Laboratory for UV and X-ray Optical Research

DEPARTMENT OF INFORMATION ENGINEERING
UNIVERSITY OF PADOVA

EUV-XUV Spectroscopic Technology and Instrumentation

P. Nicolosi

1st Int. Conf. on Frontiers in Diagnostic Technologies
Lab. Nazionali Frascati - 25 – 27 Nov 2009

Environmental physical conditions (plasma parameters, fields, particles…….) affect atomic and ion inner fields (i.e. energy levels: broadening, shifting, splitting, polarization………..)

Consequently

Emission of photons and particles carries the signature of the local plasma and fields parameters

Spectroscopic diagnostics can be a powerful tool to gain physical insight

Recently

the development of new sources FEL and Ultrashort Lasers has disclosed the field of new physics related to photon-matter interaction at ultra-short ultra-intense fields

Furthermore

the Space Exploration and the need to understand better how the Sun can affect the eliosphere and the life on our planet have stimulated the growth of new space programs within the "Living With a Star" international space program.

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OUTLINE OF PRESENTATION

I will present some EXAMPLES of spectroscopic technological solutions developed for

- FREE ELECTRON LASERS
- HIGH ORDER HARMONICS GENERATION
- SPACE EXPLORATION - SOLAR PHYSICS
- CONCLUSION

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EUV-VUV FREE ELECTRON LASER

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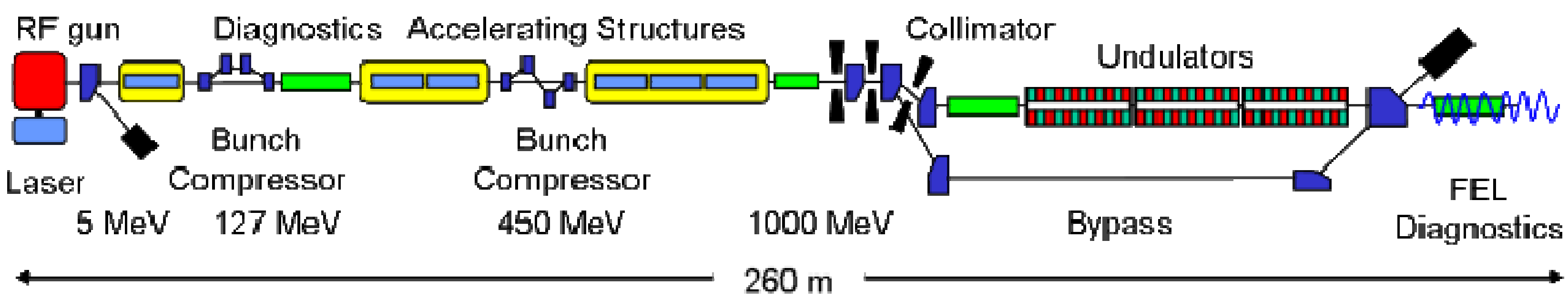
Many scientific disciplines ranging from **physics**, **chemistry** and **biology** to **material sciences**, **geophysics** and **medical diagnostics** need a powerful X-ray source with pulse lengths in the femtosecond range. This would allow, for example, time-resolved observation of chemical reactions with atomic resolution. Such radiation of extreme intensity, and tunable over a wide range of wavelengths, can be accomplished using high-gain free-electron lasers (FEL).



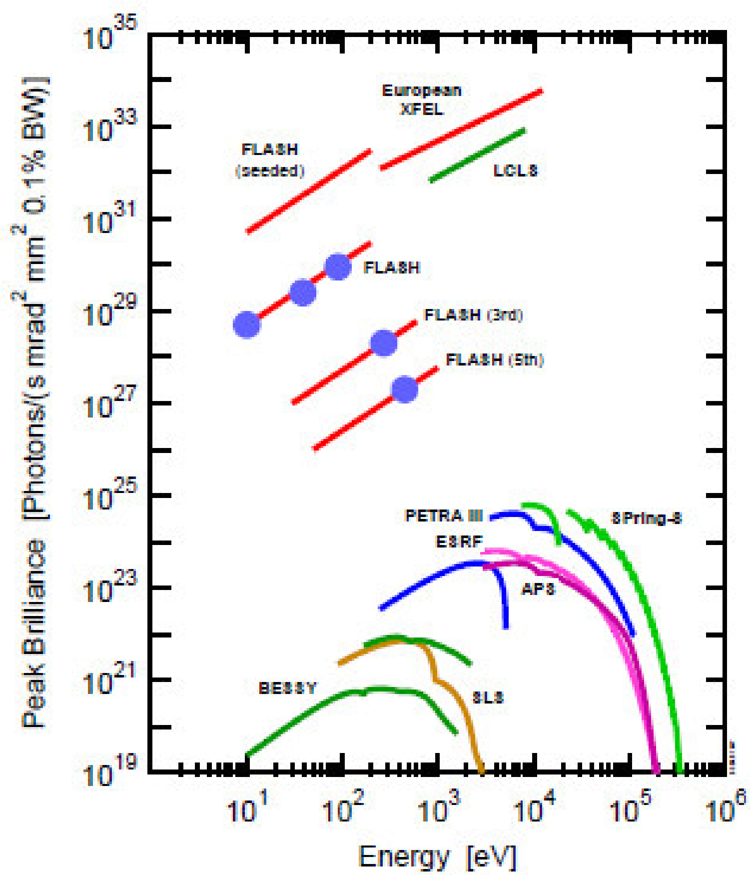
Layout of the **EUV FEL 'FLASH'** at DESY, Hamburg
Ayvazyan et al. 2006 *Eur. Phys. J. D* **37** 297

Peak brilliance of X-ray FEL's vs 3rd Generation SR sources. Blue spots experimental data FLASH (Ackermann W et al. 2007 *Nature Photonics* **1** 336)

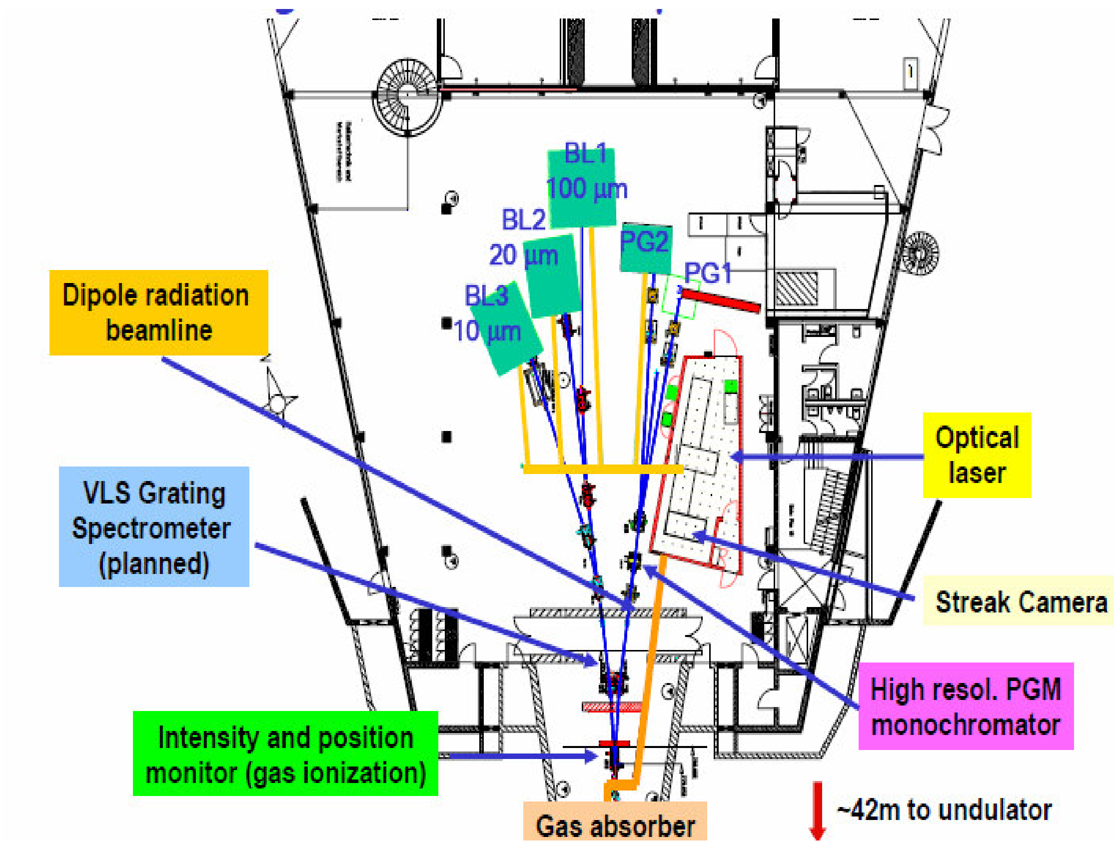
PEAK INTENSITY AT FOCUS
>10^{13} W/cm^2
HIGH PHOTON ENERGY

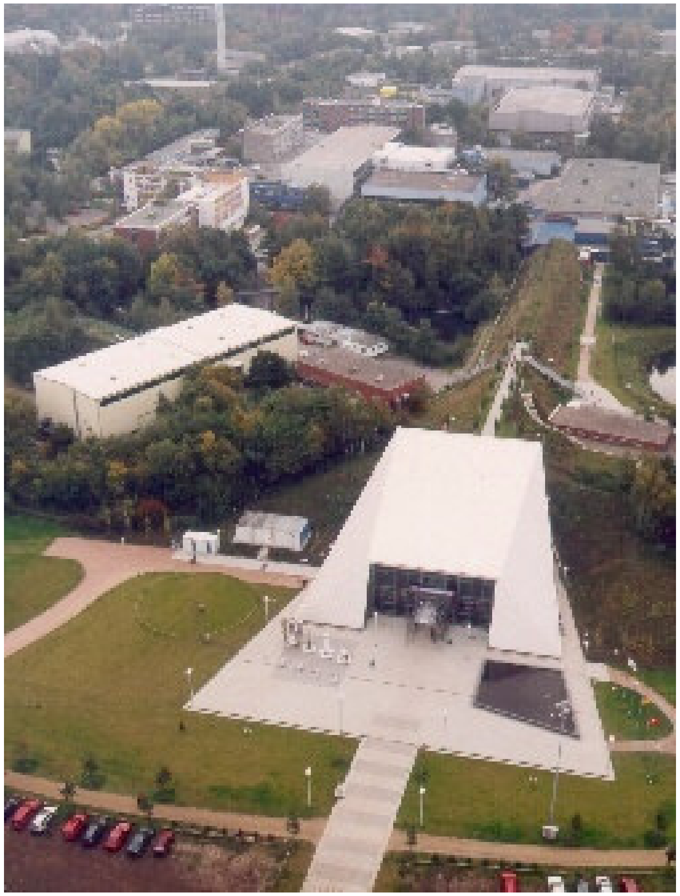
⇓

NON-LINEAR OPTICS AND SPECTROSCOPY



FLASH @ DESY HAMBURG





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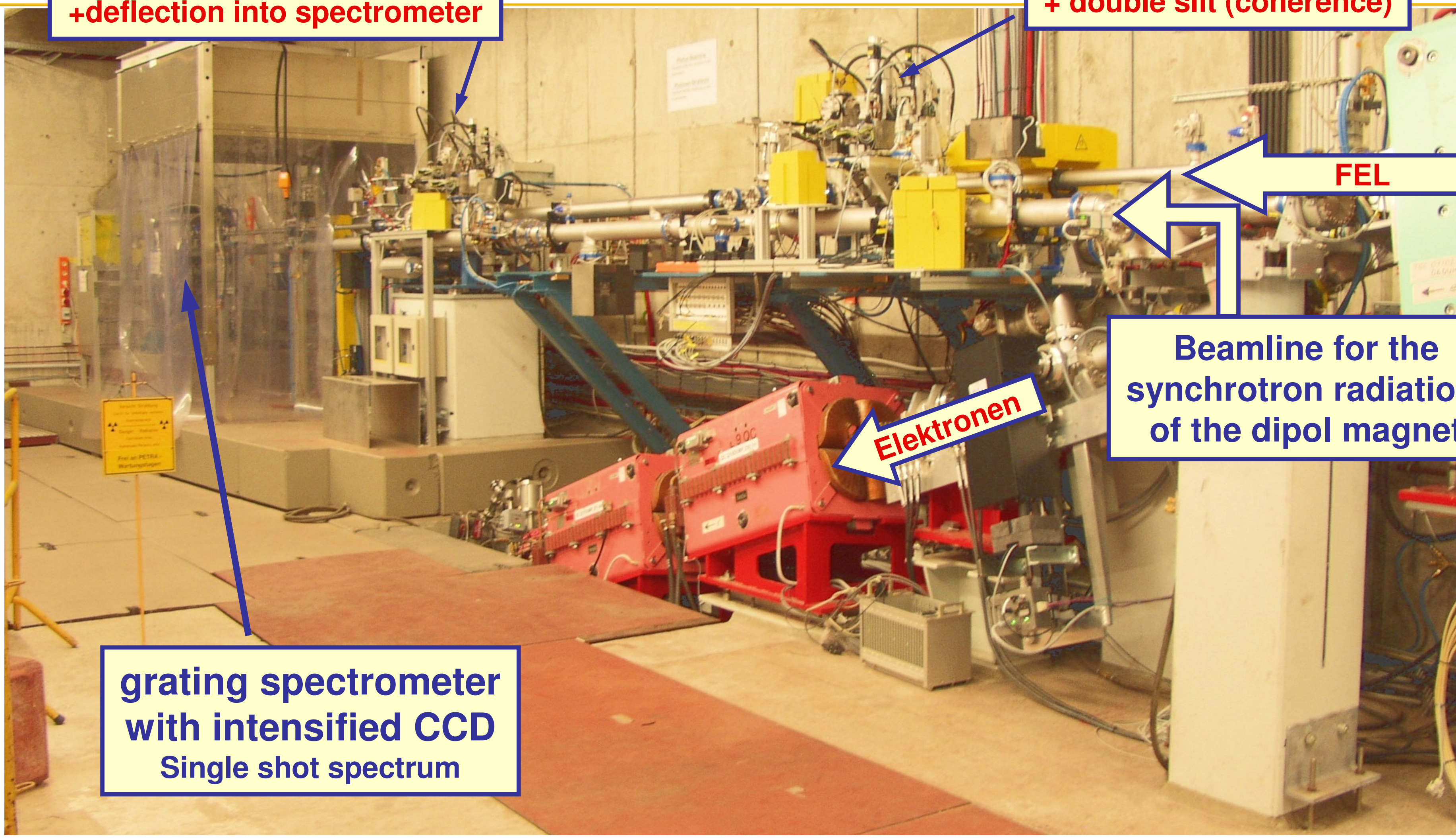
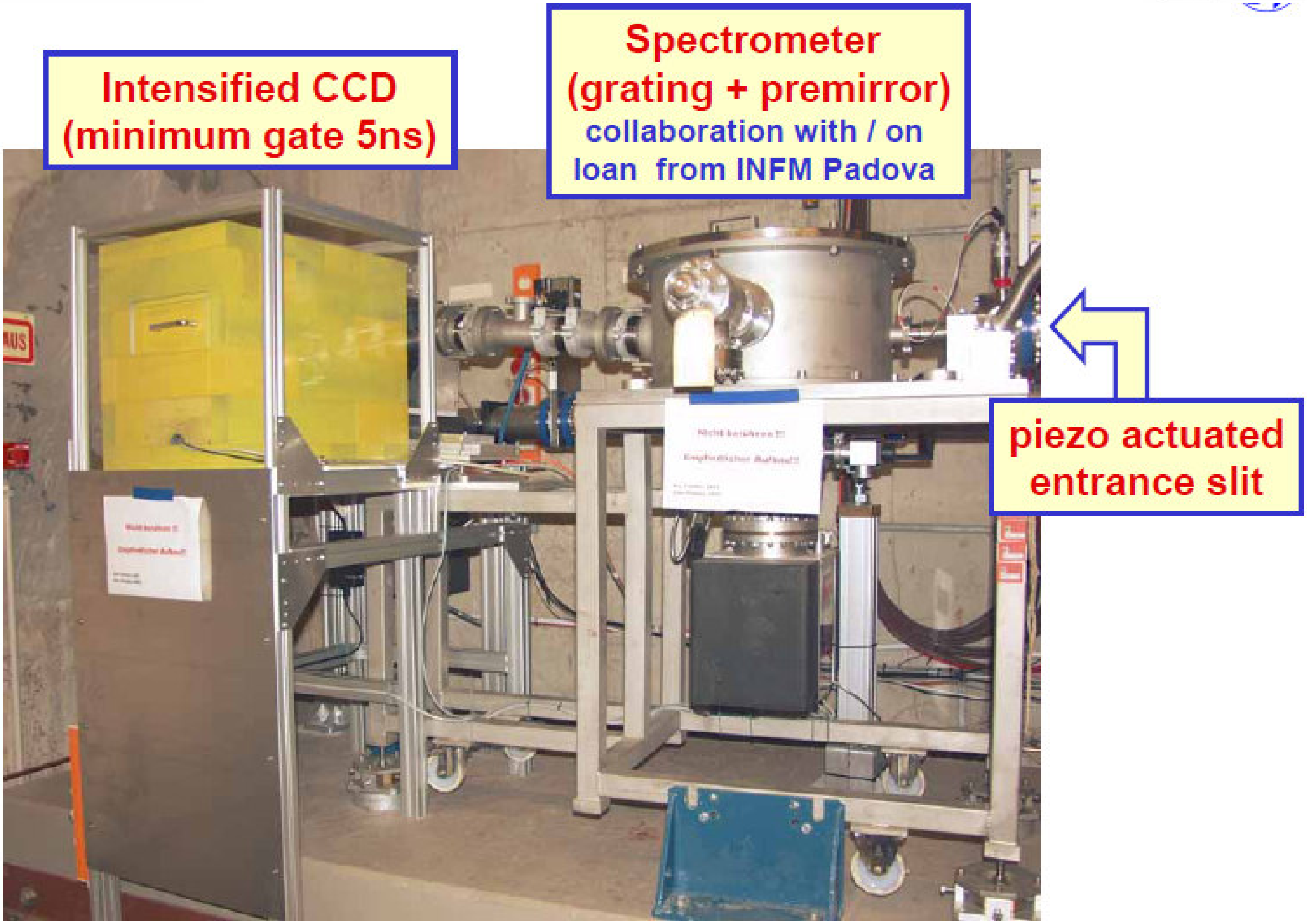
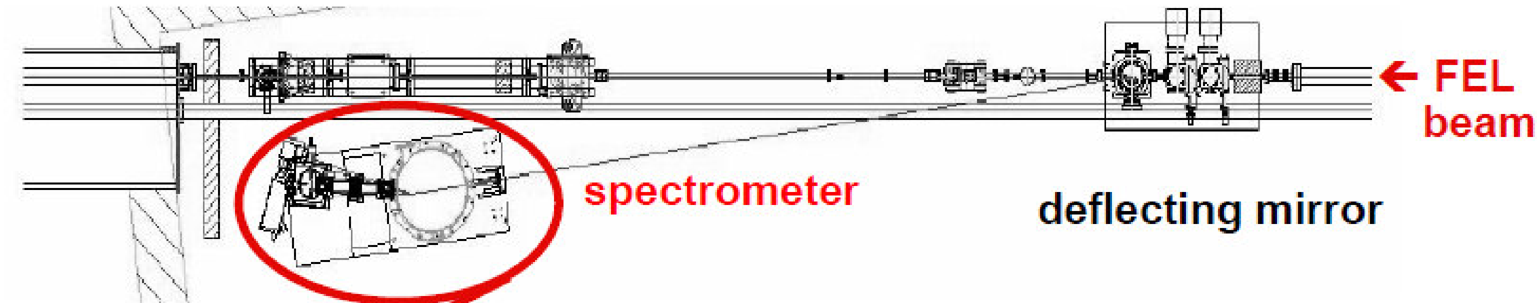
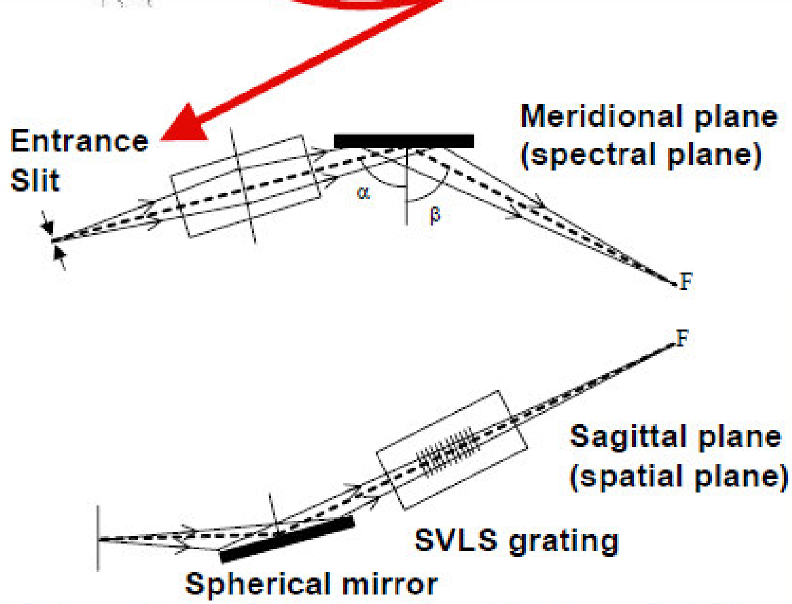


Laboratory for UV and X-ray Optical Research

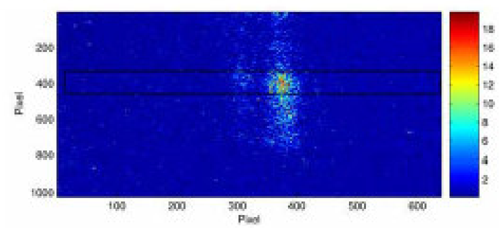


VUV spectrometer in the FEL tunnel





Collaboration with University of Padova (INFM)



- grazing-incidence spherical VLS (variable line spacing) grating + spherical mirror, resolution ~ 1500
- Ce:YAG screen at spectrometer exit plane converts VUV to visible light
- Intensified gated camera records single-shot spectra

VUV Spectrometer at FLASH

The dispersive element is SVLS grating – Grazing Incidence flat field spectrometer

Defocusing and Higher order aberrations are minimized by a proper choice of grating groove space variation

$$d(y) = d_0 + d_1 y + d_2 y^2 + d_3 y^3$$

d(y): local groove density

d_0: central groove density

d_1, d_2, d_3 : parameters for groove density variation

VUV Spectrometer at FLASH

The main aberration to be minimized in order to realize a high-resolution spectrometer is the defocusing in the plane of spectral dispersion.
The spectral focus equation, i.e. the equation of the surface where the spectral defocusing is zero, is expressed by:

$$\frac{\cos^2\alpha}{r}+\frac{\cos^2\beta}{r'}-\frac{\cos\alpha+\cos\beta}{R}+(\sin\alpha+\sin\beta)\frac{d_1}{d_0}=0$$

r , *r'* grating entrance and exit arm respectively, R grating radius,
α, β incidence and diffraction angle at wavelength λ,

$$\sin\alpha+\sin\beta=m\lambda d_0$$

R, d_1 are optimized once defined the others parameters

d_2, d_3 are used to minimize the coma and spherical aberration

VUV Spectrometer at FLASH

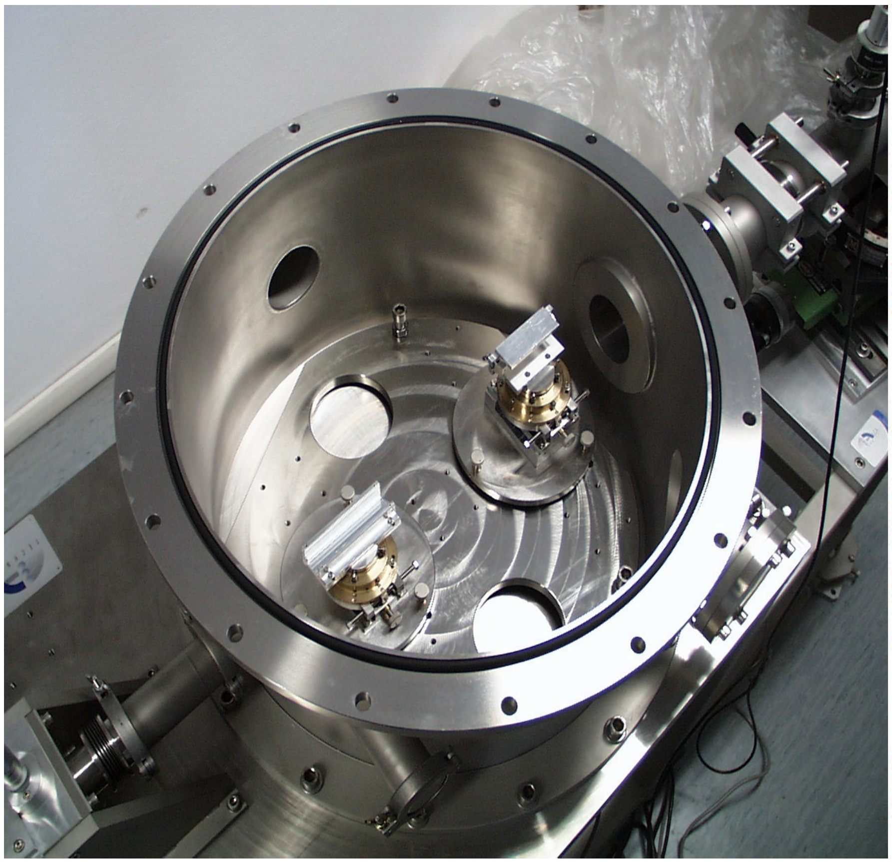
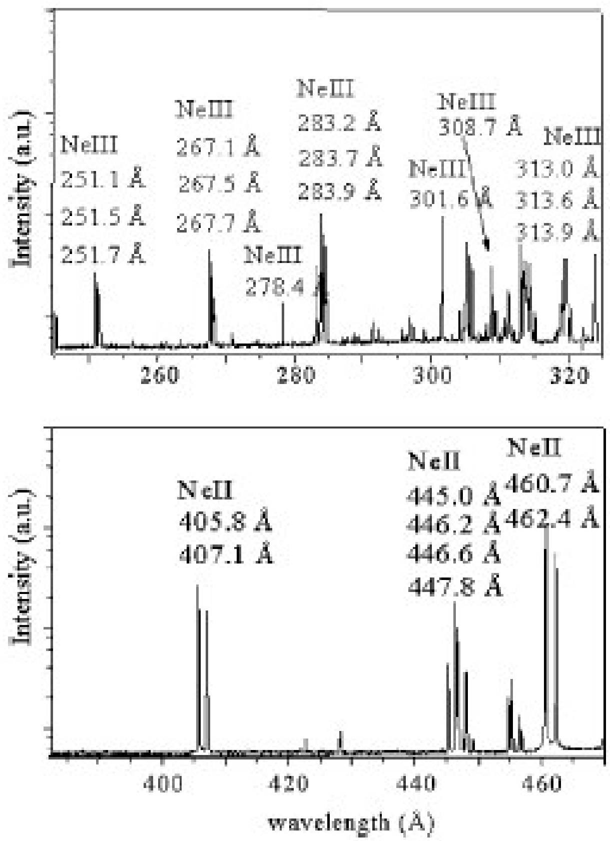


TABLE I. Instrumental parameters.

Spherical mirror	
Entrance arm	400 mm
Medium exit arm	1000 mm
Incidence angle	87.5°
Radius	13 000 mm
Size	100 mm × 10 mm
SVLS gratings	
Spectral range	50–450 Å
Entrance arm	650 mm
Medium exit arm	750 mm
Incidence angle	87°
Central groove density	1200 lines/mm
Ruling parameters	$d_1=-2.82$ lines/mm^2
	$d_2=5.44\cdot10^{-3}$ lines/mm^3
	$d_3=-1.15\cdot10^{-5}$ lines/mm^4
Radius	16 000 mm
Size	65 mm × 10 mm



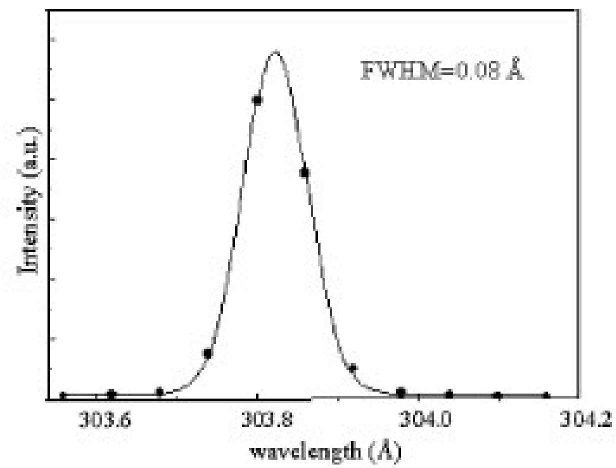


FIG. 7. HeII 303.8 Å spectral line and its Gaussian fit.

resolution is limited by the CCD pixel size – Res=1500 in 3-48 nm range

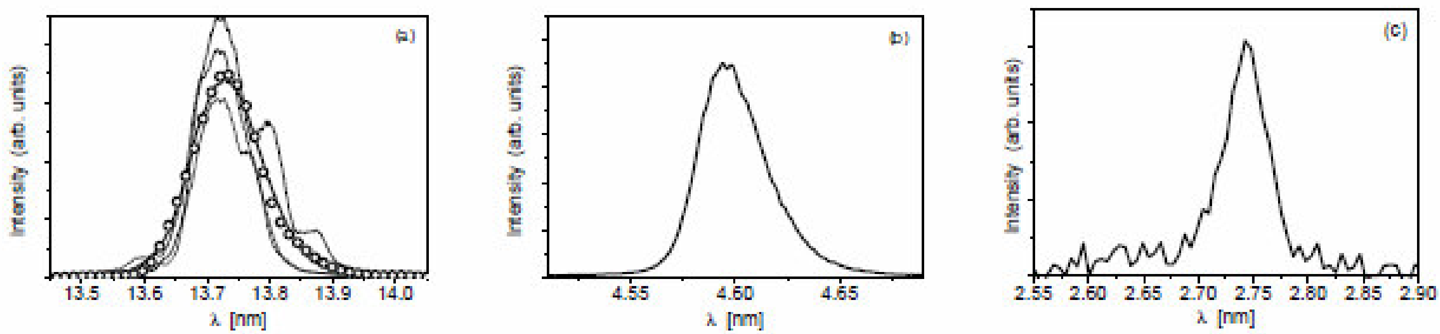
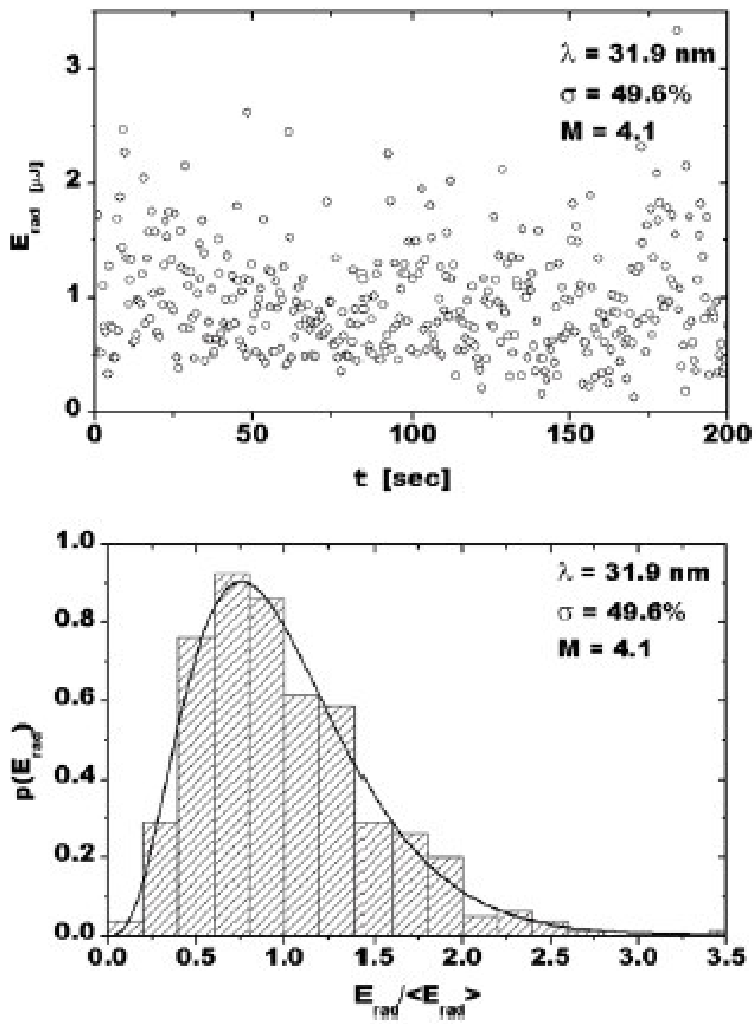
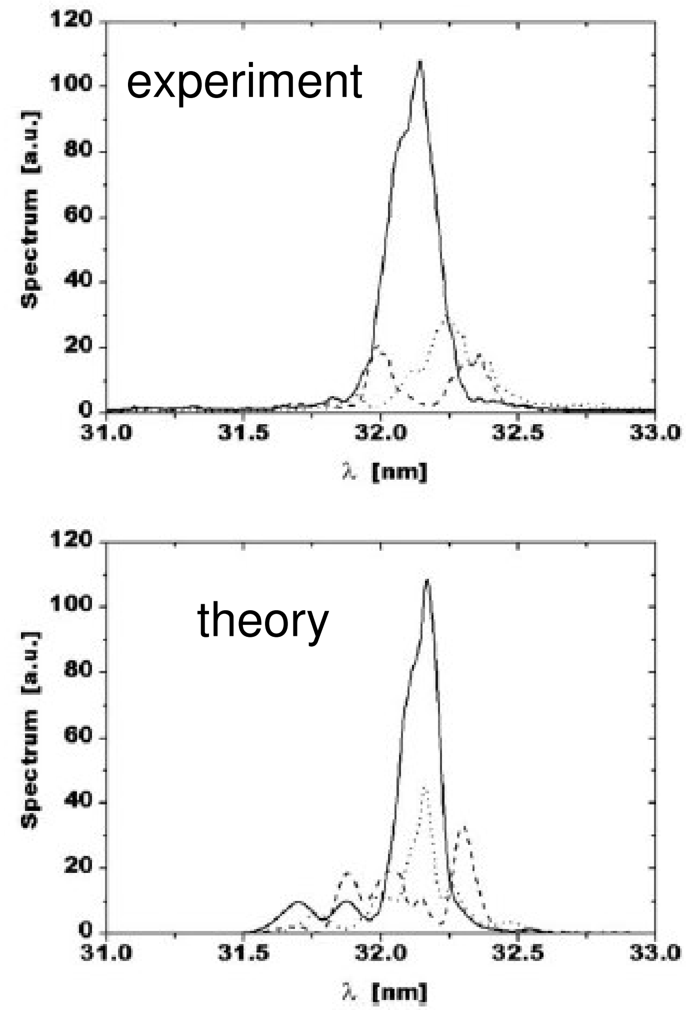


FIG. 5: EUV spectra of the fundamental (left), 3rd harmonic (center) and 5th harmonic (right) contributions to the FEL output. Bold lines show averaged spectra (mean value of 300 shots) while thin lines show single-shot spectra. Circles on the left plot represent averaged spectra simulated with the code FAST [38]. The average energy in the FEL pulse is 40 μJ.

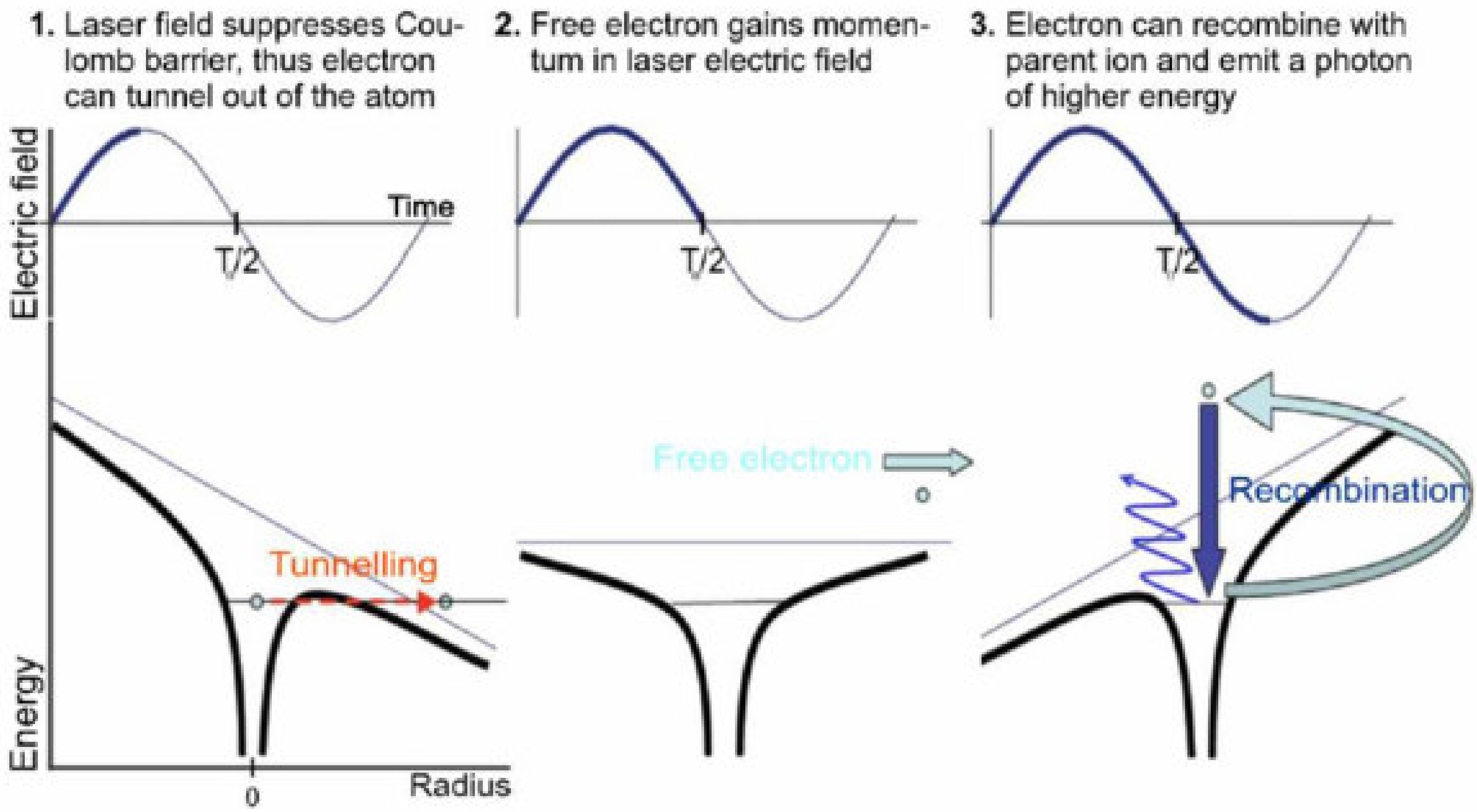
W.Ackermann et al. **Operation of a FEL from the EUV to the water window**. Nature Photonics, 1, 336 (2007)





V. Ayvazyan et al.Eur. Phys. J. D **37**, 297–303 (2006)

High Order Harmonic Generation



• Odd harmonics of the fundamental are emitted and the spectrum extends up to the water window related to the intensity of the laser pulse

• laboratory sized source of coherent EUV and soft X radiation

Atto-physics

• the HH emission corresponds to fraction of the laser field cicle,

• for fs laser pulses we enter in the as regime (150 as is the time one electron takes on the Bohr orbit in the H atom).

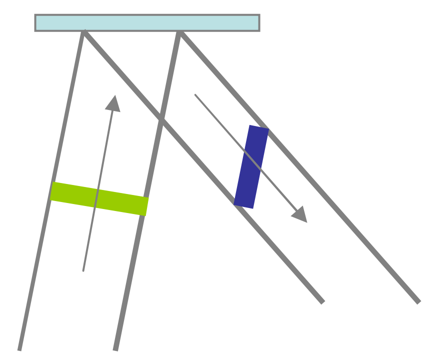
SPECTROSCOPY OF ULTRASHORT PULSES

• Spectroscopic observation of ultrashort pulses has to face the problem of time stretcching due to the diffraction process with conventional gratings.

• In the case of a diffraction grating the maxima correspond to the in phase superposition of rays from the various grooves

• i.e. the various optical paths differ an integer number of wavelength ($\Delta_{op}=Nm\lambda$)

• in conclusion the effect is time stretching by diffraction: a fraction of ps not negligible for fs pulses

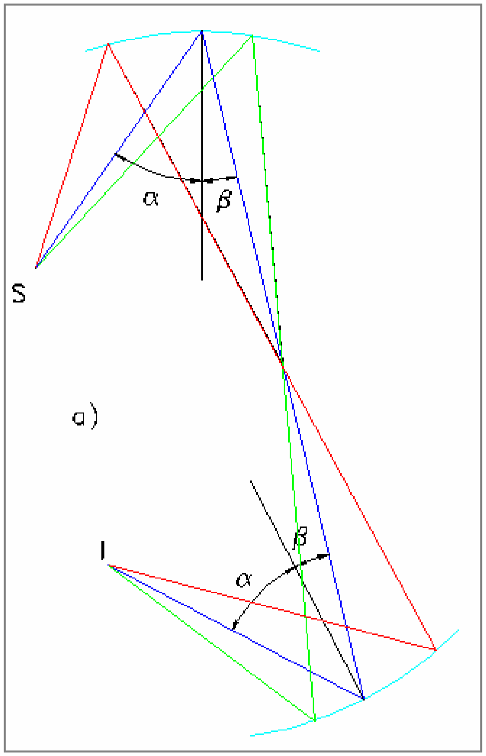


300 l/mm – 20 mm grating: 0.8 ps @ 40 nm

It results in reduced time resolution and peak intensity @ detection

DOUBLE GRATING DESIGN

Scheme for path length equalization: the mechanism which originates the path difference must be canceled.



P. Villoresi, Appl. Opt. **38,** 6040 (1999)

- equalization of path length for different spectral components
- combination of two diffractive elements in negative dispersion
- correction of the optical aberrations

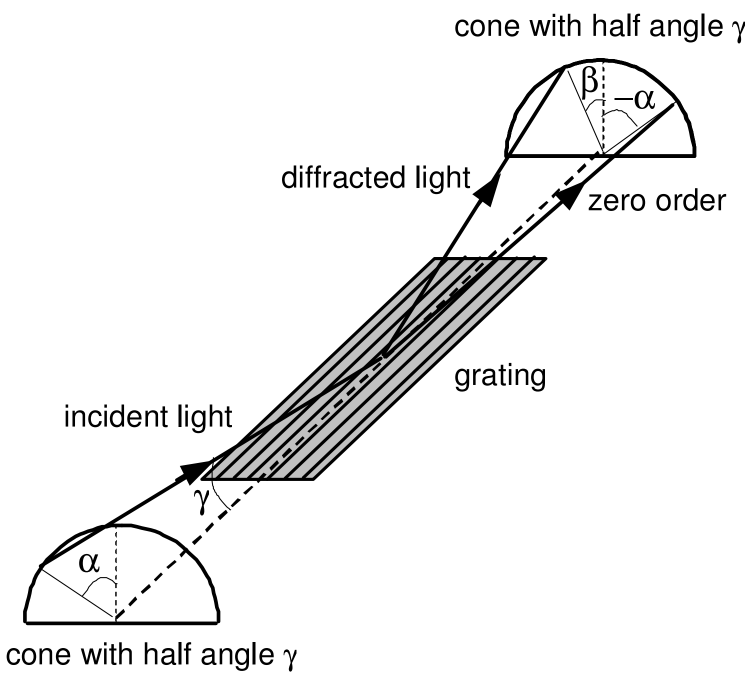
DRAWBACKS OF THE DOUBLE-GRATING DESIGN

LOW EFFICIENCY (two gratings)

DESIGN NOT SUITABLE FOR BROAD-BAND MONOCHROMATORS AT GRAZING INCIDENCE

Time-Compensated Grazing Incidence Monochromator

Conical diffraction: high efficiency on a wide spectral range



W. Cash, Appl. Opt. **21,** 710 (1982)

OFF-PLANE MOUNT ⇒ the incident and diffracted wave vectors are almost parallel to the grooves

The direction of the incoming rays is described by two parameters, the altitude γ and the azimuth (α, β)

The grating equation is

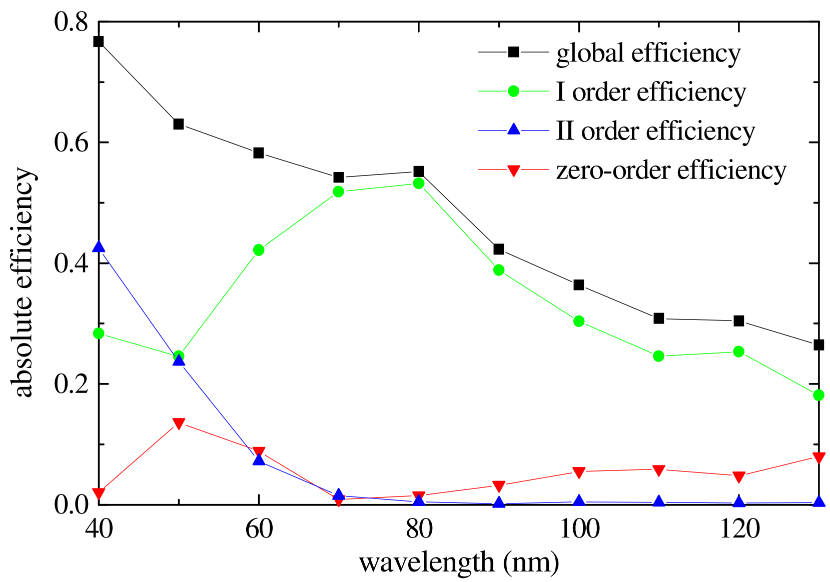
$$\sin\gamma(\sin\alpha + \sin\beta) = m\lambda\sigma$$

When used as monochromator $(\alpha = \beta)$

$$2\sin\gamma\sin\delta = m\lambda\sigma$$

Off-plane mount: efficiency

THE EFFICIENCY IS CLOSE TO THE REFLECTIVITY OF THE COATING, so much higher efficiencies than the classical mounting can be obtained.



EUV efficiency of gratings in the off-plane mount measured at Elettra (Trieste)

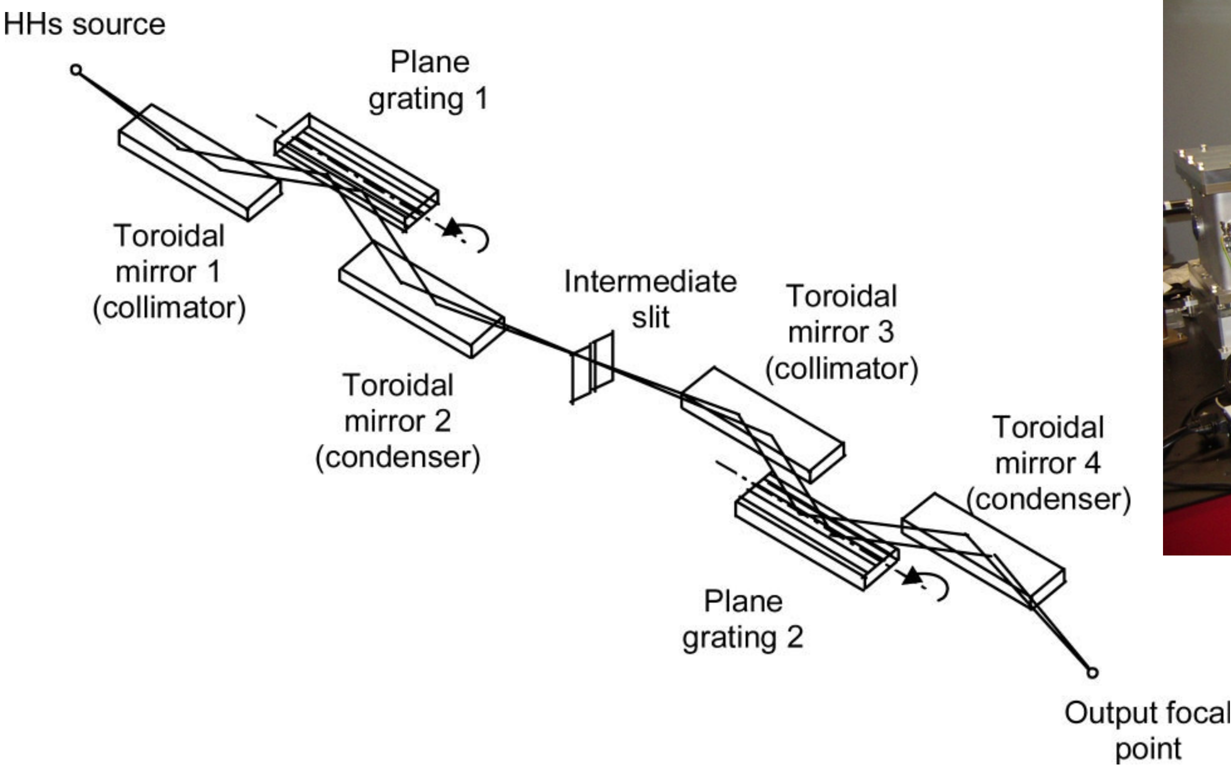
Grating: 600 gr/mm, 7 deg blaze angle, gold-coated, 11° altitude

EFFICIENCY: 55% AT 80 NM !!

L. Poletto et al, SPIE Proc. **5534**, 144 (2004)
M. Pascolini et al, Appl. Opt. **45,** 3253 (2006)

Double-grating monochromator

The two gratings are mounted in COMPENSATED CONFIGURATION and SUBTRACTIVE DISPERSION.



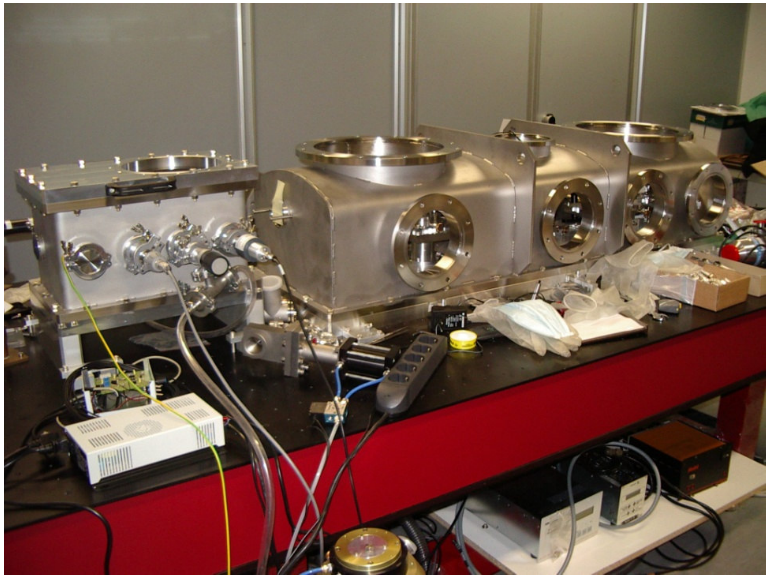
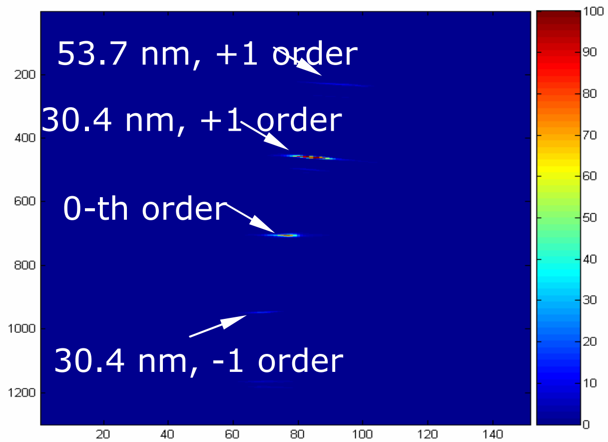


Image performance, wavelength calibration, efficiency



Harmonic order	ΔSLIT	ΔTOT
H15 (53.3 nm)	64 μm (210 fs)	1.2 μm (4.0 fs)
H19 (42.1 nm)	50 μm (170 fs)	0.8 μm (2.5 fs)
H31 (25.8 nm)	30 μm (100 fs)	0.3 μm (1.0 fs)

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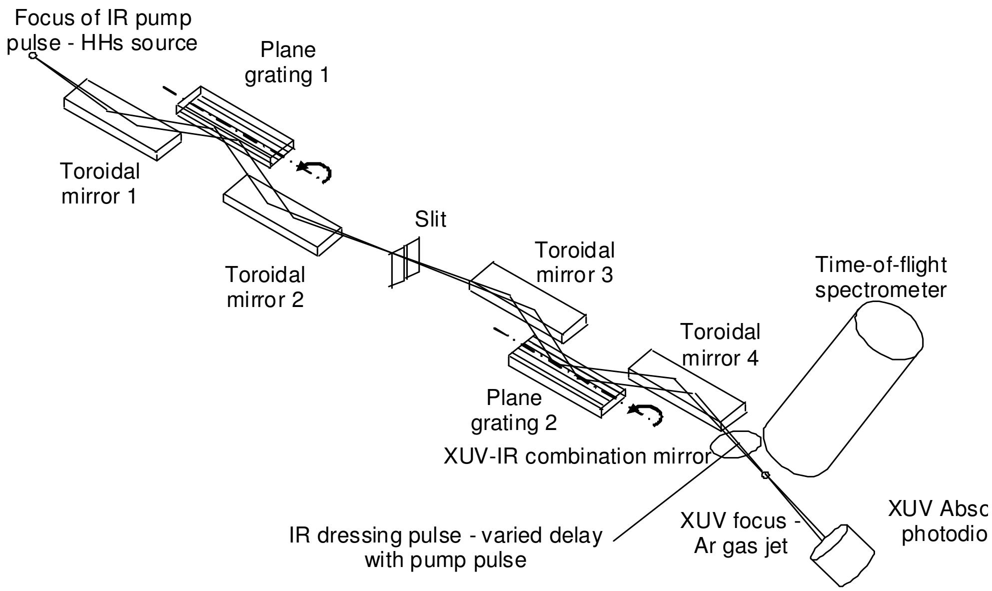

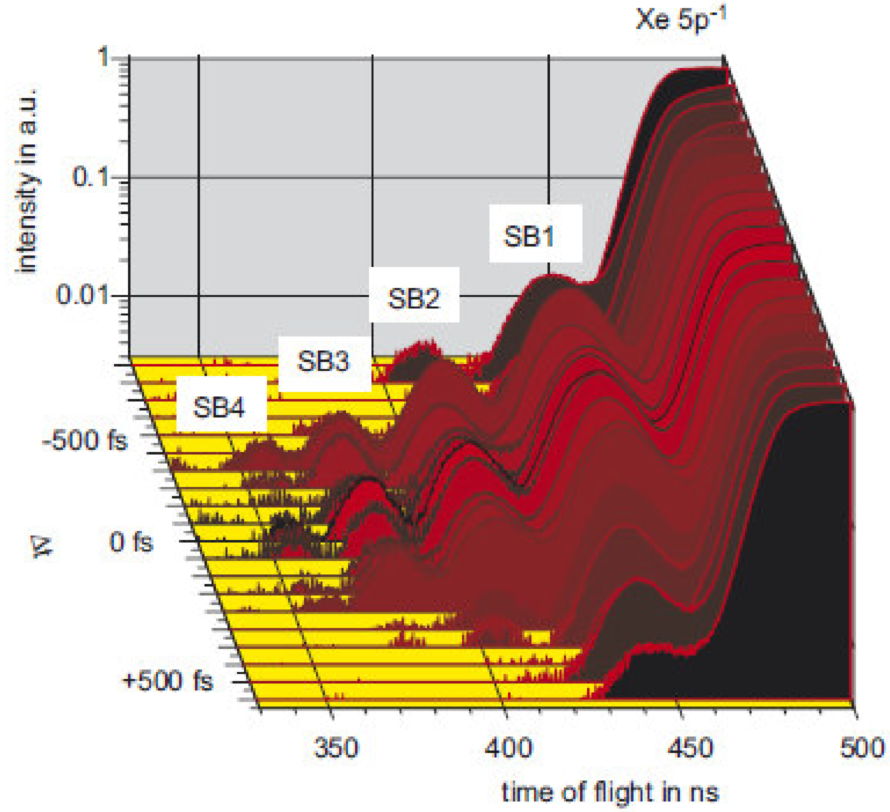

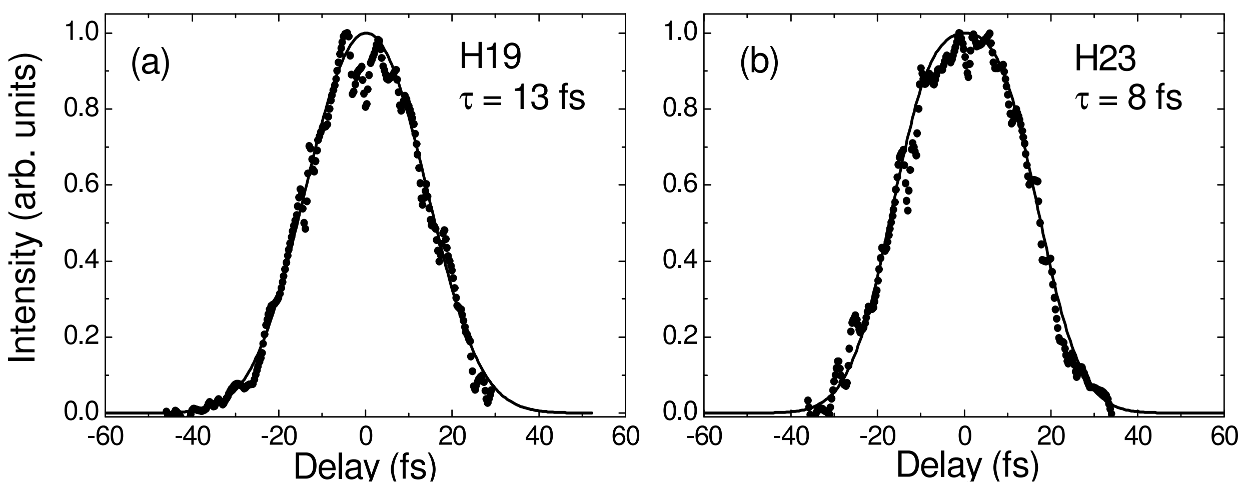

correlation signal.

L. Poletto et al, Opt. Lett. **32**, 2897 (2007)
L. Poletto et al, JOSA B **25**, B44 (2008)

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REFLECTION OF ULTRASHORT EUV PULSES WITH MULTILAYER OPTICS

1st Int. Conf. on Frontiers in Diagnostic Technologies
Lab. Nazionali Frascati - 25 – 27 Nov 2009

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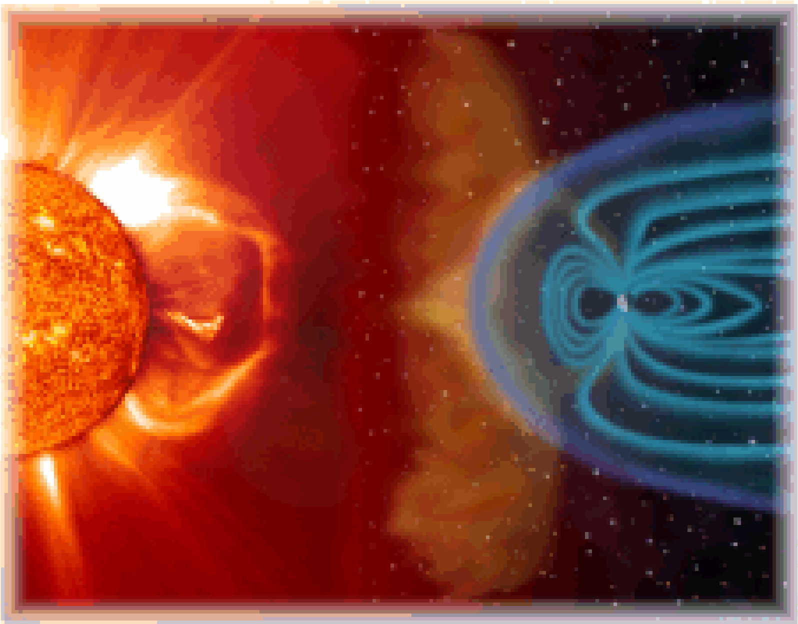
SPECTROSCOPIC INSTRUMENTATION FOR SPACE AND SOLAR PHYSICS



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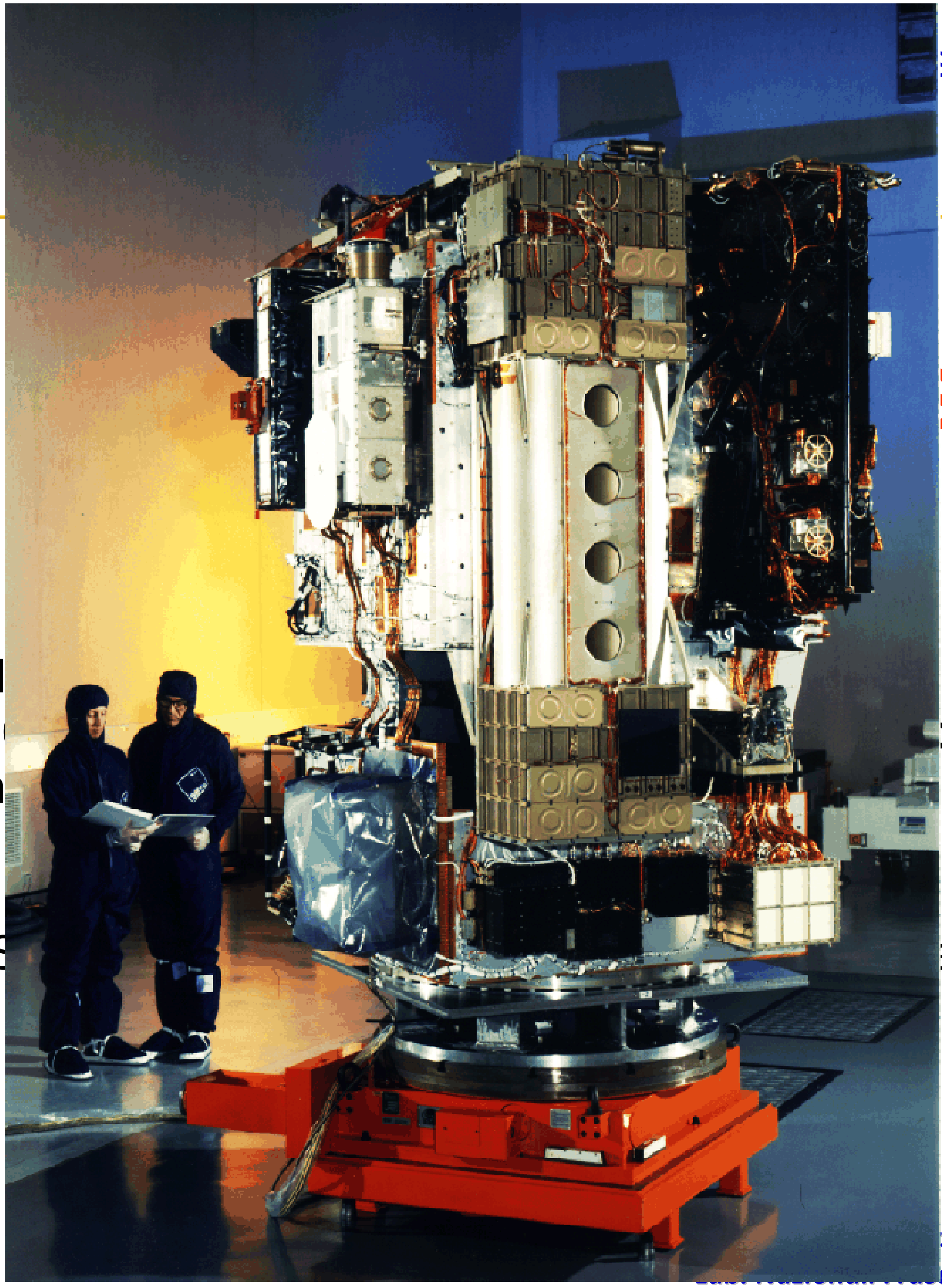

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Table 2.3.1. Instruments in the SOHO payload.

Investigation	*Principal Investigator*	*Collaborating Countries*	*Measurements*	*Technique*
Helioseismology				
Global Oscillations at Low Frequencies (GOLF)	A. Gabriel, IAS, Orsay, F	F, ESA, DK, D, CH, UK, NL, E, USA	Global Sun velocity oscillations (l=0-3)	Na-vapour resonant scattering cell, Doppler shift and circular polarisation
Variability of solar IRradiance and Gravity Oscillations (VIRGO)	C. Fröhlich, PMOD/WRC, Davos, CH	CH, N, F, B, ESA, E	Low-degree (l=0-7) irradiance oscillations and solar constant	Global Sun and low-resolution (12-pixel) imaging and active cavity radiometers
Michelson Doppler Imager (MDI)	P.H. Scherrer, Stanford Univ, California, USA	USA, DK, UK	Velocity oscillations high-degree modes (up to l=4500)	Doppler shift with Fourier tachometer, 4 and 1.3 arcsec resolution
Solar Atmosphere Remote Sensing				
Solar UV Measurements of Emitted Radiation (SUMER)	W. Curdt, MPAe, Lindau, D	D, F, CH, USA	Plasma flow characteristics (temperature, density, velocity); chromosphere through corona	Normal-incidence spectrometer, 50-160 nm, spectral resolution 20000-40000, angular resolution 1.2-1.5 arcsec
Coronal Diagnostic Spectrometer (CDS)	A. Fludra, RAL, Chilton, UK	UK, CH, D, USA, N, I	Temperature and density: transition region and corona	Normal and grazing-incidence spectrometers, 15-80 nm, spectral resolution 1000-10000, angular resolution 3 arcsec
Extreme-ultraviolet Imaging Telescope (EIT)	J-P Delaboudinière, IAS, Orsay, F	F, USA, B	Evolution of chromospheric and coronal structures	Full-disc images (1024×1024 pixels in 42×42 arcmin) at lines of HeII, FeIX, FeXII, FeXV
Ultraviolet Coronagraph Spectrometer (UVCS)	J.L. Kohl, SAO, Cambridge, MA, USA	USA, I, CH, D	Electron and ion temperature densities, velocities in corona (1.3-10 $R_\odot$)	Profiles and/or intensity of selected EUV lines between 1.3 and 10 $R_\odot$
Large Angle and Spectrometric COronagraph (LASCO)	R. Howard NRL, Washington DC, USA	USA, D, F UK	Structures' evolution, mass, momentum and energy transport in corona (1.1-30 $R_\odot$)	One internally and two externally occulted coronagraphs. Spectrometer for 1.1-3 $R_\odot$
Solar Wind ANisotropies (SWAN)	J.L. Bertaux, SA Verrières-le-Buisson, F	F, FIN, USA	Solar wind mass flux anisotropies. Temporal variations	Scanning telescopes with hydrogen absorption cell for Lyman-alpha
Solar Wind 'in situ'				
Charge, ELement and Isotope Analysis System (CELIAS)	P. Bochsler, Univ. Bern, CH	CH, D, USA, Russia	Energy distribution and composition. (mass, charge, charge state) (0.1-1000 keV/e)	Electrostatic deflection, time-of-flight measurements and solid-state detectors
Comprehensive SupraThermal Energetic Particle analyser (COSTEP)	H. Kunow Univ. Kiel, D	D, USA, J, F, E, ESA, IRL	Energy distribution of ions (p, He) 0.04-53 MeV/n and electrons 0.04-5 MeV	Solid-state detector telescopes and electrostatic analysers
Energetic and Relativistic Nuclei and Electron experiment (ERNE)	J. Torsti, Univ. Turku, SF	FIN, UK	Energy distribution and isotopic, composition of ions (p-Ni) 1.4-540 MeV/n and electrons 5-60 MeV	Solid-state and plastic scintillation detectors

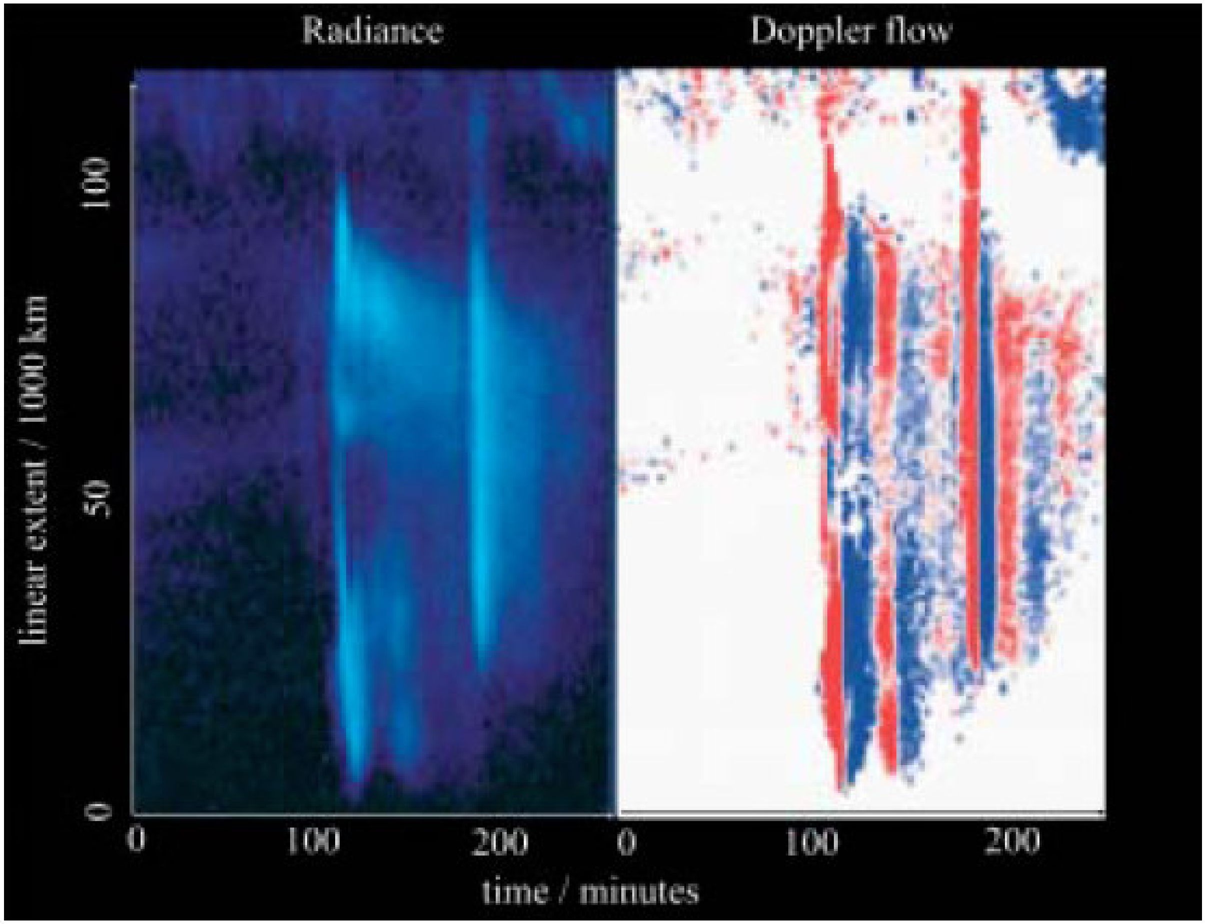
SUMER

CDS

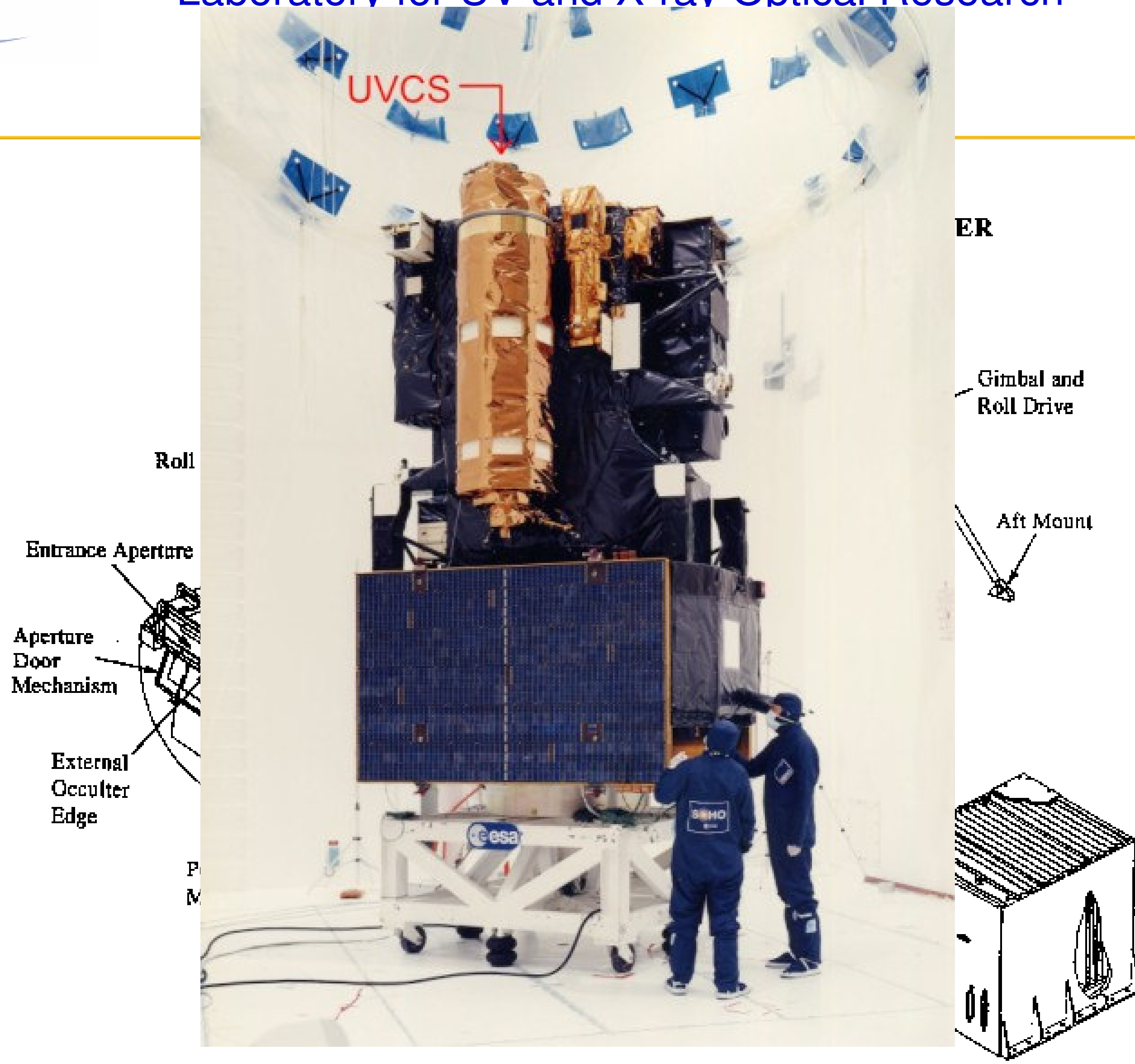
EIT

UVCS

- **Figure 2.3.2.** Hot loop oscillations as observed by SUMER. Intensity (left) and velocity (right) variations of loops observed with a thin slit (time goes from left to right in each half). Red means receding material, blue means approaching.



SUMER has discovered strong Doppler-shift oscillations in hot loops above active regions, identified as slow magnetoacoustic standing waves. The periods 10-20 min, with a comparable decay time scale. The oscillations are seen only in hot flare lines(> 6MK, e.g. Fe XVII, Fe XIX, Fe XXI). Lines formed at 'normal' coronal temperatures (1MK, e.g. Fe XII, Ca XIII, Ca X) do not show any signature of these oscillations.


ER
Gimbal and
Roll Drive
Roll
Aft Mount
Entrance Aperture
Aperture
Door
Mechanism
External
Occulter
Edge
UVCS

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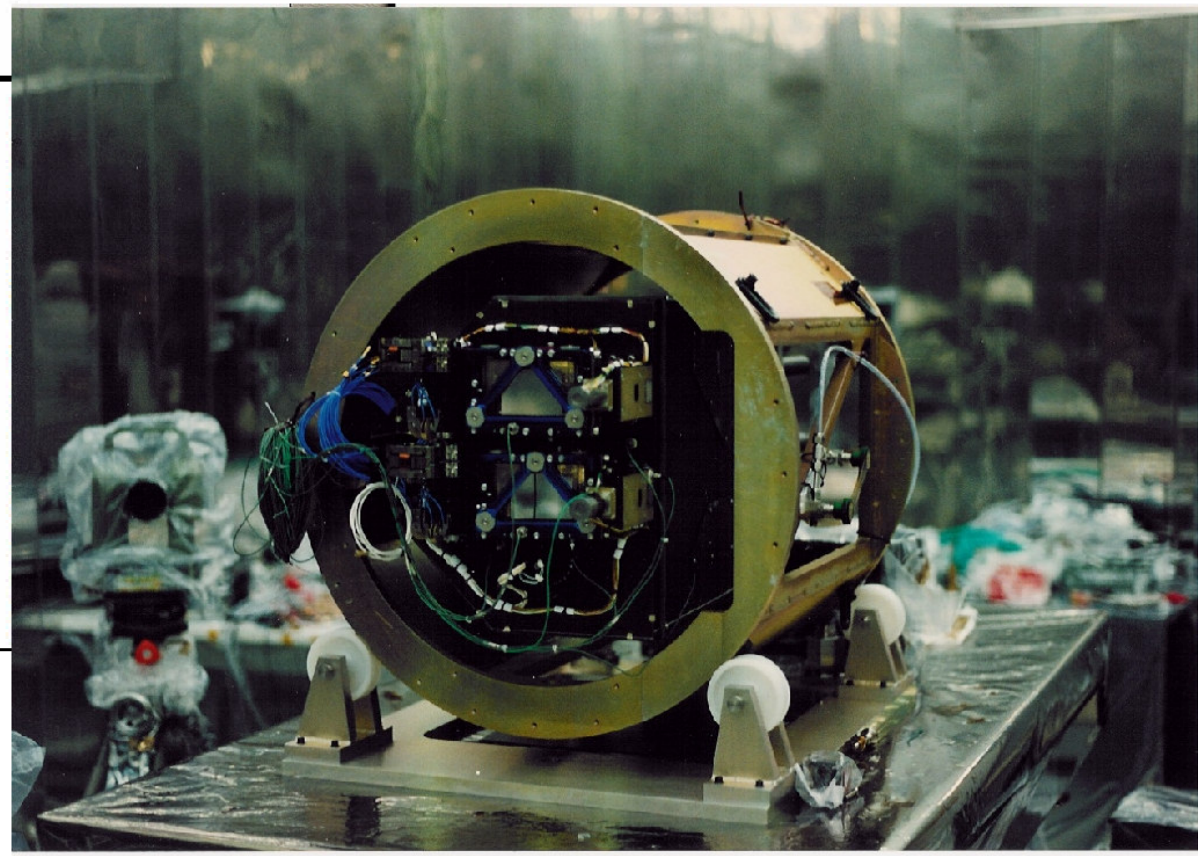
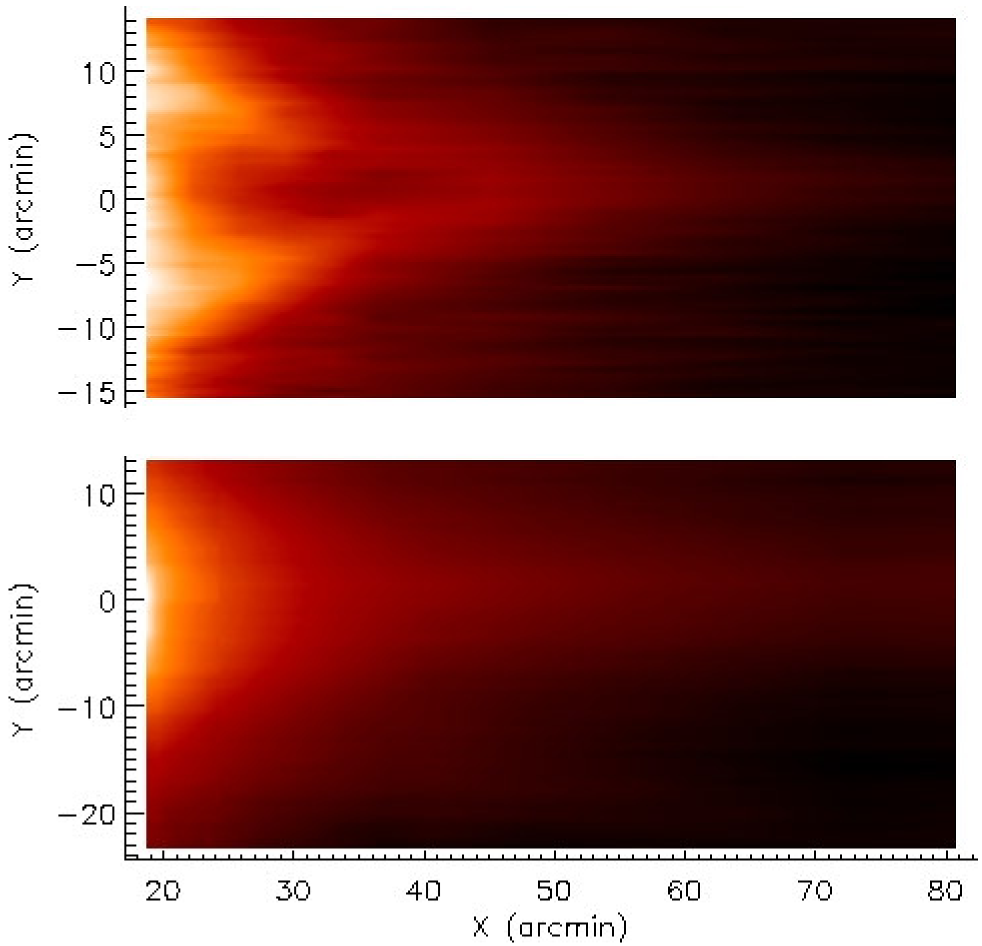
Parameters
Type
Number of line/mm
Angle of incidence
Angle of diffraction
Main radius of curvature R
Minor radius of curvature ρ
Reciprocal dispersion
Spectral bandwidth of pixel
Spatial width of pixel
Ruling process
Coating



Toroidal Gratings for stigmatic high spectral resolution acquisitions

0.014 nm/ 7''

$$\rho/R=\cos\alpha\cos\beta$$


10
5
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Y (arcmin)
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30
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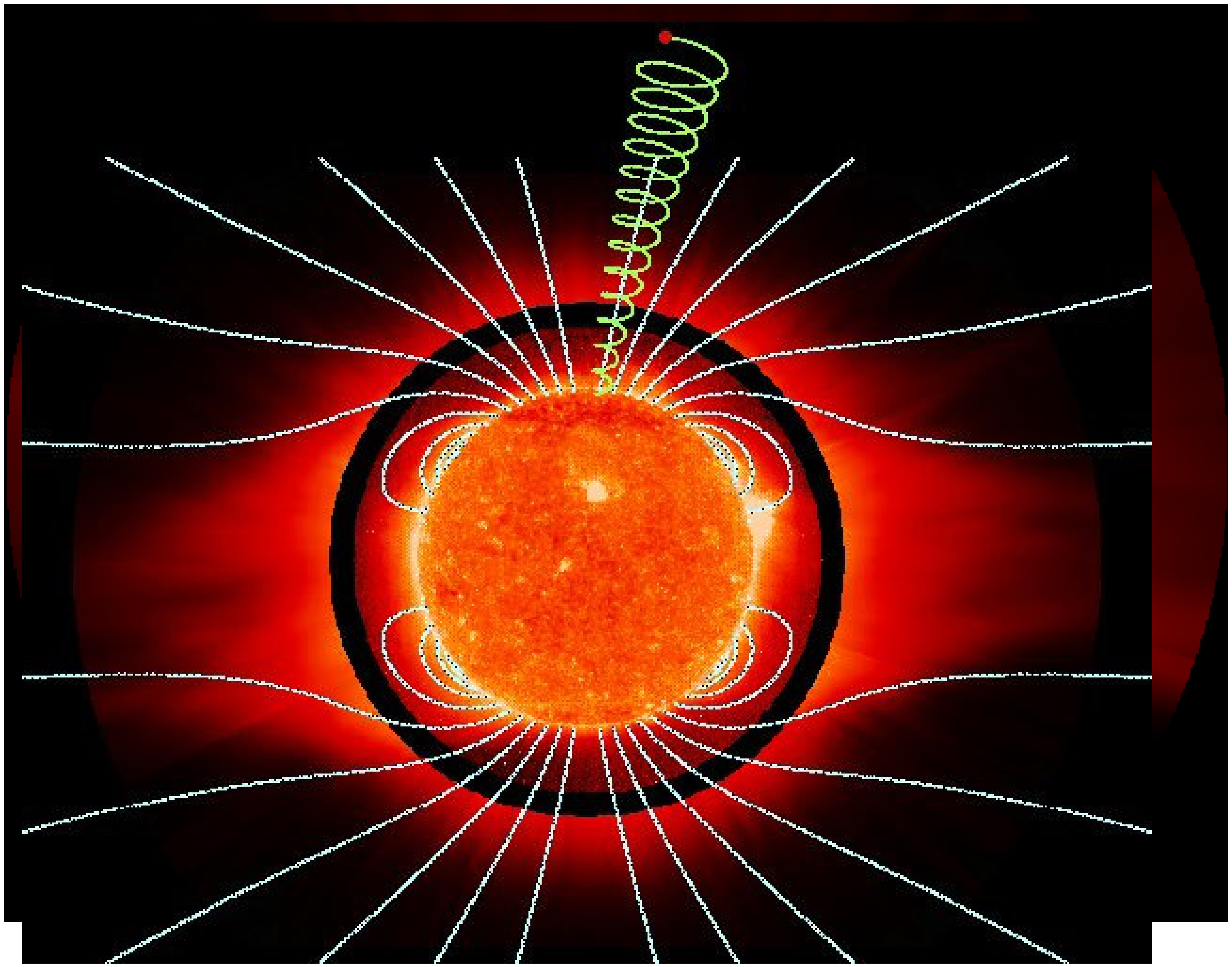
60
70
80
X (arcmin)



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MULTILAYERS FOR SOLAR PHYSICS

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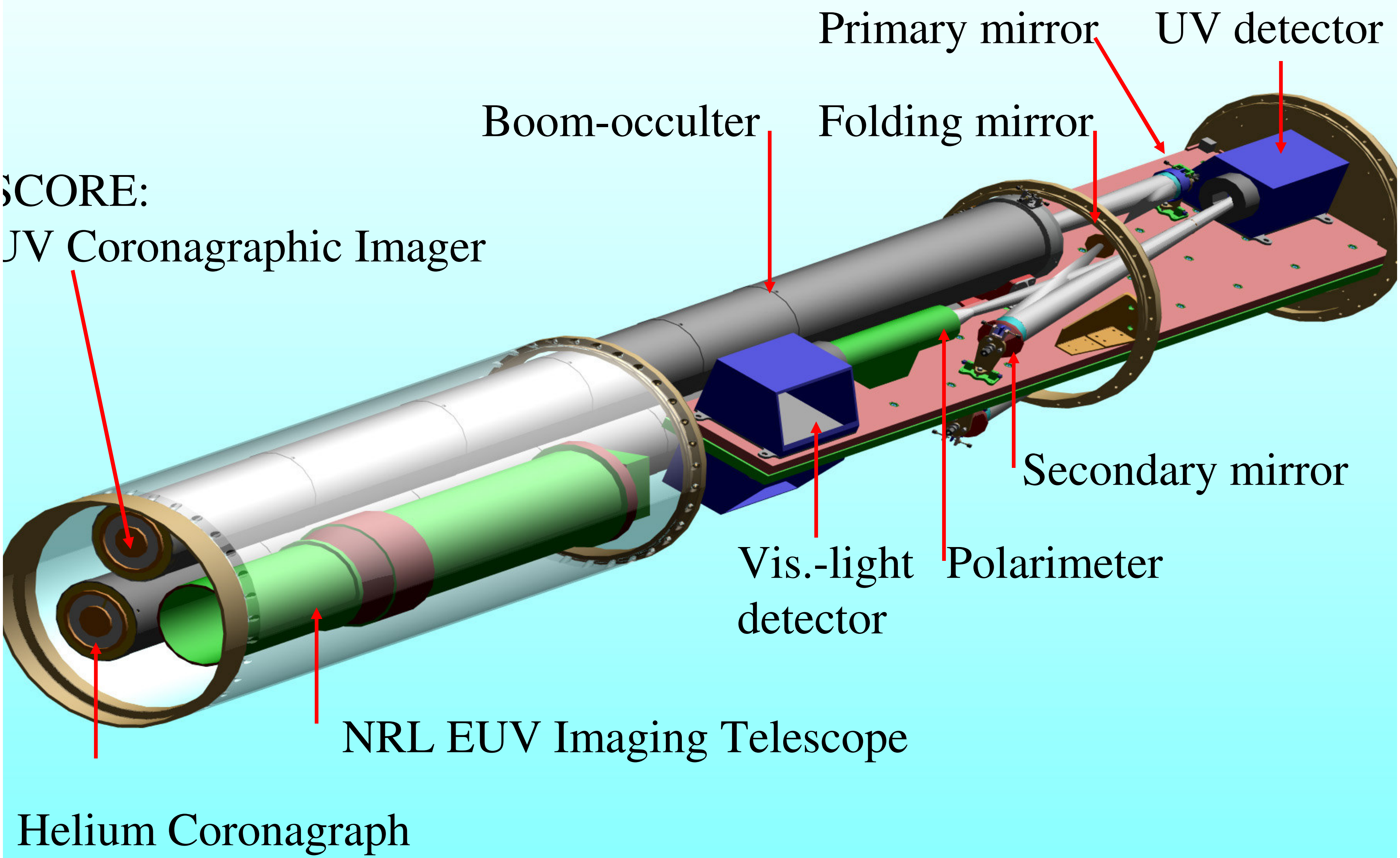
MLs for Solar Physics

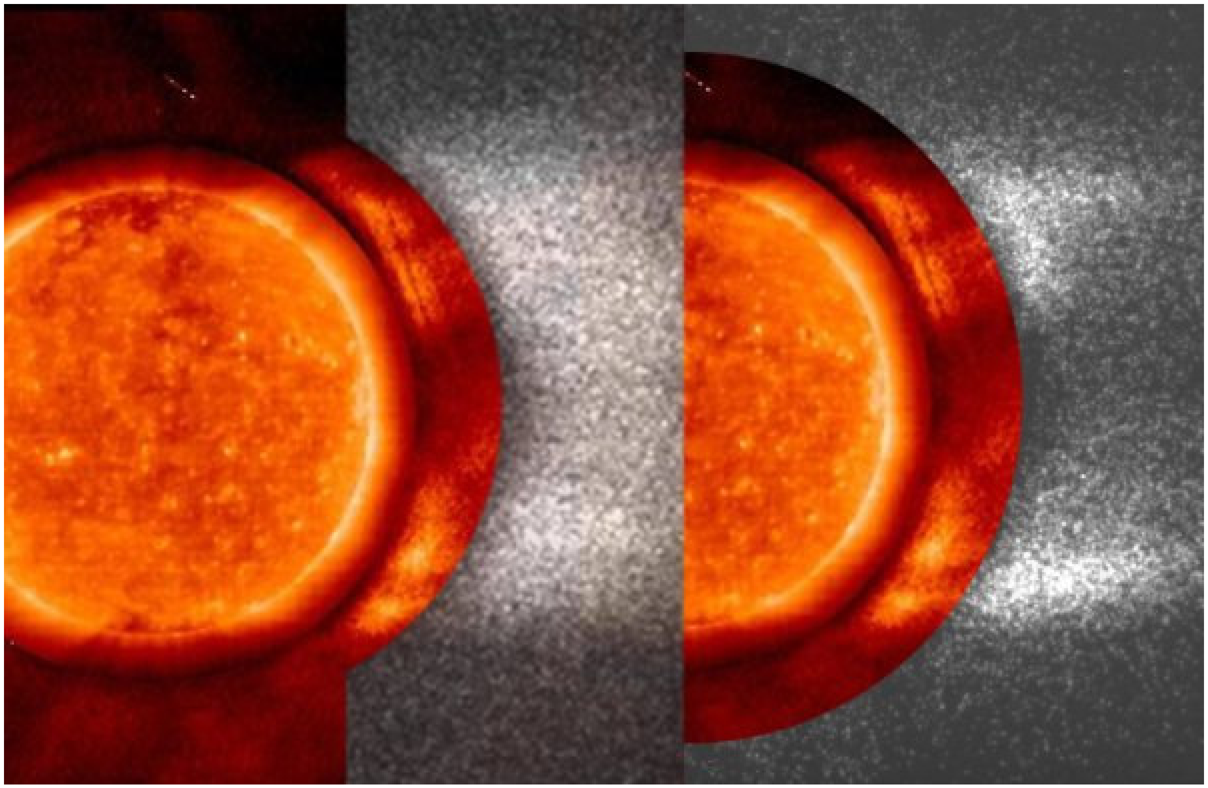
Multilayer for solar line observations have been fabricated at Fe-IX (17.1 nm), Fe-XII (19.5 nm), Fe-XV (28.4 nm) and He-II (30.4 nm).

Performance of such MLs are mainly evaluated in terms of peak reflectivity at working wavelength and rejection capability of unwanted lines; in fact, such coatings have not negligible bandwidth

Mo/a-Si multilayer coatings with improved signal to noise ratio have been designed at LUXOR, specifically designed to reject unwanted lines while preserving the peak reflectivity of the ML.

HERSCHEL Sounding-Rocket Payload





cromosphere (HEIT), inner corona (HECOR) @ He 304 A and outer corona (SCORE) @ HI 1216 A

cromosphere (HEIT), inner corona (HECOR) @ He 304 A and outer corona (SCORE) @ He 304 A

CONCLUSION

•The development of new radiation sources (FEL, HHG) as well as space exploration are stimulating the design of new spectroscopic instruments.

•High spectral resolution, stigmatism, band selectivity, time/phase compensation etc. are some of the peculiar characteristics driving the performances of these instruments.

•Some of the most significant examples , in our opinion, have been presented.

- only a very partial view of technology and science related to the design of EUV spectroscopic instrumentation has been given

- for instance both **crystal spectrometers** and **detection systems** have been neglected

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