low energies.*

BASIC CHOICES

✓ **Travelling or standing wave structure**

- Travelling wave
  - *Power is fed at one end propagates through the structure and then absorbed by a load*
  - *Steady state is reached when the structure is filled with energy after one pass.*
- Standing wave
  - *Only one coupler*
  - *The fields build up through multiple reflections*
- There is no a definitive answer to this choice. Generally traveling wave structures are used when dealing with short pulses. Standing wave are preferred if the pulse length is long or for CW machines.

✓ **Choice of the frequency:**

- Depends on many factors:
  - *Shunt impedance*
  - *Beam current*
  - *Cavity filling time*
  - *Dimensional tolerances*
  - *Availability of suitable RF sources*

    L-band: 1.3, 1.5 GHz, many SC linac

    S-band:3 GHz , established technology for TW NC linac

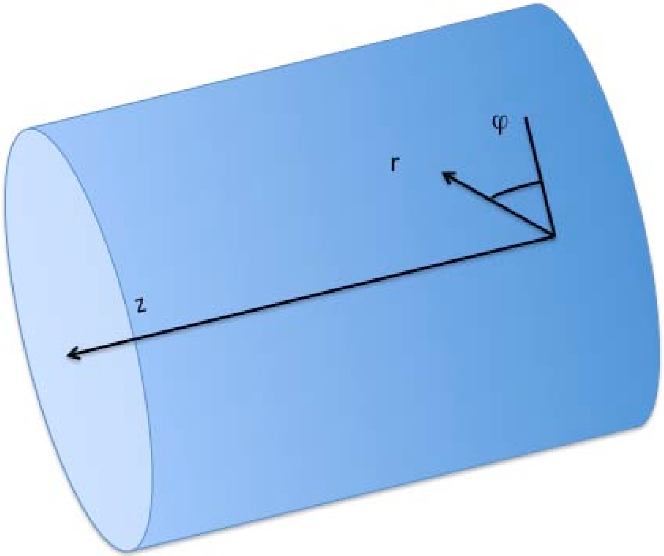
    C band: 5.7 GHz

    X band: 12 GHz

TRAVELLING WAVE STRUCTURES

CYLINDRICAL WAVEGUIDE

- ✓ Uniform waveguide: a dielectric volume limited by conducting cylindrical walls
- ✓ For this case we can solve the Maxwell equations in cylindrical coordinates
- ✓ The simplest solutions with an axial electric field is the TM_{01} mode, which has radial and longitudinal electric field and azimuthal magnetic field components.



$$E_r = j\frac{k_z}{k_c}E_0 J_1(k_c r)e^{-jk_z z}e^{j\omega t}$$

$$E_z = E_0 J_0(k_c r)e^{-jk_z Z}e^{j\omega t}$$

TM_{01} *in cylindrical coordinates*

$$H_\varphi = j\frac{k}{Z_0 k_c}E_0 J_1(k_c r)e^{-jk_z z}e^{j\omega t}$$

$k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$ *wave number*

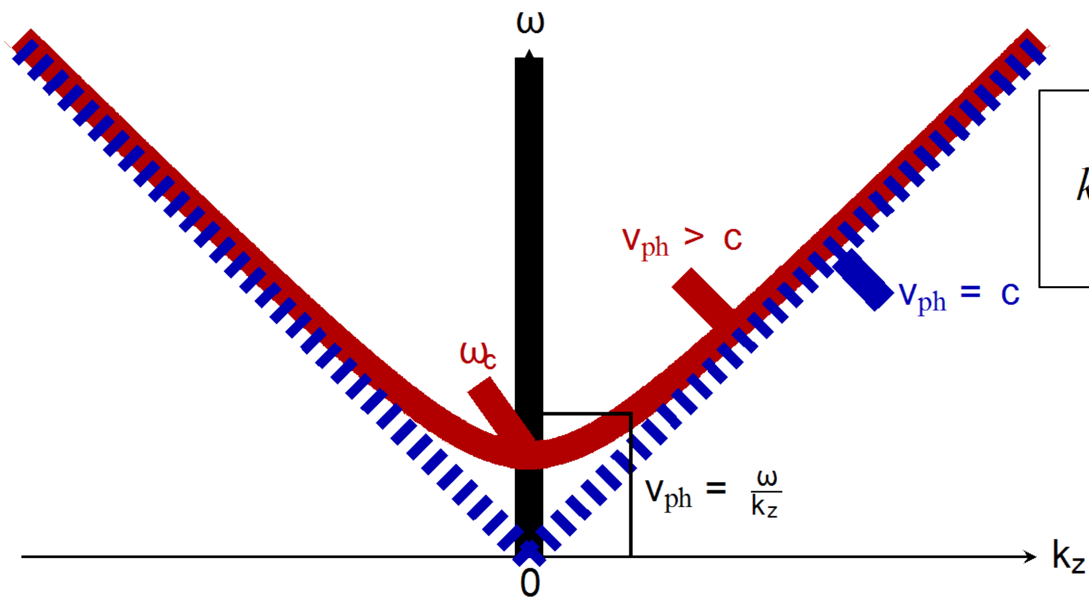
$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\Omega$ *free-space impedance*

$\lambda_c \approx 2.61a$ *cut-off wavelength (TM_{01})*

$k_c = \frac{2\pi}{\lambda_c} = \frac{\omega}{c}$ *cut-off wave number*

$k_z^2 = k^2 - k_c^2$ *propagation constant*

CYLINDRICAL WAVEGUIDE



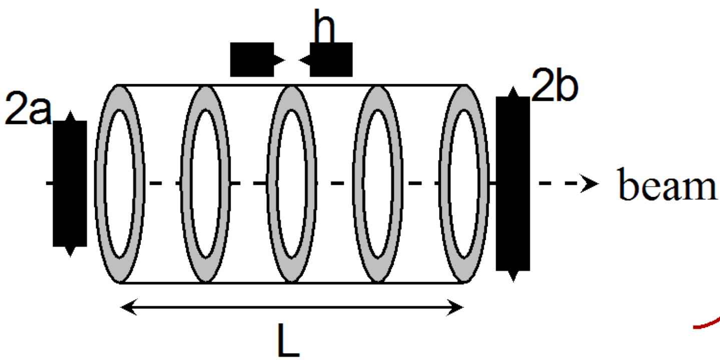
$$k_z^2 = \frac{\omega^2}{v_{ph}^2} = \frac{\omega^2}{c^2} - \frac{\omega_c^2}{c^2}$$ *dispersion relation*

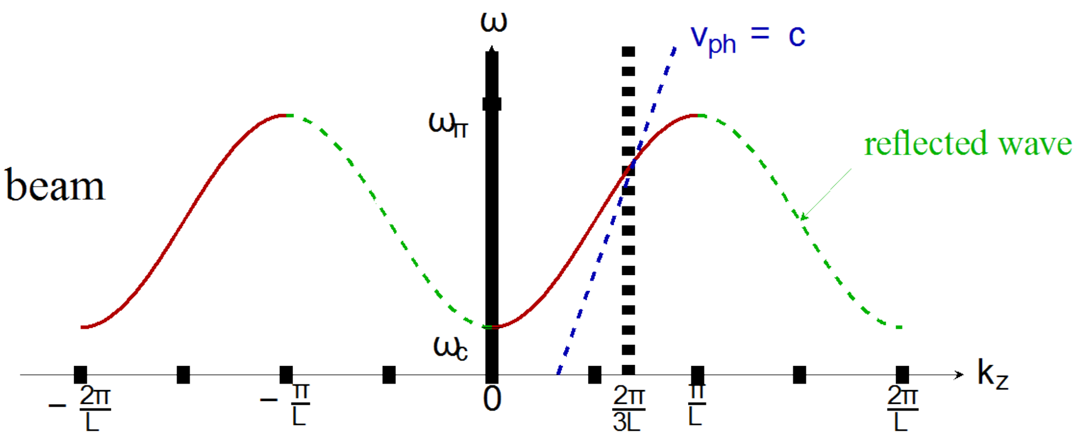
$$v_{ph} = \frac{\omega}{k_z}$$ *phase velcity*

Brillouin diagram for cylindrical waveguide

- ✓ Each frequency correspond to a certain phase velocity
- ✓ Propagation in a waveguide is always possible above the cut-off frequency
- ✓ The phase velocity is always higher than the speed of light
- ✓ It is impossible to accelerate particle in a cylindrical waveguide because synchronism between particle and RF is impossible
- ✓ NB. Information and energy travels at the group velocity $v_g = d\omega/dk_z$ and is always lower than c

TRAVELLING WAVE STRUCTURE



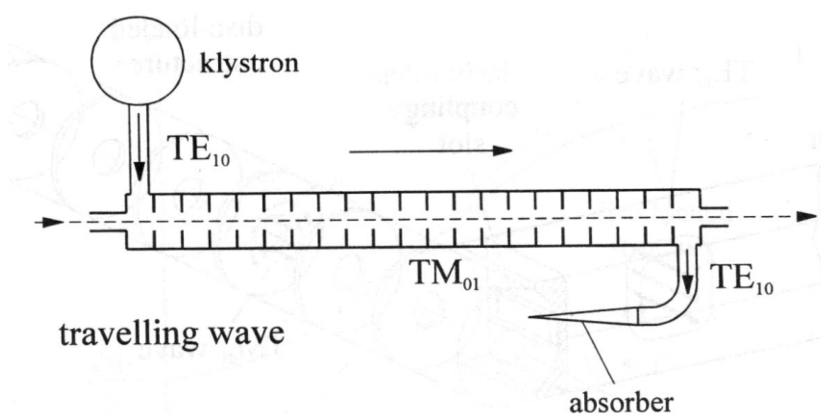


$$\omega = \frac{2.405c}{b}\sqrt{1+\kappa(1-\cos(k_z L)e^{-\alpha h})}$$ *dispersion relation for disc-loaded travelling wave structure*

$$\kappa = \frac{4a^3}{3\pi J_1^2(2.405)b^2 L} \langle\langle 1$$

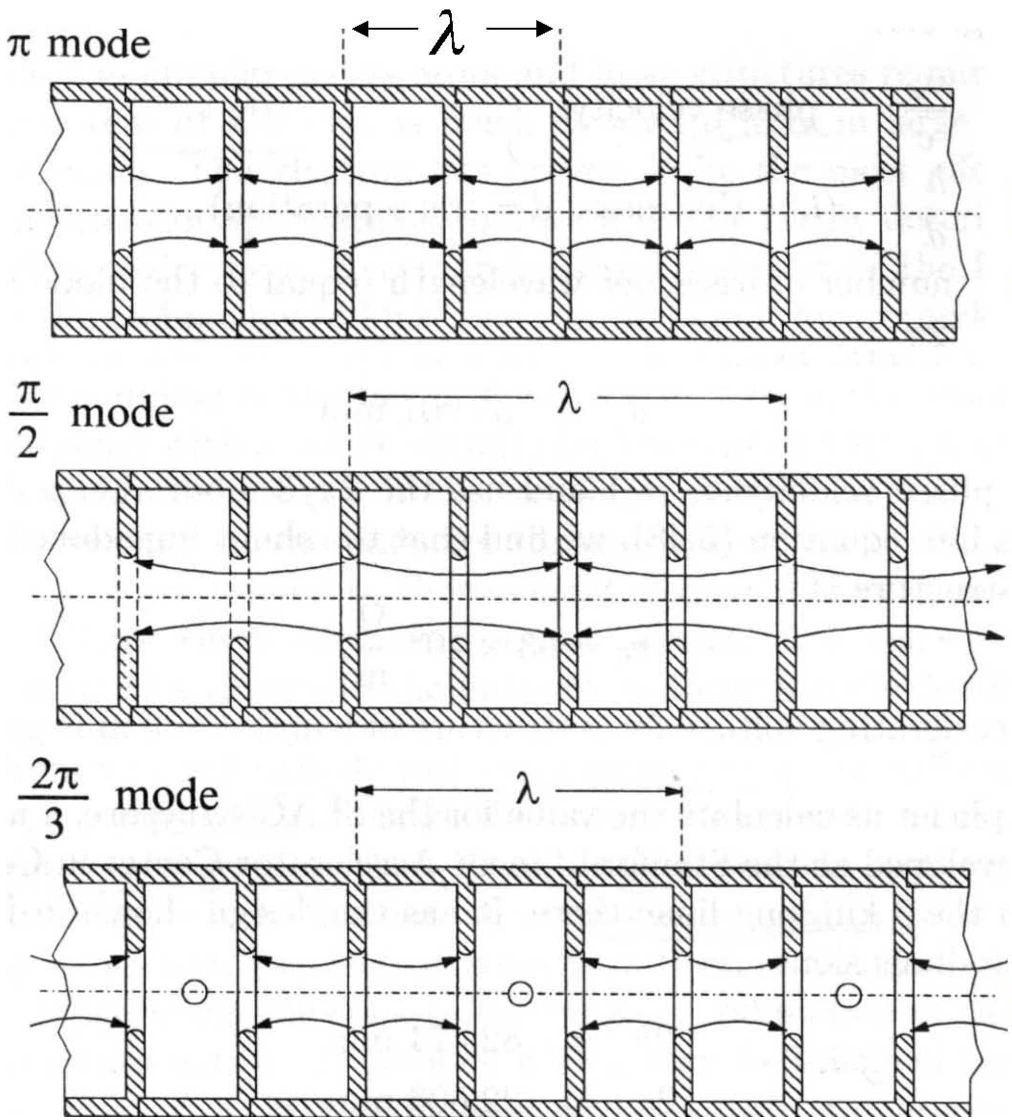
$$\alpha \approx \frac{2.405}{a}$$

✓ **Modes with phase velocity below c exist**



OPERATION MODES

✓ Operation mode is defined as the phase difference between adjacent cells



Long initial settling or filling time, not good for pulsed operation.

Small shunt impedance per length.

Common compromise.

From G. Hoffstattetter, USPAS 2010,

BASIC PARAMETERS

Shunt impedance per unit length

- ✓ It is a measure of the excellence of the structure
- ✓ It depends only on the structure itself (configuration ,dimension, etc.)
- ✓ It is usually expressed in $M\Omega m^{-1}$

$$Z_s = \frac{E_a^2}{-dP/dz}$$

E_a is the axial electric field component

dP/dz is the RF power dissipated on the cavity walls per unit length

- ✓ *Note: one can demonstrate that the shunt impedance is proportional to the square root of the frequency, so higher frequencies are more efficient for acceleration. Also breakdown problems are diminished at higher frequency (kilpatrickck limit).*
- ✓ *However since at high frequency structures are smaller, they might not have sufficient aperture for intense particle beams.*

BASIC PARAMETERS

Quality factor

$$Q = \omega \frac{W}{-dP/dz}$$

ω *is the angular frequency and* W *is the stored energy per unit length*

Ratio Z_s/Q

This ratio depends only on the structure geometry and not on the quality of the surface walls.

$$\frac{Z_s}{Q} = \frac{E_a^2}{\omega W}$$

BASIC PARAMETERS

Group velocity

$$v_g = \frac{P}{W}$$

where P is the power flowing in the structure

- ✓ An effective way to control the group velocity is to adjust the inner radius of the disk along the section.

Attenuation constant

- ✓ Defines the ratio of output power to input power

$$\tau_0 = \int_0^l \alpha(z)dz$$

τ_0 *is the annuation constant*

$\alpha(z)$ *is the attnuation per unit length of the strucures*

CONSTANT IMPEDANCE STRUCTURES

- ✓ Iris diameter remains fixed.
- ✓ The fields decay exponentially with the attenuation constant. The overall attenuation constant is $\tau=\alpha L$
- ✓ The energy gain for a particle accelerated at an angle θ from the peak is:

$$V = \int_0^L E_a(z)dz = E_0 L \cos\theta \frac{1-e^{-\tau}}{\tau}$$

for on crest acceleration:

$$V = \frac{1-e^{-\tau}}{\sqrt{\tau}}\sqrt{2Z_s PL}$$

- ✓ The function has a broad maximum for τ_0=1.26.
- ✓ This parameter can be controlled by the group velocity (the larger v_g, the smaller τ). However due to other design requirements, such as the need to decrease the filling time (inversely proportional to v_g), typically a value around 0.8 is chosen, with only a small degradation in the energy gain compared to the maximum.

CONSTANT GRADIENT STRUCTURES

- To keep the accelerating voltage constant, the structure is made non uniform by varying the group velocity, i.e. the aperture along the accelerator.
- The condition for constant gradient is $dP/dz = const$
- Group velocity decreases linearly along the structures
- The energy gain for on crest particle is:

$$\Delta V = \sqrt{Z_s P_0 L (1 - e^{-2\tau})}$$

P_0 *is the power into the structure*

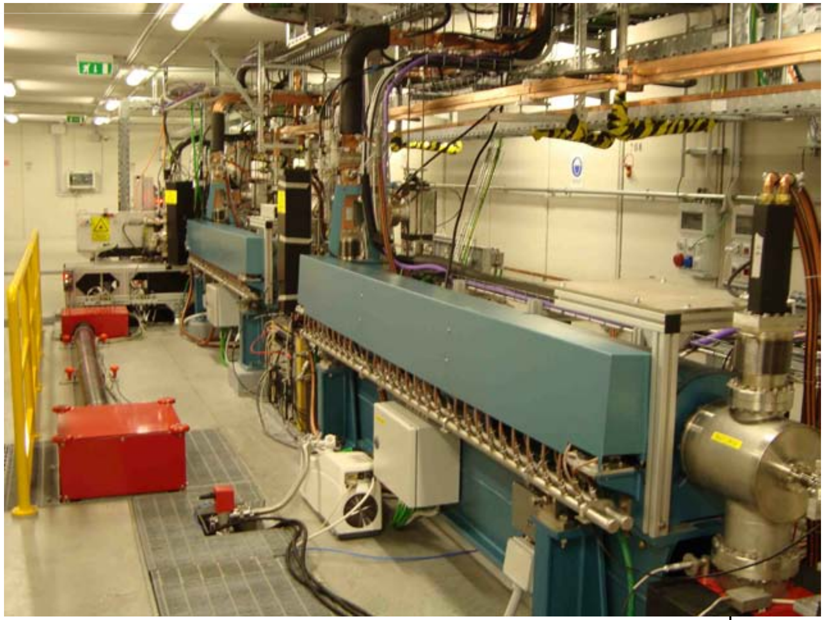
- The improvement in energy gain with non-identical cells is worthwhile for large particle accelerators.

EXAMPLES OF TW STRUCTURES

$$\frac{2\pi}{3}\text{mode}$$

Drawing from F. Gerick

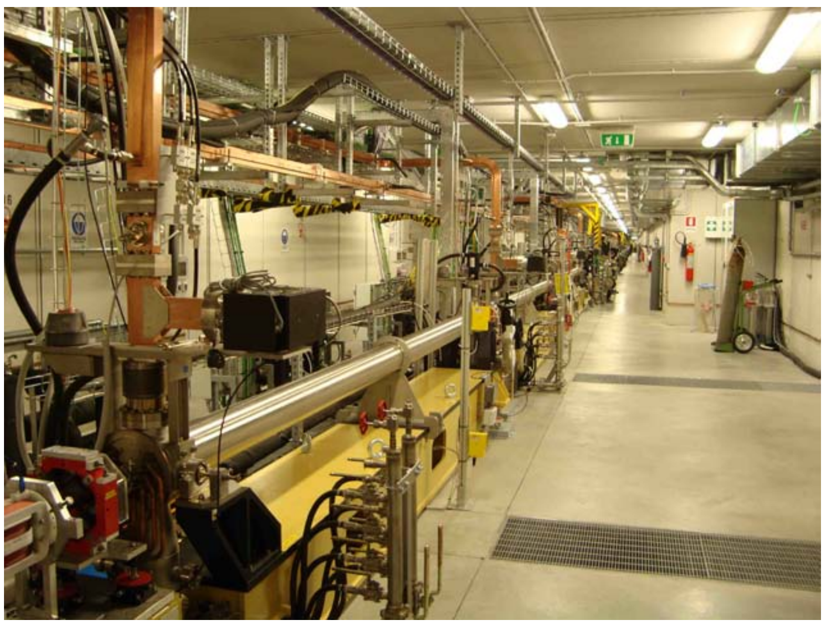
Mode	**2π/3 TW on axis coupled**
Type	Const. grad
Frequency	2998.010 MHz
Eff. length	3.166 m
Q	14000
Rs	67 MΩ/m
Filling time	0.903 µsec



S-band dB TW sections in the FERMI linac

EXAMPLES OF TW STRUCTURES

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



S-band LIL sections in the FERMI linac

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

S-band BTW sections in the FERMI linac

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STANDING WAVE STRUCTURES

STANDING WAVE STRUCTURES

- ✓ Standing wave operation can be considered as the superposition of forward and reflected travelling waves in a resonant structure.
- ✓ Electric fields build up in time.
- ✓ All input power is used for the acceleration process.
- ✓ Only one coupler. No termination load.
- ✓ Attenuation in the structure must be much less in the SW case to ensure the proper combination of the waves. Structures need to be designed to optimize the effective shunt impedance.
- ✓ Electric fields build up in time. In three filling times 95 % of the field is attained

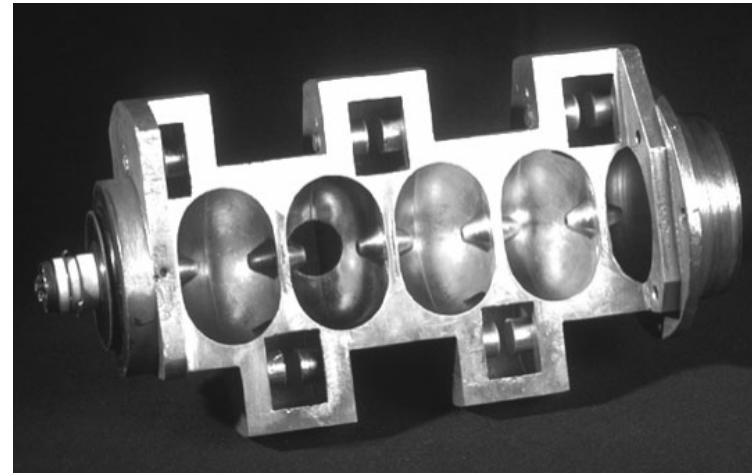
$$t_f = 2Q_L / \omega \quad t_f \text{ filling time}$$

STANDING WAVE STRUCTURES

- ✓ Standing wave wave structures are generally built at fixed coupling, i.e. they cannot be matched in all conditions.
- ✓ Standing wave are preferred if the pulse length is long or for CW machines.
- ✓ For high gradient in a short length with relatively low power and pulses of few ms, SW are an advantage because the one-way wall losses are low and the large number of reflected waves build up high level fields. This can be the case of electron medical linacs.
- ✓ A TW structure could be competitive in this case only if designed with low group velocity, high filling time and hence low iris diameters and so with potential difficulties in beam transmission and in dimensional tolerances.

ESXAMPLES OF STANDING WAVE STRUCTURES

TESLA 1.3 GHZ



Side coupled module for a 6 MeV linac

LEP superconducting 352 Mhz

BUILDING BLOCKS

BASIC ELEMENTS

- ✓ GUN
  - Electrons can be generated by a cold cathode, a hot cathode, a photocathode or an RF gun.
- ✓ Prebuncher and buncher. This is not needed in case of RF gun.
- ✓ One or more accelerating structures.
- ✓ One or more RF sources to power the structures. Typically these are klystrons (or magnetrons in case of low power machines).
- ✓ Waveguides systems for transport the RF power.
- ✓ If necessary for high stability requirements an advanced LLRF system.
- ✓ Magnets for beam orbit control.
- ✓ Diagnostic elements to measure the beam parameters.
- ✓ Vacuum system.
- ✓ Control system.

FERMI LINAC

ELETTRA LABORATORY

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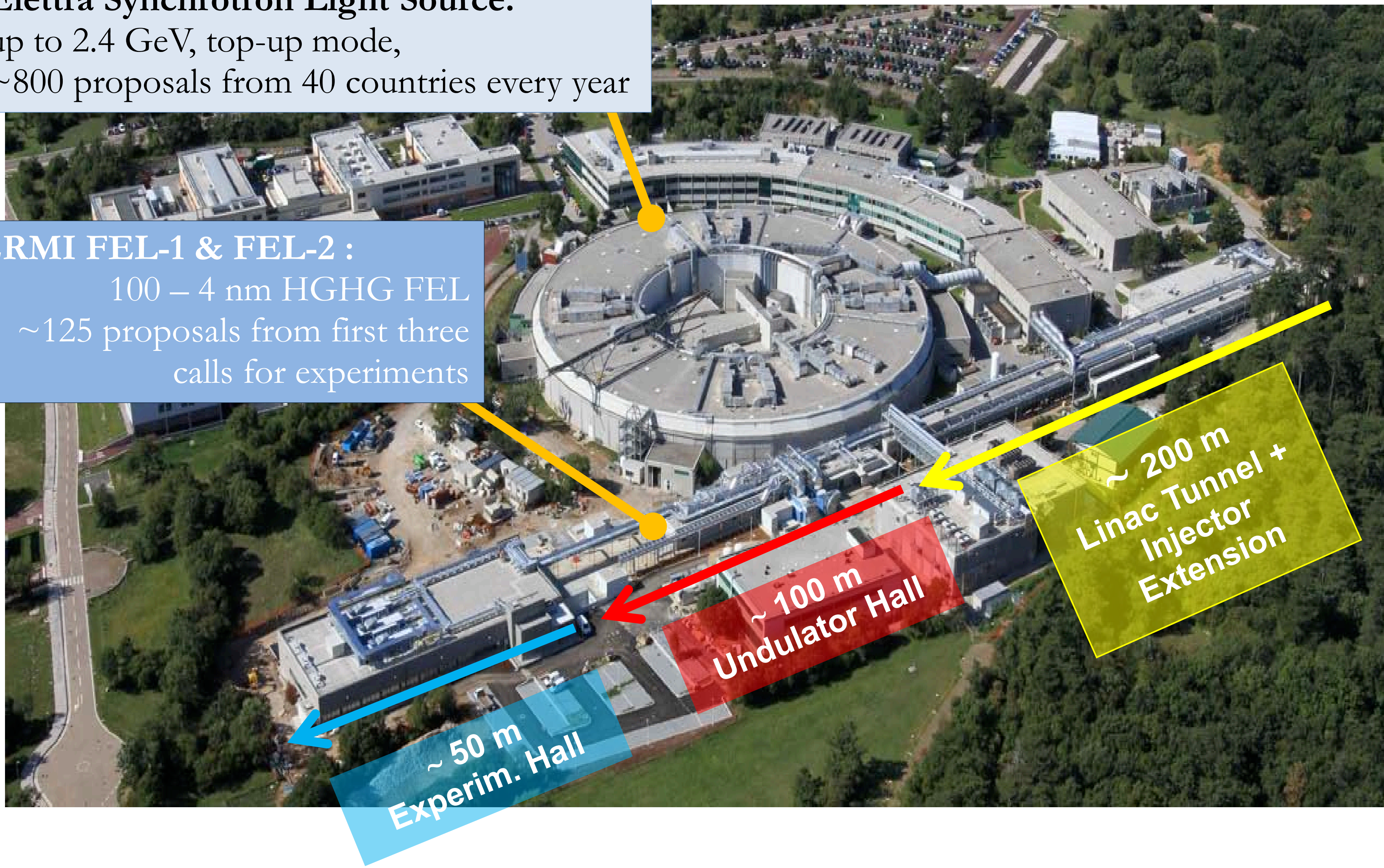
Elettra Synchrotron Light Source:
up to 2.4 GeV, top-up mode,
~800 proposals from 40 countries every year

FERMI FEL-1 & FEL-2 :
100 – 4 nm HGHG FEL
~125 proposals from first three calls for experiments



FERMI OVERVIEW

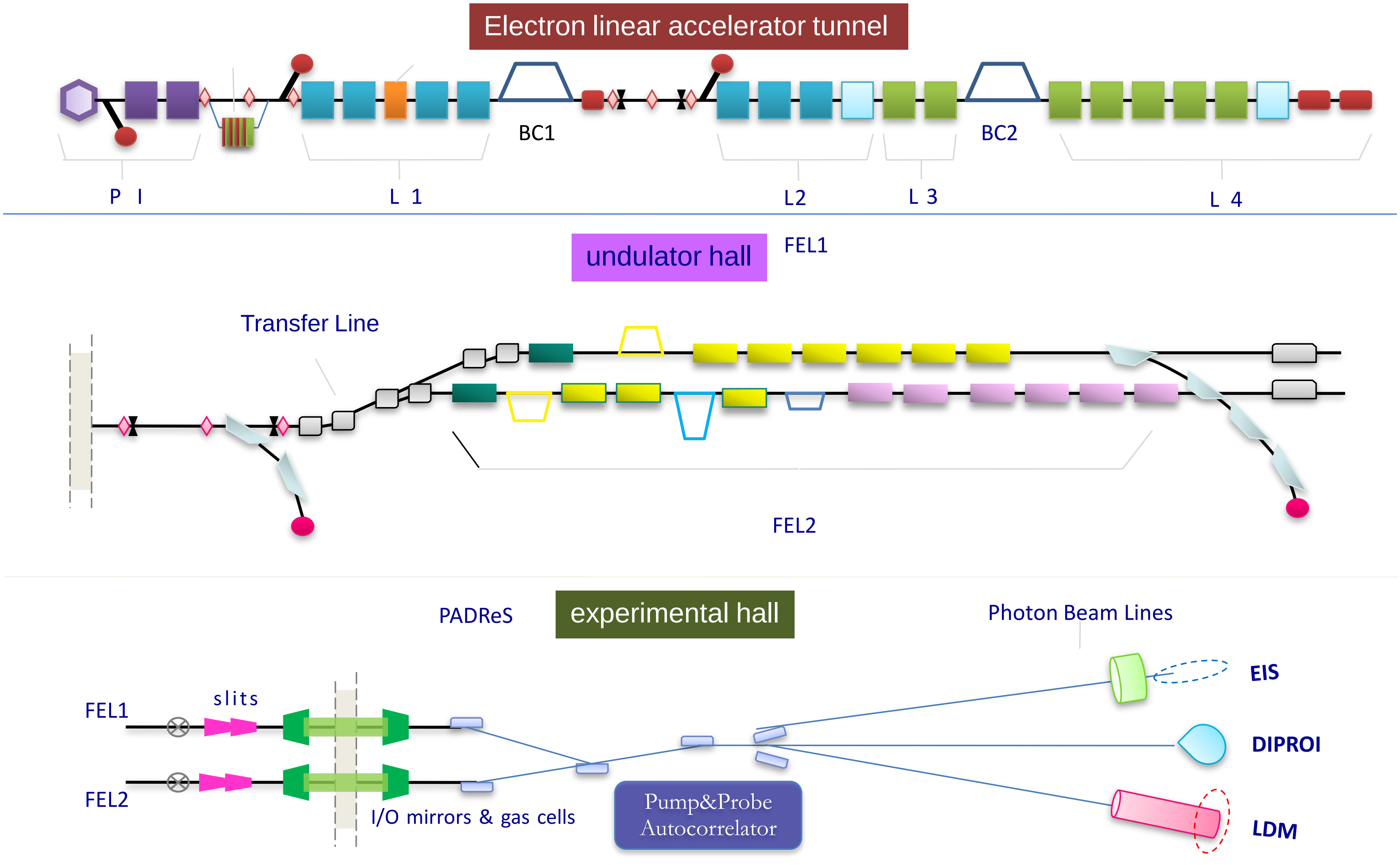
Courtesy of the FERMI Commissioning Team

- FERMI: 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 ; $\varepsilon n \sim 1$ mm mrad ; Energy= 1.2-1.5 GeV

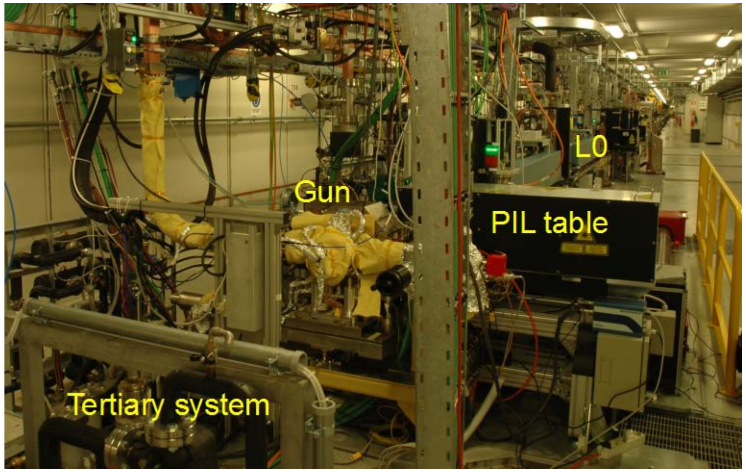
- FEL-1: single stage cascaded FEL, full specifications achieved in 2012, now dedicated to user experiments
- FEL-2: double stage, fresh bunch, cascade FEL, in commissioning, will open to external users in the next months.

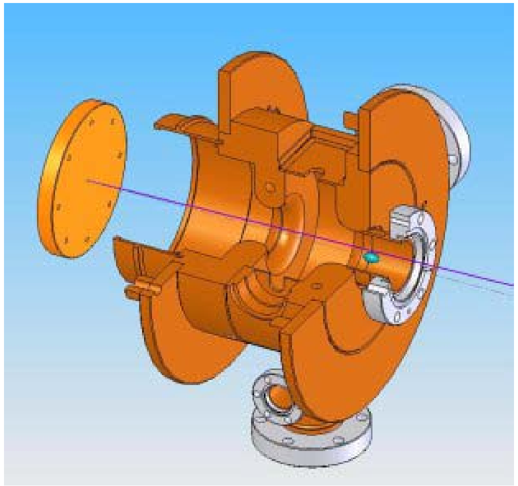
FERMI LAYOUT



FERMI COMPONENTS

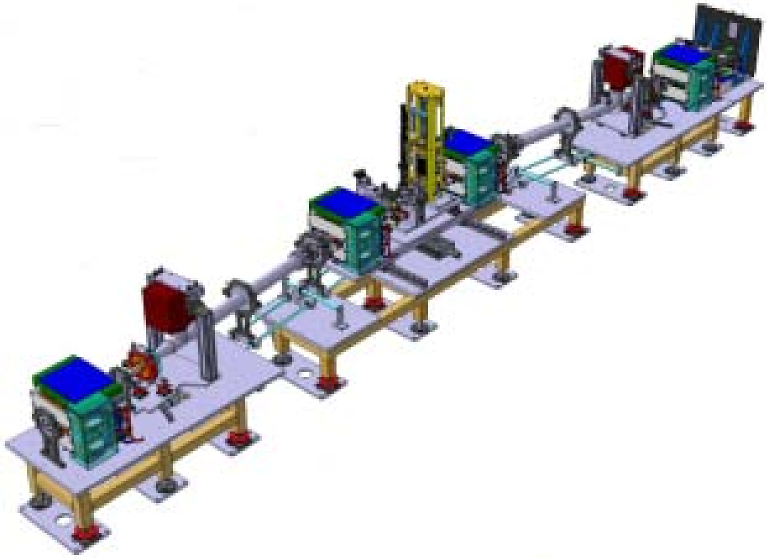
Photocathode Gun (courtesy M. Trovo')



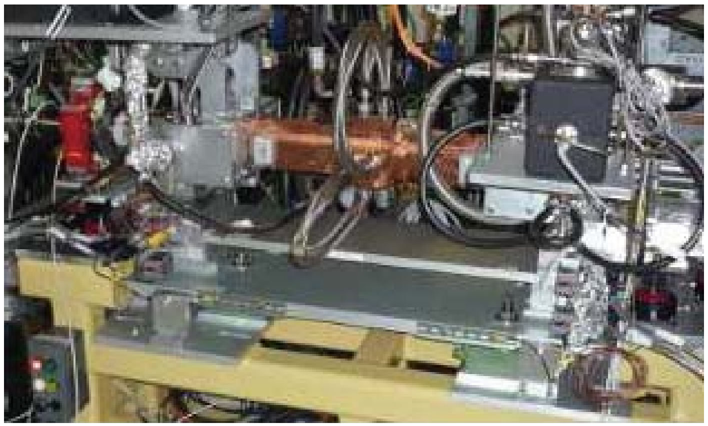


1.6 cell electron gun
BNL/SLAC/UCLA design
Built by Radiabeam Technologies
Single feed
50 Hz repetition rate
5 MeV

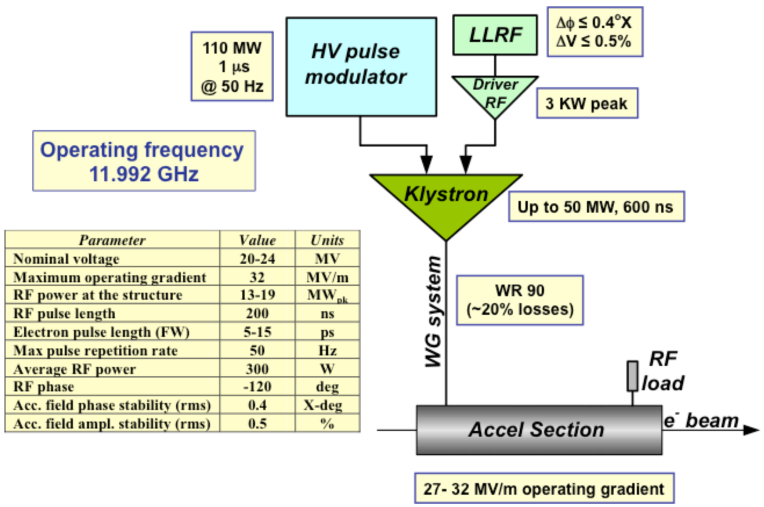
Magnetic compressor (courtesy S. Di Mitri)



FERMI COMPONENTS

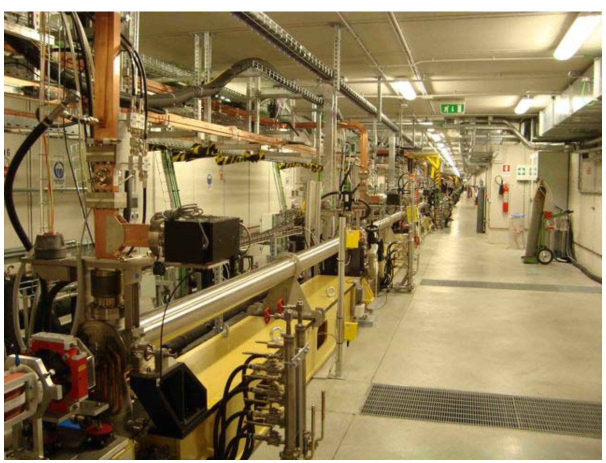


Linac X-band (courtesy of G. D'Auria)



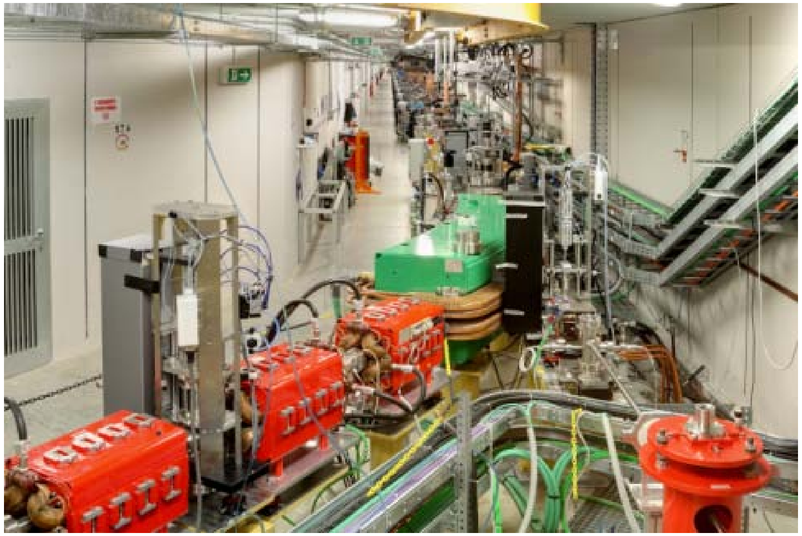
Parameter	*Value*	*Units*
Nominal voltage	20-24	MV
Maximum operating gradient	32	MV/m
RF power at the structure	13-19	MW_{pk}
RF pulse length	200	ns
Electron pulse length (FW)	5-15	ps
Max pulse repetition rate	50	Hz
Average RF power	300	W
RF phase	-120	deg
Acc. field phase stability (rms)	0.4	X-deg
Acc. field ampl. stability (rms)	0.5	%

Linac Low Energy

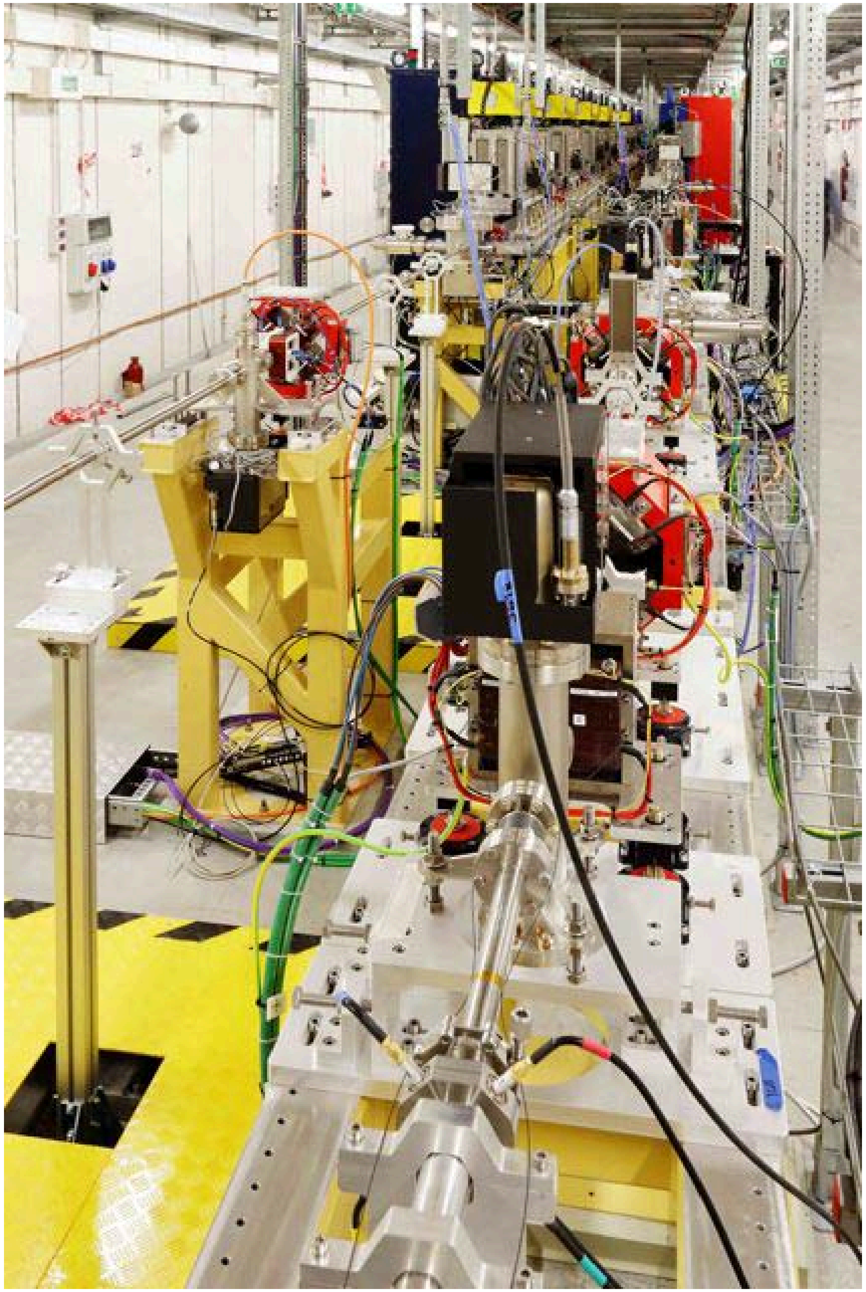


Linac High Energy

FERMI COMPONENTS



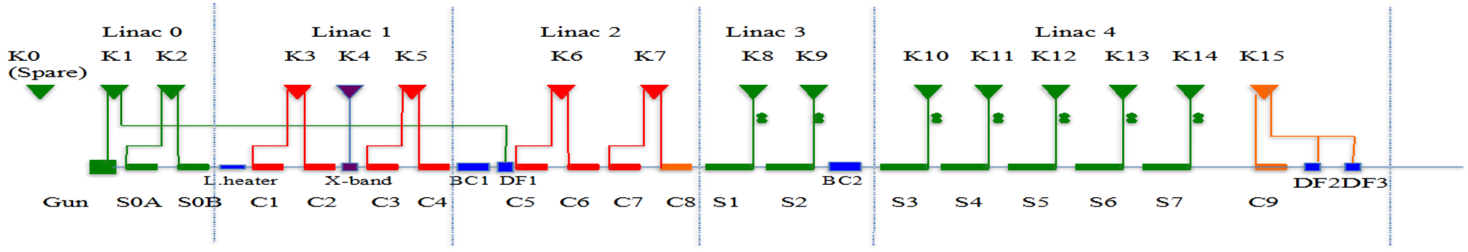
Linac End



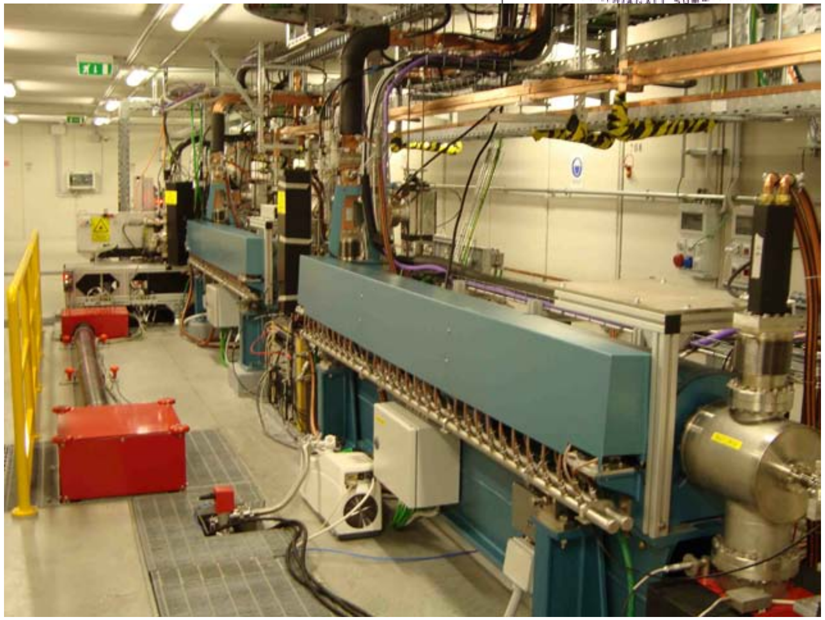
Undulator hall

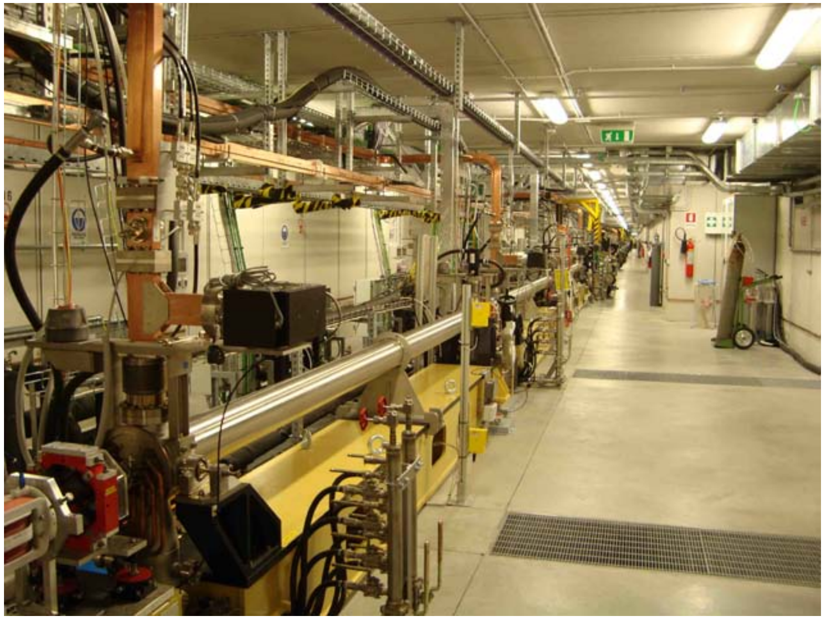
FERMI S BAND RF

- **15 S-band power plants** in operation (including the spare for the two plants of the injector linac).
- **16 accelerating structures.**
- Power plants also feed the gun, the LERFD and the two HERFD.
- **15 LLRF controllers.**



FERMI ACCELERATING STRUCTURES





Sixteen accelerating structures in operation:

- Linac0: two TW from old Elettra injector
- Linac1 and Linac 2: seven TW from CERN
- Linac 3 and 4: seven BTW from old Elettra injector, equipped with SLED

Two more accelerating will be installed. Tender in course

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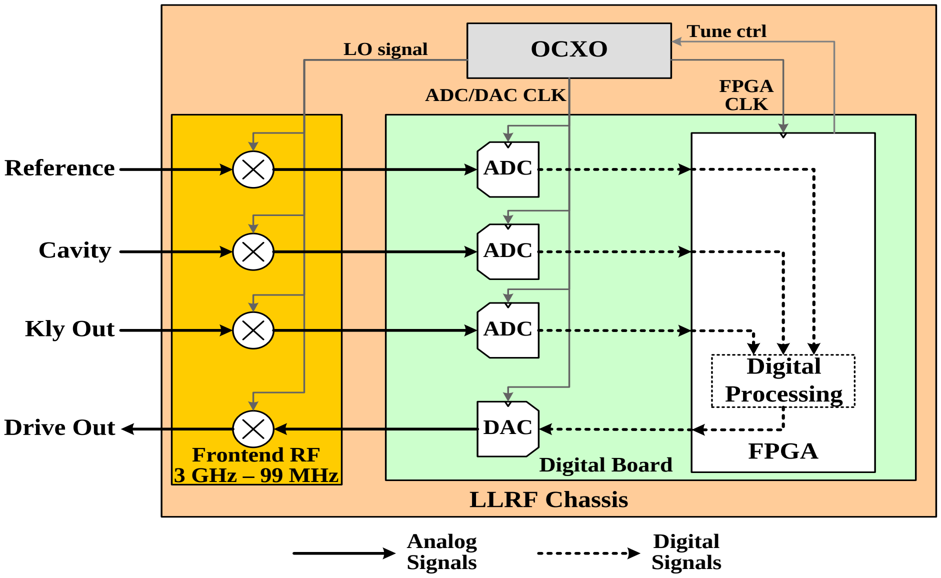
POWER PLANTS

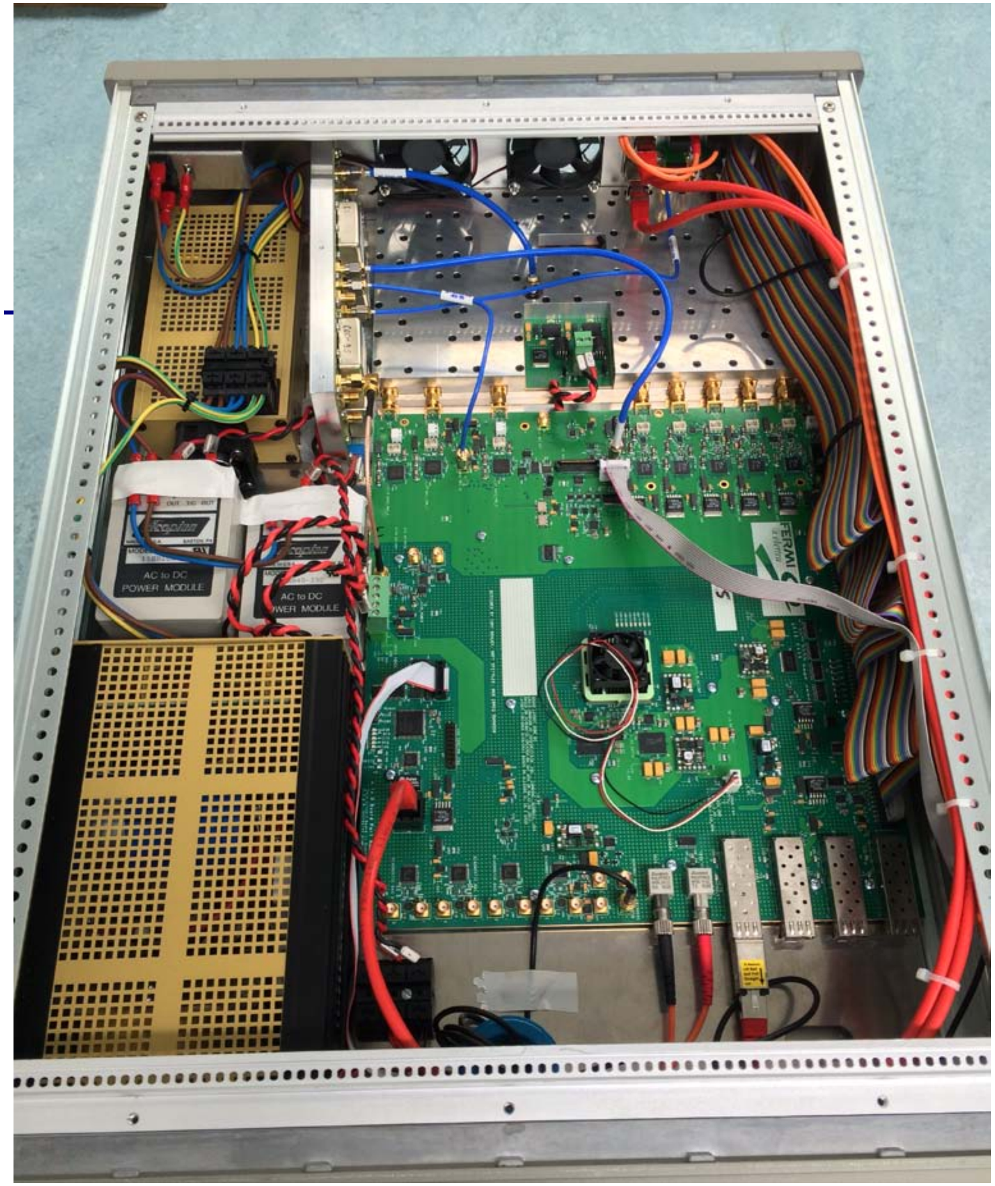
PFN Modulators – typical parameters	
Maximum output voltage	320 kV
Maximum delivered current	350 A
Repetition frequency	10-50 Hz
RF pulse width	4.5 μsec
Risetime / falltime	< 2 μsec
Pulse flatness	< ± 1%

- **pfn modulators designed by Elettra and assembled by local companies.**
- Operating hours/year: 6400
- 45 MW klystron (TH2132A from Thales)
- Klystron peak power level is in the range 32-34 MW, with the exception of K1 and K15.
- Typical statistical lifetime: 32000 hours (but we have operating tubes which reached 64000)

LLRF

- 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.





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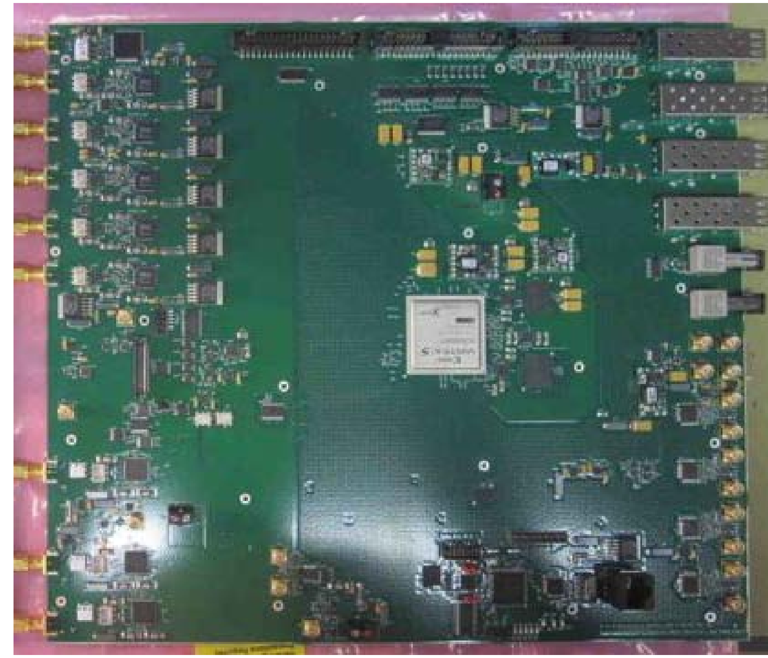
LLRF

- AD board
  - 5 ADC input 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.



Amplitude stability with FERMI LLRF (0.030%)

Phase stability with FERMI LLRF (0.046 deg@3GHz)

Amplitude stability with FERMI LLRF (0.030%)

Phase stability with FERMI LLRF (0.046 deg@3GHz)

- **All basic loops needed have been implemented :**
  - Loops: amplitude, phase, cable calibration and phase locking loop.
  - SLED: phase reversal and phase modulation.
- Future firmware
  - intra-pulse feedback,
  - real time communications between LLRF units
  - Iterative learning studies

ELETTRA PRE-INJECTOR

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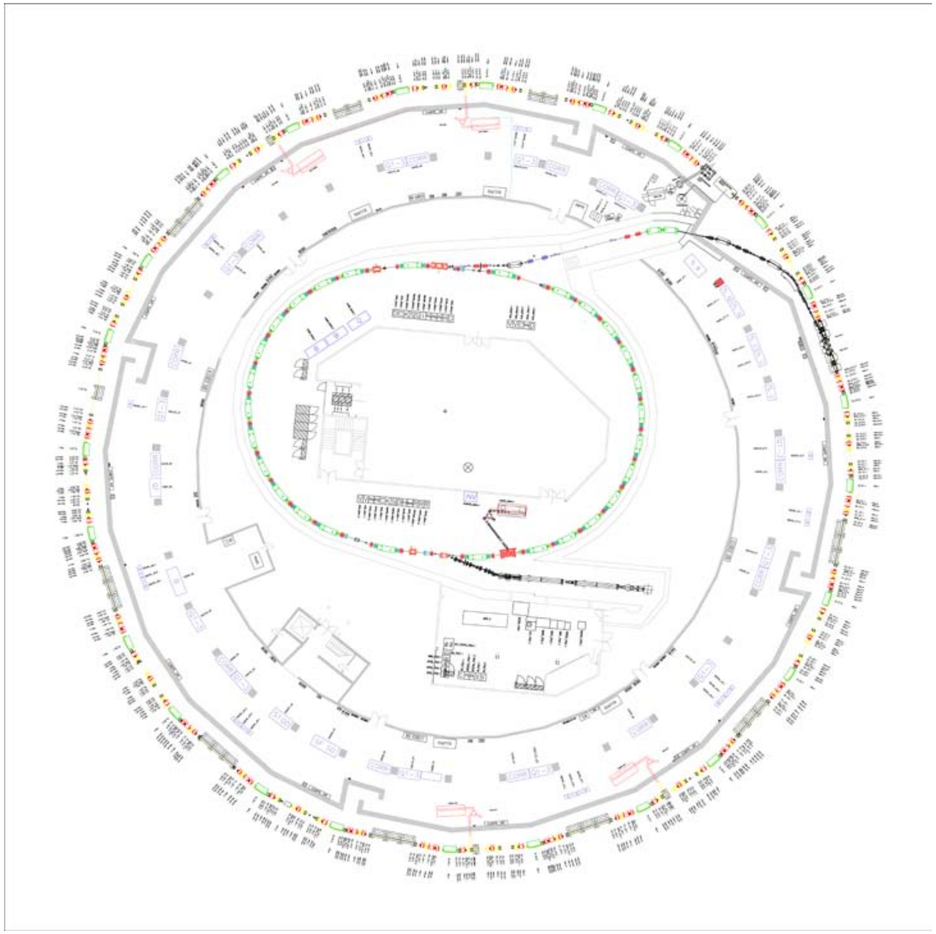
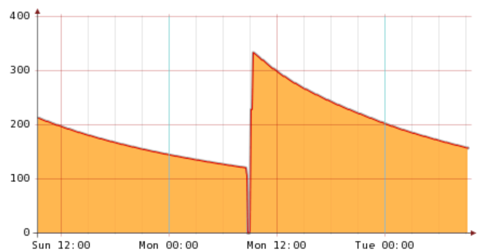
ELETTRA OVERVIEW



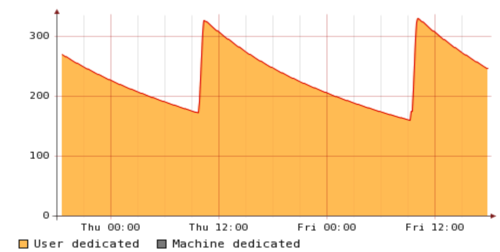
- Third generation light source.
- Commissioning started in October 1993 and the machine was open to users in 1994. It has been the first third generation light source for soft-X rays in Europe.
- Continuously upgraded over the years
- The machine complex now consists of:
  - 2.4 GeV third generation light source synchrotron (259.2 m circumference)
  - 2.5 GeV Booster
  - 100 MeV conventional linac
- 26 Beam lines.

ELETTRA UPGRADES

1994 - 2007 Ramping



Since 2008 full energy injection



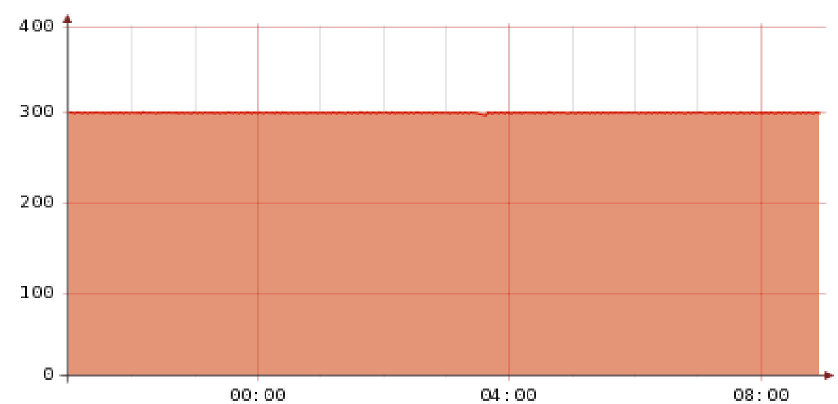
Decay mode, 2 GeV (340mA) and 2.4 GeV (140) – SRFEL at 1 GeV.

Since May 2010 Top-up

Top-up at 2 GeV (310 mA)

&

2.4 GeV (160 mA)



The only source operating at 2 different beam energies

ELETTRA PARAMETERS

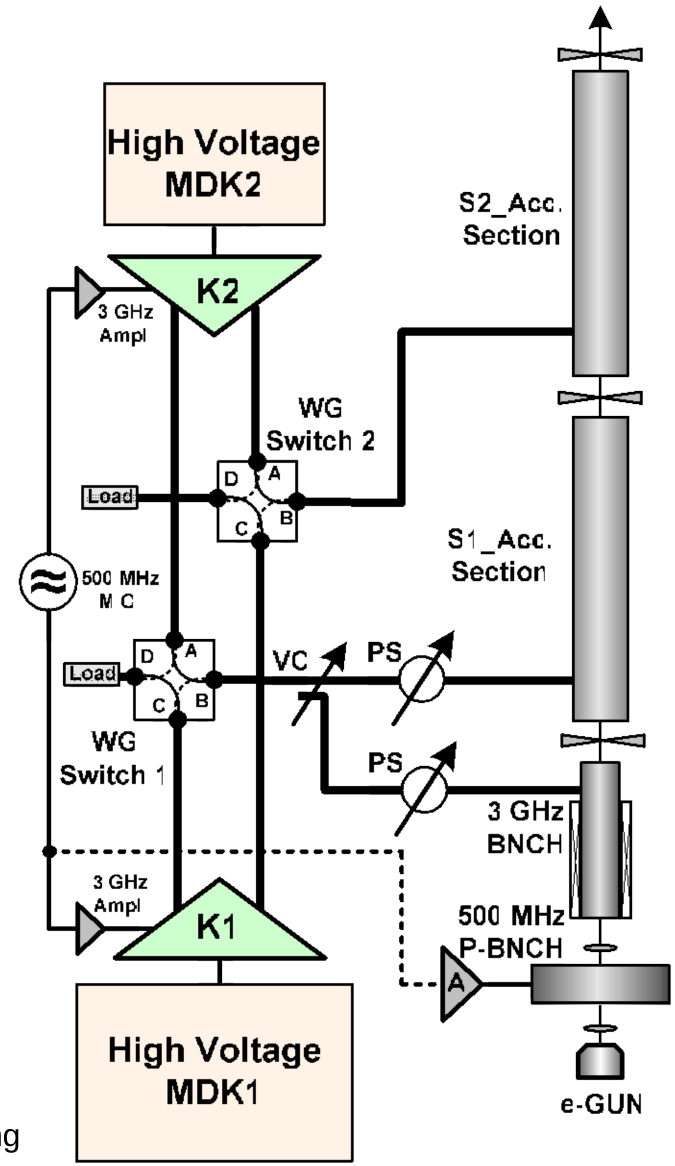
The machine typically operates around 6400 hours/year, more than 5000 hours are for users.

MAIN PARAMETERS	
Energy range	0.75- 2.5 GeV
Injection energy	All energies up to 2.5 GeV
User Operating Energy	2.0 GeV (75% of user time) 2.4 GeV (25% of user time) 1.0 GeV (SR-FEL)
Operating mode	Top-up
Operating current (user request)	300 mA at 2.0 GeV (lifetime 26 h) 160 mA at 2.4 GeV (lifetime 40 h)
Top-up injection rate	1 mA every 6 min at 2.0 GeV 1 mA every 20 min at 2.4 GeV
Filling pattern	Any (single, few, multi etc.); most requested multibunch filled at 95% of the ring circumference (864 ns) and hybrid (multibunch with a single bunch in the dark gap)
Bucket size (bunch to bunch distance in multi-bunch)	2 ns
Dark gap when fill at 95%	43 ns
Operating details	Long Lifetime - Instability Free (multi-bunch and orbit fast Feedbacks and super-conducting 3rd harmonic cavity operating) Id gap/current control to the users

PREINJECTOR OVERVIEW

100 MeV linac to provide electrons to the booster injector to the storage ring.

Table 1: Preinjector main beam parameters



Ref. G. D'Auria et al., Installation and Commissioning of the 100 MeV Preinjector of the new Elettra Injector, EPAC08

Elettra Sincrotrone Trieste

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COMPONENTS

Electron gun

- ✓ Grounded grid triode gun
- ✓ 1 cm^2 emitting surface
- ✓ 2 ns (SB) or 10-300 ns (MB) electron pulses
- ✓ Injection voltage 60 keV

✓ Bunching section

- ✓ 500 MHz sub-harmonic pre-buncher (pill box cavity TM_{010} mode)
- ✓ 3 GHZ standing wave buncher, partially embedded with an iron screen and horizontal coils
- ✓ Five magnetic lenses and two sets of horizontal and vertical steering coils

Ref. G. D'Auria et al., Installation and Commissioning of the 100 MeV Preinjector of the new Elettra Injector, EPAC08

COMPONENTS

Accelerating structures

- ✓ Two LIL type S-band accelerating sections
- ✓ 4.6 m long
- ✓ TW, Constant gradient, $2/3\pi$

LLRF

- ✓ 500 MHz master oscillator
- ✓ Solid state amplifiers with frequency multipliers
- ✓ No feedbacks

RF plant

- ✓ Two TH2132A klystrons, each one powered by a pfn type conventional type modulators
- ✓ Only one is needed in principle to power the linac
- ✓ The second one is a hot-spare system connected to dummy loads.
- ✓ The waveguide system allows to switch between one klystron to the other providing a quick backup in case of failures.

SUMMARY

- ✓ Electron linac are used in several projects.
- ✓ A good knowledge of beam physics is also involved, as well as expertise in different technological area such as:
  - ✓ Radiofrequency and microwaves
  - ✓ High voltage
  - ✓ High speed technologies
  - ✓ Vacuum
  - ✓ Mechanical engineering
  - ✓ ……………………….
- ✓ This lecture is just to give a taste of the many interesting aspects involved.
- ✓ Topics not covered include:
  - ✓ Beam dynamics
  - ✓ Accelerating structures design
  - ✓ Application of electron linacs in other contexts
  - ✓ ………………………………

Thank you!

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