Chapter 27

Flying Circus EUV Source Metrology and Source Development Assessment

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Contents

27.1 Historical Overview of Metrology Development and Standardization

Soon after the first explorations of the potential of EUVL, it became obvious that the wafer throughput of future EUVL systems, and thus the EUV source brightness, was a key factor in the industrial value of this new imaging technology. The need for plasma-based light sources of moderate temperature, though strongly confined in space and critically optimized for emission at 13.5 nm, implied the use of suitable diagnostics, well adjusted for the particular application. Especially in the early days of EUVL development, a variety of source diagnostics were being used by the different source developers, each having backgrounds in different research and technology areas. These diagnostics ranged from uncalibrated grating spectrographs and luminescent detectors to broadband detection systems, such as filtered calorimeters and photocathodes, each detector obviously having its own characteristics.[1–3] The measurement units applied varied correspondingly, ranging from $J \cdot eV^{-1} \cdot J_1^{-1}$ to percent.[4,5]

From the data collected with these devices, extrapolations were then made to the most relevant quantity, namely, the true EUV power within the bandwidth and the radiation acceptance angle of the total EUVL system. In order to allow a direct comparison of the performance of the different candidate EUV sources, in 2000 ASML sponsored a source metrology activity by FOM and Philips Research for which a portable, absolutely calibrated set of diagnostics was used. The approach was to assess each of the different sources with one single diagnostics set, circumventing any uncertainty introduced by the specific properties or calibration of the various metrology devices. In addition, the measurement procedure was standardized. Collecting data from sources on different locations worldwide, the activity became known as Flying Circus, or FC for short, and initially resulted in a full benchmark characterization of five candidate EUV light sources and the development of a common diagnostic standard.[6,7] The follow-up project, Flying Circus 2 (FC2), sponsored by International SEMATECH, had the broader scope of further assessing the progress of EUV source performance, calibrating EUV source metrology equipment from different EUV source suppliers, and continuing the development of globally accepted EUV source measurement procedures. Nowadays, more then a dozen sources are characterized in this way, and the FC-type diagnostic has found permanent use at the majority of the source development laboratories. FC diagnostics are commercially offered by Scientec Engineering (www.scientec.nl). The general acceptance of the method and the continued program of on-site calibration using the portable FC equipment at the different source labs, as well as further-developed FC hardware, considerably assisted in the standardization of source performance representation.[8]

27.2 Metrology Concept

The choice for the FC metrology concept is based on results from applied physics research at various laboratories on characterization of laser-plasma XUV emission, as well as the development of appropriate XUV diagnostics.[9–12] Notably, an early comparative study on plasma heating conditions for EUV generation and the progress in multilayer research contributed to the definition of the FC concept.[13,14] Essential in the approach is the use of a multilayer optic as the main bandwidth-selective and light-collimating element.[15,16] By adding a matched filter for the long-wavelength cutoff and a semiconductor junction diode, a versatile detector system is formed, enabling an accurate and straightforward calibration procedure (Fig. 27.1).[17–19] The modular ultrahigh vacuum (UHV) construction of FC allows *in situ* alignment and *in situ* verification of detector linearity and absence of filter damage or contributions by out-of-band (OOB) radiation. The EUV light collimation by the curved multilayer allows either relatively long working distances with enhanced calibration lifetime, or enhanced filtering, both factors being helpful in the everyday practice of source monitoring. Collimation, adjustable by the use of different apertures, is also helpful in limiting the detector's acceptance angle, which is an advantage with respect to mirror lifetime and the determination of the value of the acceptance angle for the conversion to the standard solid angle of 2π sr. The use of a single mirror at near-normal incidence, similar to most of the multilayer

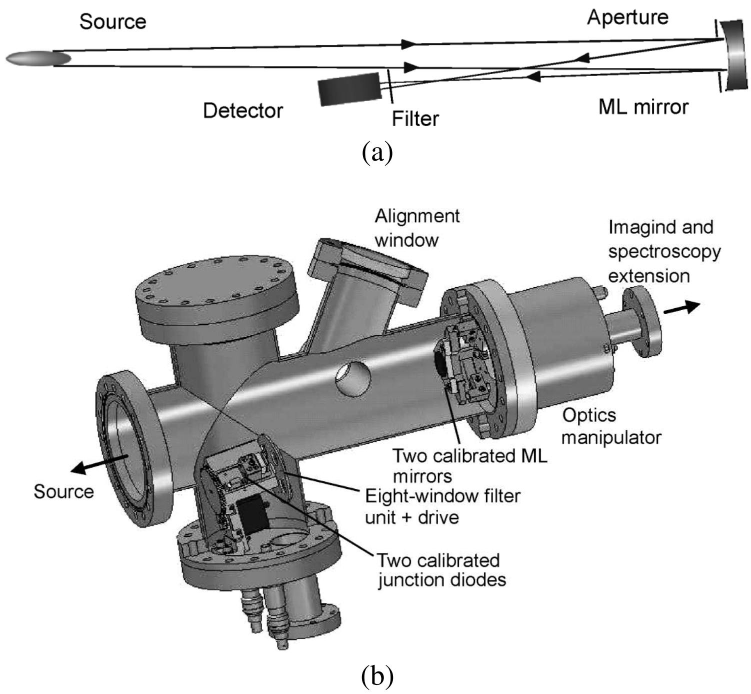

Figure 27.1 (a) Basic geometry of the FC EUV diagnostic. (b) Hardware schematics in the classic mode of operation of FC2.

optics in the EUVL tool, reduces the chance of polarization effects or alignment uncertainties, as compared to the use of multiple multilayer elements at off-normal incidence. The ability to do *in situ* alignment, finally, is of practical value, notably for source development use of FC.

In the classical mode of operation, the FC equipment allows direct measurement of the absolute inband EUV power, the pulse-to-pulse intensity stability, the OOB vacuum ultraviolet (VUV) and IR radiation, the maximum and steady-state repetition rate, the type and pressure of the surrounding gas, and the source-facing condenser's lifetime. Using an add-on source imaging extension, the inband source size can be measured within a few-percent-wide bandwidth around 13.5 nm, as well as the pulse-to-pulse spatial stability and the EUV intensity distribution across the plasma. Indirectly measurable are the average angular distribution of the radiation, the available collection solid angle, key risk areas for operating the EUV source and its critical component lifetime, and the electrical power dissipated by the source. These properties represent the range of source parameters currently agreed on for regular EUV source assessment.

27.3 EUV Source Metrology Calibration Procedures

The initial FC diagnostic allowed the measurement of the absolute EUV energy and average power in two wavelength bands, viz., 11.4 and 13.4 nm. In addition, the pulse-to-pulse and long-term EUV stability of the source were assessed, as well as the contamination of multilayer optics exposed to the source. Nowadays, the focus is at 13.5 nm, the commonly accepted wavelength for EUVL. All optical elements are pre- and post-calibrated in a band including a wavelength by the Physikalisch-Technische Bundesanstalt at the storage ring Bessy II. A comprehensive description of the calibration procedure is found in Refs. 20 and 21, including an analysis of geometrical factors and the influence of the spectral emissivity of the source on the calibration. The calibration is performed for the centroid wavelength, for the full bandwidth of the diagnostic, and for OOB ranges (Fig. 27.2). The total uncertainty in the absolute calibration amounts to less than 5%, while the shot-to-shot repeatability is within 2%. This uncertainty is mainly determined by external factors such as the presence of a background gas and spectral source characteristics.[21]

The everyday practice of monitoring EUV source properties means that a number of other factors must be taken into account, such as contamination by source debris or background pressures, polarization effects, plasma and target gas EUV absorption, and detector linearity. The determination of the linear operating range of detectors was verified in the visible wavelength range using a method to generate pulses with a well-known pulse shape and length, both inherently calibrated.[22] This method consists in sweeping a dc laser beam through a known aperture using a fast-rotating deflecting mirror. The sensitivity of the AXUV-100 photodiode, investigated this way, remained constant as a function of the pulse length at radiation intensities up to 118 mW, when applying a reverse bias voltage of 9 V in an electronic circuit suitable for pulse lengths up to 5 µs. This is well within the normal

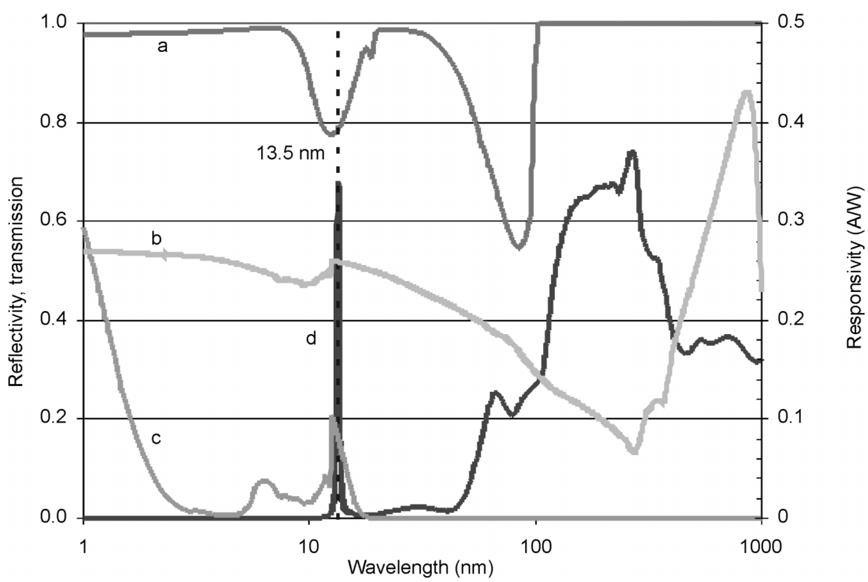

Figure 27.2 Example of the spectral response of the different metrology components: (a) Xe gas transmission, (b) AXUV-100 photodiode responsivity, (c) Si_3N_4/Nb filter transmission, and (d) Mo/Si multilayer mirror (MLM) reflectivity for the wavelength range from 1 to 1000 nm.

working range encountered at most sources. Recent studies on the linearity of the photodiodes applied have confirmed a linear operating range up to typically 5 nC. The FC detection sensitivity is normally adjusted by scaling the mirror aperture or the overall source-to-detector distance. Linearity in the EUV range is argued to be similar, but remains to be verified.[23]

At least down to the currently useful accuracy level of a few percent, there appears to be no need to calibrate the diagnostic as an assembled unit; due to the straightforward optical configuration, a separate calibration of the individual components (MLM, junction diode, filter) was shown to lead to at least the same overall accuracy as obtained using the full unit. A study performed at NIST showed that the responsivity based on separate component calibration agrees to within 1% with the responsivity of the assembled unit, with the total uncertainty of the beamline being 3.5% (1σ). This means that the total responsivity of FC2 and similar EUV metrology devices can indeed be derived from the calibration of the individual components. From a practical and cost point of view, individual component calibration is a preferred method for (re)calibrating EUV diagnostics. Ultimately (i.e., when applied at the final EUV scanners), verification of this procedure at much higher accuracy levels is desirable. This need can be foreseen for dedicated metrology tools or EUV dose monitors at (for instance) the wafer stage or intermediate points in the illuminator and projection-box optics. It can be argued that such dedicated monitors still need to allow regular cross-calibration with transfer standards.

Yet, a main issue in the everyday practice of source diagnostics is the need for frequent recalibration of components at appropriate EUV calibration facilities. The risks of contamination or damage of metrology components—e.g., by source debris or hydrocarbon or oxygen background pressures—calls for such possibilities, preferably available in the form of small-scale, lab-source-based metrology calibration setups.[24] Regular cross-calibration of such facilities with synchrotron-based setups, as well as correlation of results from different synchrotron facilities, will remain necessary in future, with accuracies typically within 1%.

Cross-calibration of EUV energy detector systems has been explored in detail using the FC2 system and also the E-MON system as developed by Jenoptik Mikrotechnik. Both detectors are intended for monitoring of EUV source characteristics.[25] A discharge and a laser-plasma EUV source were employed, developed by XTREME technologies. The FC2 and E-MON measurements showed agreement within 10%, in some setups down to 1%. The comparison showed a strong dependence on source properties (stability, isotropy, spectral emission) and measurement procedure (Xe absorption, triggering) when cross-calibrating two devices. The comparison also indicated that procedures for EUV absorption correction need to be standardized.

27.4 FC Source Progress Assessment

The initial FC activity resulted in a first comprehensive source benchmarking effort, with data reported on five EUV light sources, each of a different concept.[6,20]

This benchmark, established in the first half of 2000, constitutes a point of reference in the development of EUV sources. The maximum power recorded then was 2.8 W, achieved by the Sandia laser plasma. The discharge systems investigated included the PLEX Z pinch, the Cymer plasma focus, the Sandia capillary plasma, and the Fraunhofer hollow-cathode source: all showed a power of less than 0.1 W in 2% bandwidth per collectable angle. By early 2004, the average power increased to an impressive level of several tens of watts, even while the required point of measurement was changed to the so-called intermediate focus (IF), i.e., including loss factors from collection optics or debris mitigation schemes. At the time of this writing, the power level achieved is typically up to several tens of watts in a 2% bandwidth at the IF, and several source developers are extrapolating to the lithography-required level of 115 W (Fig. 27.3).

The list of EUV sources either partially or fully assessed by FC over the past few years currently includes the following sources, listed in chronological order of the measurement: the laboratory gaseous-Xe-based laser plasma source at FOM, laser- and capillary-discharge plasma sources at Sandia National Laboratories, the Xe dense plasma focus at Cymer, the hollow-cathode-triggered (HCT) discharge source at the Fraunhofer Institut für Lasertechnik (Aachen), the Z-pinch and Star Pinch sources at PLEX LLC (Cambridge, MA), the discharge plasma at Philips EUV (Aachen), laser and discharge plasmas at XTREME technologies (Jena and Göttingen), an rf-excited plasma source at LBNL (Berkeley, CA), and a Sn-based

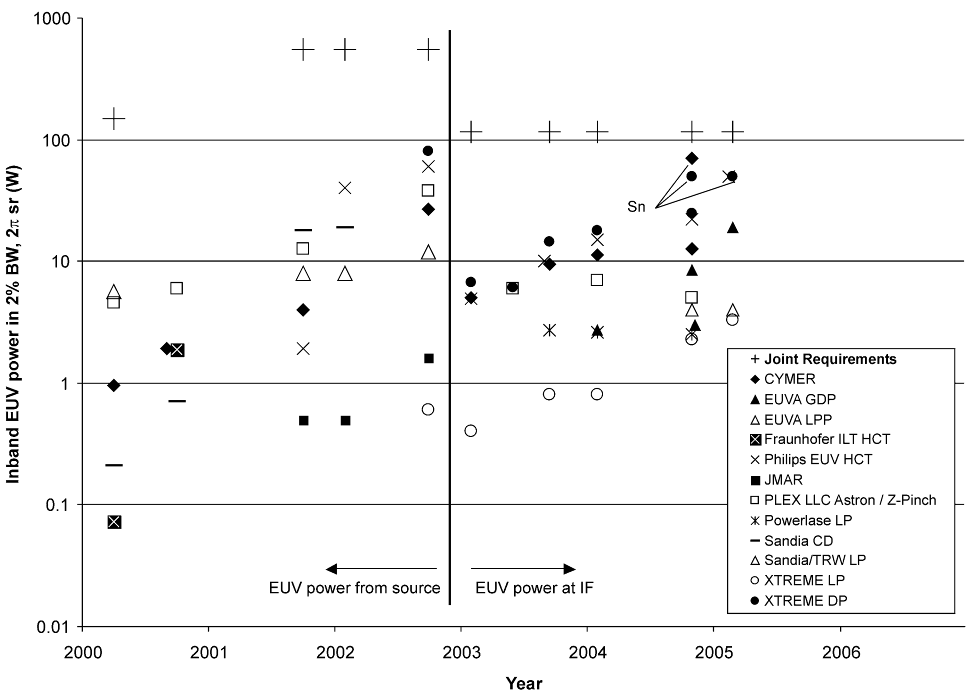

Figure 27.3 Summary of FC and supplier data on EUV source performance development. From 2002 on, the power values in the IF are shown.

laser plasma source at CREOL (Orlando, FL), many with individual reports available.

By way of example of the scope of typical FC source assessments, a summary of the results of measurements collected by the end of 2003 at the PLEX LLC Star Pinch is given (Table 27.1).[26] The table shows the main source properties as currently being quantified within the FC program, as well as the measurement units applied for each of the source characteristics. This listing also reflects the consensus among source and system developers on relevant source characteristics. The full report describes the equipment developments, the calibration and analysis procedure, and a discussion on the results.[26] It is noted that the data do not necessarily represent the latest performance of the particular source due to the rapid development of sources.

27.5 Diagnostic Extensions and New Developments

The FC optical concept of employing a curved multilayer optic enables an extension by a second multilayer optic, so that an EUV multilayer telescope is formed (Fig. 27.4). This can be used to image the EUV source onto a CCD camera at magnifications between 2 and 10. These narrowband images, showing only the EUV-emitting part of the plasma, can differ considerably from the widely used pinhole-camera images, which show the broadband source size. The latter can result in incorrect estimation of the collectable power due to limitations in the collection efficiency given a certain etendue of the collector optics. Experimental results show that there is no general relation between EUV size and broadband source size, so that one would have to verify the inband size when changing major plasma conditions. Imaging results on a gaseous Xe laser-plasma source at FOM showed a 40% smaller inband size than the broadband size, and studies at Philips Extreme UV showed an 18% broader source at 13.5 nm with a different energy distribution across the source.[27,28] Larger inband sizes would result from plasmas that radiate primarily at wavelengths from higher ionization stages in the plasma, of which the radiation originates usually from a smaller core. The wavelength-band averaging occurring in pinhole cameras then can lead to a smaller size than for images from inband multilayer telescopes.

Source intensity measurements are normally based on one or two reflections from MLMs, resulting in data for a 3.9% and a 3.3% bandwidth, respectively. Additional spectral data are then needed to convert the intensity to the 2% standard

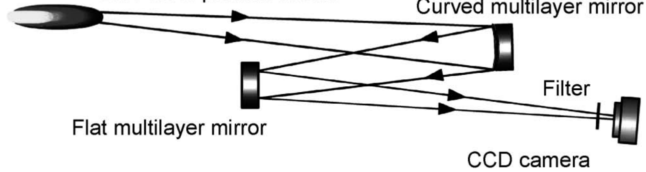

Figure 27.4 Imaging mode of FC operation.

Table 27.1 Typical measurement quantities and standardized units as assessed by the Flying Circus program.

Parameter	Unit	Value	Comment
Absolute collectible inband EUV power measured (2% BW)	mJ/sr	3.7–6.4	Measured at 500 Hz; energy values dependant on Xe flow
Max. collectible inband EUV power measured (2% BW)	mJ/sr	6.9	Measured at 1250 Hz
Estimated power at IF at steady-state rep. rate (2% BW, 500 Hz)	W	1.3	Assuming 2.5-sr collection from 1.6-mm length out of measured 4.8-mm source, and 50% optical efficiency to focus
Estimated max. power at IF (2% BW, 1.25 kHz)	W	4	(See above)
Estimated max. power at IF (2% BW, 2 kHz)	W	6	Assuming energy measured at 1.25 kHz is reproduced at 2 kHz
Angular emission uniformity, over 40-deg half angle	%	≤ 2	
Etendue of source output	mm $\times$ mm	4.8×0.8	Axial length $\times$ transverse length; supplier reports plasma length is reduced to 4 mm in post-FC upgrade
Demonstrated maximum rep. rate	Hz	2000	For duration of $\approx$2 sec
Demonstrated steady-state rep. rate	Hz	500	
Pulse-to-pulse spatial stability	–	–	Total volume within 4.8×0.8 mm
Pulse-to-pulse intensity and integrated energy stability	%	9.6	At 500 Hz for average of 500 pulses. Av. energy value of 4.5 mJ
Pulse-to-pulse angular stability	%	10	Average of measurements at 0, 20, and 40 deg
Dissipated power (steady-state rep. rate)	J/pulse	9.5	Out of 27 J per pulse, 9.5 J per pulse is dissipated in the plasma. Recovery of 14 J of energy in the system. 1.25-kHz operation
Estimated conversion efficiency	%	0.42	1.25 kHz
Out-of-band power, 160–325 nm	mJ/sr	0.55	12% of 4.5 mJ [EUV + (>160 nm) band energy]
Out-of-band power, 325–715 nm	mJ/sr	0.25	6% of 4.5 mJ (see above)
Out-of-band power, 715–850 nm	mJ/sr	0.15	3% of 4.5 mJ (see above)
Out-of-band power, IR (>850 nm)	mJ/sr	0.29	6% of 4.5 mJ (see above)
Type and pressure of surrounding gas	mTorr	2.1	Xe gas at 500 Hz, relative flow 240
Source-facing condenser lifetime	–	–	
Key risk areas	–	–	
Critical component lifetime (electrode)	–	–	Supplier data: no erosion at 2×10^7 pulses

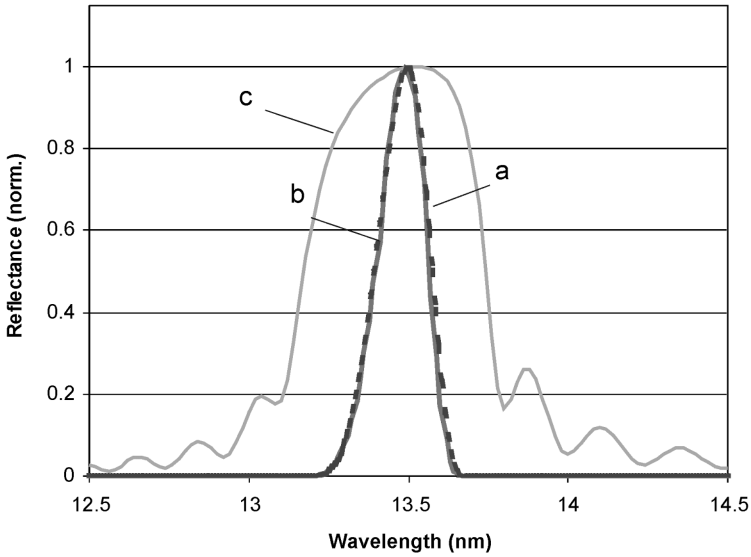

Figure 27.5 Reflectivity characteristics of a depth-graded MoSi/Si MLM (curve a) adjusted to the total response of an 11-mirror lithography system (b, dashed). Curve c represents the standard Mo/Si reflectivity response.

bandwidth. Obviously, a direct measurement within the 2% bandwidth, or even within the bandwidth of the total lithography optics, would be desirable.[29,30] At FOM, specially designed MLMs were fabricated with a reduced bandwidth of 2%, consisting of 70 layer pairs of molybdenum silicide and silicon. The first samples showed a bandwidth of 2.1% FWHM and a reflectivity of 50.1% at 13.5 nm. A first demonstration of the use of such a mirror in the existing FC2 setup showed a more than fourfold reduction of the spectral correction. The next step would be to move to the in-system bandwidth corresponding to the bandwidth of a full, 11-bounce EUVL system. By applying specially designed multilayer optics, such a system bandwidth can be mimicked by a single mirror, which is then compatible with the FC detection concept (Fig. 27.5).[30,31]

Apart from these evolutions in multilayer capabilities, the FC metrology equipment is also gradually evolving, incorporating for instance *in situ* EUV alignment using luminescent materials such as YAG:Ce crystals.[32] Diagnostics are also becoming more compact, for example, as in the FC3 system, which combines the classic FC metrology concept and an EUV telescope for inband source size measurements in a single, more compact device (Fig. 27.6).

27.6 Summary and Future Directions

The rapid progress of EUV source development and an increase in commercial interest will have the consequence that a considerably larger fraction of the results becomes proprietary. In response, the nature of FC may gradually change into a more facilitating cross-calibration-like activity. For the coming years, though, a

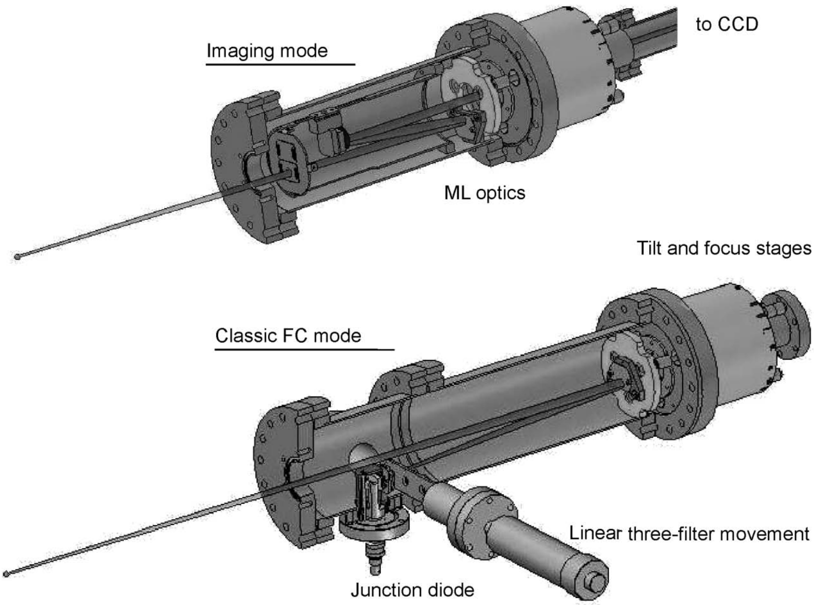

Figure 27.6 Latest version of the FC equipment, allowing EUV and OOB source characterization and EUV source imaging.

continued need to assess the progress of EUV source performance can be foreseen, as well as a need to have a noncommercial liaison activity on EUV metrology equipment in a position between EUV source suppliers and synchrotron-based or lab-scale calibration facilities. The FC formula is well suited for that purpose, though possibly with small adaptations.

In general, the range of available EUV metrology equipment is becoming noticeably broader, with more emphasis on the ability to monitor system-specific source parameters such as true inband power, inband source size, and spectral contributions in the VUV.[33] This development calls for an ongoing standardization effort in order to continue the development of EUV source measurement procedures.

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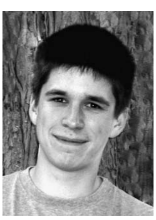
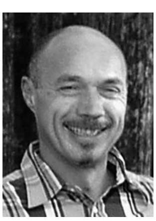


Santi Alonso van der Westen obtained an HND in engineering/applied physics in 2002. His thesis on multilayer research was done at FOM-Rijnhuizen, and as a research engineer he took part in various research activities on EUV optics and the FC2 project for plasma EUV source characterization.



Caspar Bruineman studied precision mechanical engineering at the HTS Hilversum in 1993, and did graduate work at FOM Rijnhuizen on the mechanical design of a Schwarzschild EUVL projection system. He has designed several XUV diagnostics and sources, including all the FC systems. Bruineman runs a private company, Scientec Engineering, which specializes in the design and production of high-precision UHV-compatible mechanisms, including EUV metrology.

Robert Huiting obtained an HND in precision engineering in 2001 and an HND in business engineering in 2003. Since then he has been working at FOM-Rijnhuizen as a research engineer and worked on EUV sources and XUV and plasma diagnostics, including the FC.

René de Bruijn obtained a Ph.D. in physics at the Technische Universiteit Eindhoven in 2004 for laser plasma research performed at FOM. His thesis addressed the characterization and enhancement of EUV emission of laser-produced Xe plasmas. De Bruijn participated in several FC activities. In 2004 he joined XTREME technologies GmbH, where he is involved in EUV gas discharge sources.

Remko Stuik obtained a Ph.D. in experimental physics at the Technische Universiteit Eindhoven in 2002 for research performed at FOM on the development of techniques for the characterization and optimization of EUV sources. Stuik was the lead member of the first FC team. His scientific interests include the design and use of optical instrumentation, ranging from visible to XUV wavelengths. Currently Stuik is at the Leiden Observatory and engaged in the development of adaptive-optics-assisted instruments for large ground-based telescopes.