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ABSTRACT

The scope of this paper is to outline the main marks and performances of the MagneDyn beamline, which was designed and built to perform ultrafast magnetodynamic studies in solids. Open to users since 2019, MagneDyn operates with variable circular and linear polarized femtosecond pulses delivered by the externally laser-seeded FERMI free-electron laser (FEL). The very high degree of polarization, the high pulse-to-pulse stability, and the photon energy tunability in the 50–300 eV range allow performing advanced time-resolved magnetic dichroic experiments at the K-edge of light elements, e.g., carbon and at the M- and N-edge of the 3d-transition-metals and rare earth elements, respectively. To this end, two experimental end-stations are available. The first is equipped with an *in situ* dedicated electromagnet, a cryostat, and an extreme ultraviolet Wollaston-like polarimeter. The second, designed for carry-in user instruments, hosts also a spectrometer for pump-probe resonant x-ray emission and inelastic spectroscopy experiments with a sub-eV energy resolution. A Kirkpatrick-Baez active optics system provides a minimum focus of $\sim 20 \times 20 \mu\text{m}^2$ FWHM at the sample. A pump laser setup, synchronized with the FEL-laser seeding system, delivers sub-picosecond pulses with photon energies ranging from the mid-IR to near-UV for optical pump-FEL probe experiments with a minimal pump-probe jitter of few femtoseconds. The overall combination of these features renders MagneDyn a unique state-of-the-art tool for studying ultrafast magnetic and resonant emission phenomena in solids.

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I. INTRODUCTION

Optical manipulation of magnetization with femtosecond laser pulses has opened a new paradigm shift in our knowledge about magnetization and spin dynamics in solids. Since the very first demonstration of femtosecond laser-induced demagnetization in 1996 by Beaurepaire *et al.*,¹ the optical manipulation of magnetically ordered materials has developed into a highly active area of research. At the same time, several questions of fundamental physics have come to light requiring a major development of experimental facilities and theoretical models. The MagneDyn beamline at the FERMI free-electron laser (FEL)^{2,3} has been designed and

built to provide a state-of-the-art tool to perform out-of-equilibrium and ultrafast magnetic dynamics experimental studies based on pump-probe setup arrangements by using FEL and optical lasers synchronized ultrashort light pulses as probe and pump pulses, respectively. MagneDyn exploits the time structure, full coherence, variable polarization, and harmonic content/multi-color operation of the FERMI FEL source in the 50–300 eV energy range⁴ and is open to external users since 2019.

The main end-station installed at MagneDyn has been designed for magnetic dichroism experiments. At present, the chamber (magnetic chamber) is coupled to a Wollaston-like polarimeter for investigating femtomagnetism in condensed matter exploiting the

polarization-sensitive core-resonant extreme ultraviolet (XUV) Kerr and Faraday effects,^{5–8} with high angular sensitivity, reproducibility, flexibility, user-friendliness, and the capability for energy and time fast scanning.

A second experimental area is open for roll-in-roll-out users' instruments. This workstation now hosts a setup for time-resolved resonant x-ray scattering (RXES/RXIS) experiments with a combined resolving power up to 1000 at ~300 eV FEL photon energy.⁹

Our aim here is to provide scholars, engaged in advanced ultrafast magnetic dynamic studies, with the basic information for performing experiments at MagneDyn. In particular, the high monochromaticity and stability of the FERMI FEL pulses, together with the control and high purity of the polarization, linear and circular, and the tunability of the FEL photons energy, make MagneDyn a unique beamline for studying ultrafast magnetic dynamics phenomena in a large variety of solids.

II. FERMI CONFIGURATIONS AVAILABLE AT MAGNEDYN

FERMI is an XUV-soft-x-ray FEL, based on the high-gain harmonic generation (HGHG) seeding scheme for amplification of the photon avalanche.^{2,3,11,12}

In this scheme, the electron bunch is seeded with an external laser pulse in the UV regime, allowing full control of the wavelength and bandwidth of the FERMI FEL pulses by varying the parameters of the seed. A remarkable advantage derives from the fact that the FERMI FEL light is classically coherent up to the second order of longitudinal (temporal) coherence,^{13,14} which results in FEL pulses with a narrow Gaussian-like wavelength profile. Interestingly, the control of the photon-beam parameters in a seeded-FEL allows very

fine-tuning of the wavelength across the selected absorption edge, which is a stringent requirement for resonant core-level experiments. In addition, due to the APPLE-II type undulators, FERMI provides full polarization control of the radiation, which is of pivotal importance for many experiments as in magnetic scattering experiments.

MagneDyn is fed by the FEL2 branch of FERMI. This branch operates in a double-cascade scheme in which the FEL pulse generated by a modulator and three radiators are used to seed a second FEL stage.³

Because of the double-cascade generation scheme, the energy spectrum of each XUV pulse consists of copropagating components at different wavelengths: (1) the first stage seed, (2) the 2nd stage pulse and their harmonics, and (3) the optical seed. Thus, proper filtering is needed to reduce the unwanted wavelength components. The seed laser is typically filtered out by a thin sheet of aluminum, whereas the filtering in the first stage range is carried out by means of ultrathin XUV filters¹⁵ available along with the beam transport system. The typical FEL intensities as a function of the photon energy are reported on the FERMI homepage,¹⁶ while Table I shows the main photon beam parameters.

III. BEAMLINE PHOTON TRANSPORT

A brand new branch of the Photon Analysis Delivery and REduction System (PADReS)^{4,17,18} has been implemented to manipulate and characterize the photon beam down to the MagneDyn experimental end-stations. A general layout of the MagneDyn photon transport system is sketched in Fig. 1, with the main optical components listed in Table II. The elements of beamline photon transport are discussed in Secs. III A–III D.

A. BL optics, transmission and harmonic filtering

The beamline mirror's set consists of a first switching mirror that directs the photon beam to the MagneDyn endstation, an on-line spectrometer consisting of a pair of interchangeable varied line spacing gratings, and the Kirkpatrick-Baez active optics (KAOS) system,¹⁰ which focuses the photon beam in the experimental chambers. The KAOS mirrors are separated by a vertical deflecting mirror. The beamline transmission has been maximized using a 2° grazing incident geometry for all the mirrors combined with a gold coating over the substrates. The low-energy grating is coated by an amorphous-carbon layer. The beamline transmissivity ranges from 70% for the long wavelengths (7–30 nm), between 10% and 20% in the range of 3–6 nm, and drops down to 7% at shorter wavelengths.

The beamline transmittivity is also affected by geometrical losses due to the finite size of the mirrors and to the photon beam divergence, which is linearly correlated with the wavelength.

Their effect is negligible at wavelengths below 20 nm, where the beam is confined within the length of the mirrors. At a longer wavelength (>30 nm), the radiation emitted in the first stage is significantly affected by geometrical cuts.

The overall beamline transmission is shown in Fig. 2, having taken into account both reflectivity and geometrical losses. For example, considering a photon flux at the source of about 10 μ J, we expect to obtain an intensity at the sample of the order of 5.8 μ J at 30 nm and 2.0 μ J at 6 nm. These intensities will correspond

TABLE I. Standard FEL2 photon parameters available at the MagneDyn endstations. FEL2 and FEL2 first stage should be intended as different sources. The typical values of the pulse intensity reported here are not normalized by the beamline transmittivity. The minimum spot size is indicated for the magnetic chamber. The FEL source can be used either as a pump or as a probe and the available photon energy fluence range is indicated for a 200 μ m² focus. The abbreviations have the following meanings: CR: Circular Right, CL: Circular Left, LH: Linear Horizontal, and LV: Linear Vertical.

FEL2 λ	4–20 nm (310–62 eV)
FEL2 first stage λ	20–30 nm (62–40 eV)
Polarization	CR, CL, LH, LV
Pulse duration	50–100 fs
Minimum focus size	20 $\times$ 20 μ m ²
Frequency	10–50 Hz
FEL pulse decimation	Available
Typ. pulse intensities	$\left\{ \begin{array}{l} 4 \mu\text{J at 50 eV linear H,} \\ 10 \mu\text{J at 50 eV circular,} \\ 15 \mu\text{J at 60 eV,} \\ 10 \mu\text{J at 100 eV,} \\ 3 \mu\text{J at 300 eV.} \end{array} \right.$
Energy density range	0.1–320 mJ/cm ² (at 200 μ m ²)

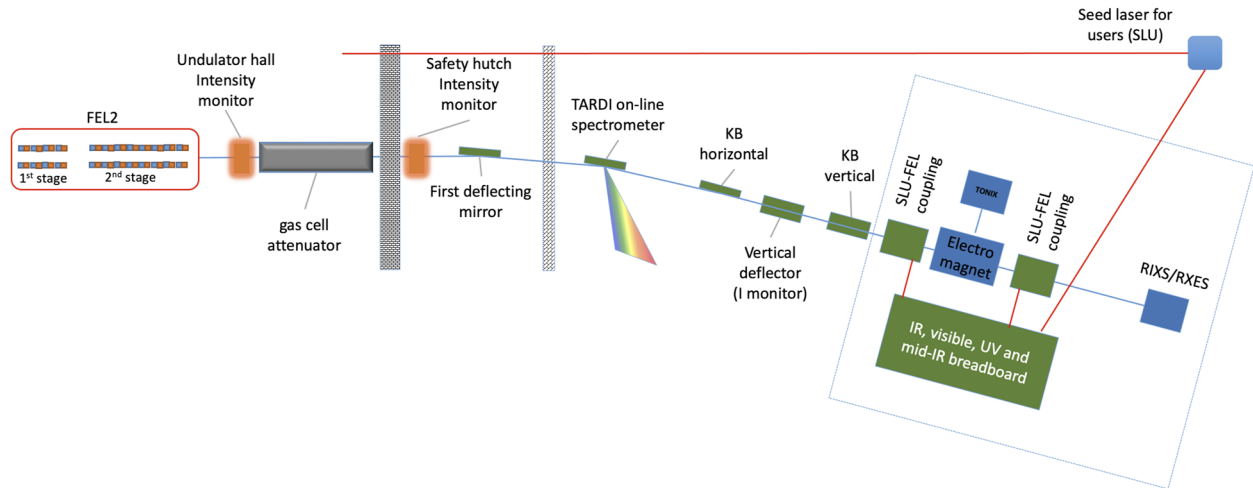


FIG. 1. General layout of FEL2 and the seed laser for users (SLU) photon delivery systems at MagneDyn. The intensity of the FEL pulses is first monitored by means of the undulator and safety hutch ionization chambers. The FEL intensity can be adjusted by using either a gas (nitrogen, neon, or helium) cell or solid-state thin film free-standing metallic filters. Then, the first deflecting mirror deviates the FEL2 pulses along the beamline. Pulse-to-pulse spectral monitoring is performed by means of a high-resolution spectrometer (TARDI). The pulses are then refocused by means of the Kirkpatrick–Baez active optics (KAOS)¹⁰ mirror bending system. A dedicated beamline delivers the SLU to MagneDyn, where a breadboard is assigned for the control and manipulation of the optical laser. The SLU consists of a portion of the seed laser that is delivered to the experimental stations via a low-vacuum beamline terminated by a quartz window. The main experimental chamber consists of an electromagnet coupled to an XUV polarimeter, a cryogenic sample environment, and pump-probe characterization tools and monitors. The second experimental station is equipped with an x-ray emission spectrometer for time/resolved RXES/RIXS experiments. The upstream chambers are equipped with a SLU–FEL coupling system made of in-vacuum mirrors, intensity monitors, solid-state filter wheels, and beam position monitors.

TABLE II. List of optical components for the MagneDyn photon transport system. The quoted values are the measured ones. The abbreviations have the following meaning: M1: Mirror, KB_H: Kirkpatrick–Baez horizontal, VDM: Vertical Deflecting Mirror, and KB_V: Kirkpatrick–Baez vertical.

BL optics	M1	KB _H	VDM	KB _V
Bulk material	Silicon	Glass-based	Silicon	Glass-based
Bulk dimensions (mm ³)	350 × 60 × 70	400 × 40 × 10	410 × 40 × 50	400 × 40 × 10
Roughness rms (nm)	<0.3	<0.3	<0.3	<0.3
Tangential radius (km)	>30	>1	>30	>1
Sagittal radius (km)	>30	>3	>30	>3
Optical area (mm ²)	300 × 30	360 × 20	390 × 20	360 × 20
Tangential slope error rms (μ rad)	<0.5	<0.5	<0.5	<0.5
Sagittal slope error rms (μ rad)	<5	<5	<5	<5
Shape error P-to-V (nm)	<10	<5	<10	<5
Coating	Au	Au	Au	Au
Manufacturer	Zeiss	Zeiss	Zeiss	Zeiss
TARDI gratings	Low energy	High energy		
Bulk material	Silicon	Silicon		
Bulk dimensions (mm ³)	250 × 25 × 40	250 × 25 × 40		
Roughness rms (nm)	<0.3	<0.2		
Grating line density (at center)	600	3750		
Slope error	<0.7 μrad rms tangential <0.7 μrad rms sagittal	<0.5 μrad rms tangential <1 μrad rms sagittal		
Wavelength range (nm)	6.75–30	1.05–9.6		
Incident angle	88°	88°		
Groove profile (holographic)	Laminar	Laminar		
Groove shape (nm)	depth = 10; ratio = 0.6	depth = 4; ratio = 0.7		
Coating	High density graphite 50 nm	Au 40 nm		
Manufacturer	Horiba	Horiba		

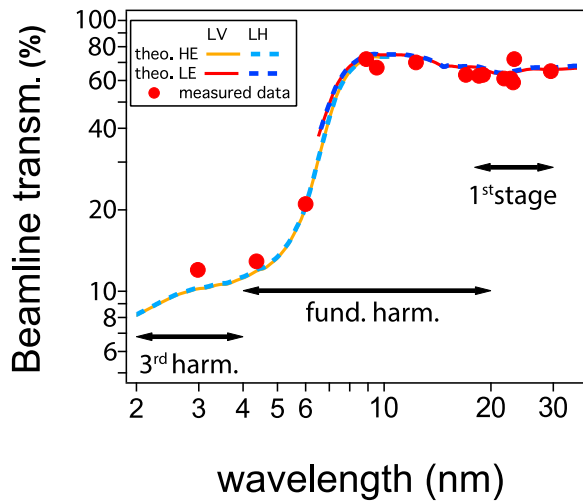


FIG. 2. The calculated beamline transmissivity for vertical and horizontal polarization is plotted against the photon energy in this log-log plot. The fundamental photon energy range of FEL2 is shown by arrows. The emission from the first stage of FEL2 and the third harmonic emission is also indicated. The beamline (BL) transmissivity is calculated considering the high energy and low energy gratings (dotted curves) of the TARDI spectrometer. Measured transmittance values are reported as single red dots.

to a fluence at the sample of the order of $2.5 \times 10^{12} \text{ Wcm}^{-2}$ and $8.2 \times 10^{11} \text{ Wcm}^{-2}$, respectively, for a focus size of $100 \times 100 \mu\text{m}^2$. The photon fluence can be attenuated by means of a set of dedicated solid-state filters (such as aluminum, zirconium, palladium, tin, etc.) and/or by using the PADReS gas cell attenuators.

B. Intensity monitors

The single pulse intensity can be monitored on a shot-to-shot base by a set of online diagnostics intensity monitors. This makes it possible to estimate the number of photons per FEL pulse. A description of these monitors is given in the following text.

Photoionization chambers: these detectors are placed in the undulator and safety halls of FERMI before the first deflecting mirror of the beamline. They are based on the photo-ionization of rare/nobel gas at the atomic density of the order of 10^{11} cm^{-3} ($p \sim 10^{-5} \text{ mbar}$). The monitors are almost completely transparent to the radiation, due to the low pressure in the vacuum chambers, and are most effective on the whole wavelength range covered by FERMI.

A silicon photodiode coupled with a YAG scintillator is available for measuring the total FEL intensity at the sample. This detector is placed before the sample and after the last refocusing mirror.

Mirror drain currents: the drain currents from the first switching mirror and the vertical deflecting mirror are also measured.

A 4-quadrant photodiode (4-QP) is used both as a beam position and intensity monitor. The 4-QP has been installed between the last KB-mirror and the sample.¹⁹

Finally, an **ultrafast microchannel plate** sniffs the beam reflected by a solid-state filter mounted in the in-coupling chamber and before the sample position.²⁰

TABLE III. Main parameters of the gratings and detectors of the on-line energy spectrometer TARDI.

Grating	Energy range usage
High-energy	130–1180 eV
Low-energy	20.5–185 eV
Detectors	
Ce:YAG + ORCA ²²	>177 eV, 50 Hz
CCD ANDOR ²³	<177 eV at 10 Hz;
	FEL harmonics;
	Low FEL intensity, 50 Hz with vertical binning

C. On-line spectrometer TARDI

The on-line single-shot single-energy spectrometer TARDI is designed to acquire the FEL2 spectrum.²¹ The main parameters of TARDI are reported in Table III. The spectrometer works at a constant grazing angle of 2° in order to deliver the beam to the MagneDyn endstations. TARDI is equipped with a high- and a low-energy grating grooved on identical Si substrates with optical surfaces of $250 \times 20 \text{ mm}^2$. The Si substrates have the central $60 \times 17 \text{ mm}^2$ -area grooved (e.g., the diffraction grating is ruled in their central part). The two gratings, planar in shape, have a varied line spacing (VLS) ruling so they can both diffract and refocus the radiation. Only a small fraction of the beam is diffracted and focused into the spectrometer detectors, while most of the beam ($\sim 97\%$ of the intensity) goes in the zeroth-order diffracted beam to the endstations. The diffracted radiation is either focused onto a Ce:YAG crystal positioned in a vacuum on a viewport and is then imaged by a CCD detector²² positioned outside the instrument, or directly on a XUV-sensitive CCD camera.²³ The resolving power of TARDI is 10^5 in all energy range.⁴ The horizontal position of the focused radiation (e.g., in the diffraction plane of the gratings) on the CCD is a function of the FEL radiation wavelength, and the spectral information is stored on a shot-by-shot basis. Instead, the vertical direction on the CCD gives the projected transverse distribution of the radiation pulse. Examples of single-shot energy spectra are shown in Fig. 3.

The low-energy grating, which is carbon-coated, covers the energy range from 20.5 to 185 eV (wavelength: 60.5 nm down to 6.75 nm), whereas the high-energy grating, gold-coated, covers the energy range from 130 to 1180 eV (wavelength: 9.6 nm down to 1.05 nm) by using both the first and second orders of diffraction.

D. KAOS focusing system

The KAOS⁴ system provides an adjustable focus size and shape that can be adapted to the measurement conditions (e.g., varying the fluence or illuminating specimens of different sizes) while preserving the spot position. Contrarily to the other KAOS systems implemented on beamlines at various FEL facilities, here the two focusing mirrors are a few meters apart. Details of the KAOS system are provided elsewhere.^{4,24,25}

TARDI Energy calibration

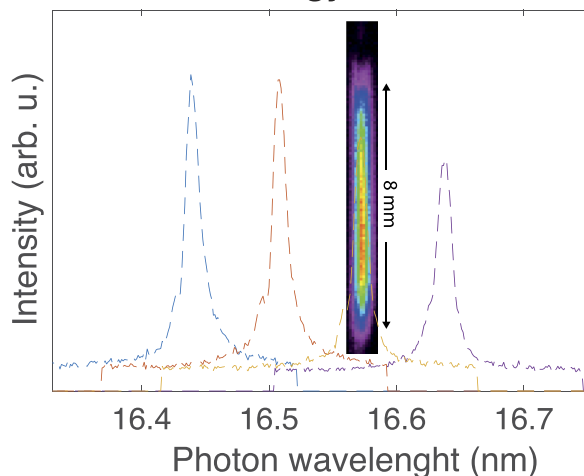


FIG. 3. Typical single-shot energy spectra taken by the TARDI spectrometer at different FEL λ 's. A single-shot image is also shown superimposed on its energy spectrum (full vertical binning). The spectrometer is used to control the quality of the FEL beam and its energy distribution. The FWHM represents the energy bandwidth.

IV. SEED LASER FOR USERS (SLU)

FERMI is designed for optical-pump/FEL-probe experiments with an extremely low timing jitter by redirecting to the experimental stations a portion of the IR laser used for the FEL external seeding. Due to the intrinsic synchronization of the FEL pulse with the seed laser pulse, the timing jitter for optical pump–FEL probe experiments, or vice versa, is about 6 fs RMS and it is also confirmed in a number of user experiments.²⁶ An additional example of pump–probe measurement demonstrating the timing jitter of 2.2 fs RMS has been measured at the FERMI (e.g., see Fig. 10 of reference Finetti *et al.*¹³ and related text.) The pulses dedicated to user experiments (referred to as SLU) are transported to the experimental stations via low-vacuum laser transport beamlines terminated by a quartz window and used for pump–probe experiments. A dedicated beam pointing feedback system secures the stability of the pointing of the laser beam to a few- μ rad level. The laser pulse energy is up to 3 mJ and it can be decreased to a sub- μ J level by a two-stage variable polarization-based attenuator. The fundamental pulse duration is about 55 fs in FWHM at the maximum compression and can be lengthened by adding either positive or negative chirp in a grating-based compressor/stretcher. A hollow-fiber-based pulse compression setup (HFC) has been recently added as an option to deliver sub-10 fs range IR pulses. The timing structure of the optical laser with 10 or 50 pulses per second reproduces the timing pattern of the FEL. The SLU system is on a dedicated optical table attached to the beamline chambers where pulse diagnostics, manipulations, and controls are performed. These include polarization state adjustment, harmonic conversion, pulse compression, pulse duration measurement, beam steering, pointing stabilization, and focusing.

A setup for non-linear frequency conversion can be used to generate the second [SHG (second harmonic generation) = 400 nm]

and third [THG (third harmonic generation) = 266 nm] harmonics of the fundamental wavelength, allowing us to optically pump a large variety of metals, semiconductors, and rare-earth/transition metals oxides. This system uses a common-path type scheme and β -BaB₂O₄ (BBO) crystals for SHG and THG generation.

Using different combinations of crystal thicknesses allows for optimizing the conversion efficiency or pulse duration depending on the needs of the measurements. The time delays between the fundamental and the SHG/THG pulses are compensated. The polarization of all harmonics can be varied ad-hoc by wave plates. Depending on the required wavelength, dielectric coated mirror sets are positioned after the SHG/THG stage for beam steering and removal of undesired lower harmonics. A compact fourth harmonic generation setup, delivering 200 nm light, is also available.

If a tunable optical wavelength is required, the fundamental SLU pulse can be, instead, used to pump a parametric amplifier TOPAS-C (Light Conversion). For this system, up-and-down-conversion units are available, allowing to provide 60–150 fs range pulse spanning from UV to mid-IR, with energy per pulse from 10 to about 200 μ J. In this case, the optical setup for transporting and focusing the desired wavelength needs to be decided well in advance before the beamtime and may be limited by the availability of optimized optical components. The laser-FEL pulse-to-pulse timing at the sample can be set in the 1 fs to 1 ns range. The focused laser beam enters the high vacuum chambers of the MagneDyn end-station via a viewport flange equipped with a broadband anti-reflection coated optical quality window.

Inside the in-coupling chambers, the optical laser beam is directed to the sample by an in-vacuum mirror with a coating optimized for the used wavelength range and mounted on a motorized tip-tilt stage. The optical laser and the FEL beams are delivered to the sample in the experimental chambers in a quasi-collinear geometry, having a 1.5° angle between the beam directions. This configuration guarantees the optimal spatial overlap of the pump and probe foci while moving over the sample surface. In addition, this geometry helps in minimizing the effects of FEL pointing instability. Typical parameters of the available SLU pulses are reported in Table IV. As mentioned above, frequency conversion units covering the DUV (240 nm) and MIR (15 μ m) spectral range are available; the parameters that can be obtained in this case are not yet fully characterized and have not been included in the table.

TABLE IV. Typical SLU pulse parameters at the sample. A lower repetition rate of the SLU can be customized with respect to the standard frequency (10 and 50 Hz). The abbreviation NM stands for "not measured."

SLU λ nm	Max pulse energy (μ J)	Min pulse duration (fs)	Min spot $1/e^2$ diam μ m
800	3000	60	100
800 (HFC)	100	10	100
400	100–300	50–80	80
266	60–100	80–150	80
OPA signal (1150–1600)	300	80	NM
OPA idler (1600–2500)	100–250	80	NM

A. SLU-FEL spatial and temporal overlap method

Stable spatial overlap and a well-defined time delay between the FEL and optical laser are crucial. At MagneDyn, the spatial overlap of the FEL and the optical laser is controlled by monitoring the beam positions with a Ce:YAG crystal located at the sample position by using a CCD camera with an Infinity K2 Distamax,²⁹ featuring 5 μm spatial resolution. Coarse and fine laser beam steering is obtained by using stepper motor-driven kinematic mounts and piezo tip-tilt platforms, respectively. Once the SLU-FEL overlap is obtained, the SLU beam position is maintained by a second section of the beam pointing feedback based on a virtual image on a CCD positioned outside the chamber (see Fig. 4) and the above-mentioned piezo tip-tilt actuator.

This monitor is positioned at the same distance l from the focusing telescope as the distance between the telescope and the sample. The temporal overlap between two pulses on a femtosecond timescale is established in two steps. First, the coarse time overlap with ~ 10 ps accuracy is achieved by monitoring the signal from a high-frequency band-pass antenna that collects the FEL and the optical laser pulses on a fast digital oscilloscope. In the second step, the search for the exact time overlap (fine time zero) is based on a measurement of transient changes in optical reflectivity induced by the FEL as a function of the time delay. The precision of temporal overlap is within 100 fs. For long measurements, a periodic check/adjustment of time zero is done for its stability.

The pump (FEL)–probe (optical) transient reflectivity is monitored by the temporal overlap method that collects the optical laser pulses reflected from a Si, GaAs, or Si_3N_4 sample.

A simplified layout of the temporal overlap method is sketched in Fig. 4, together with a set of traces measured under different probe

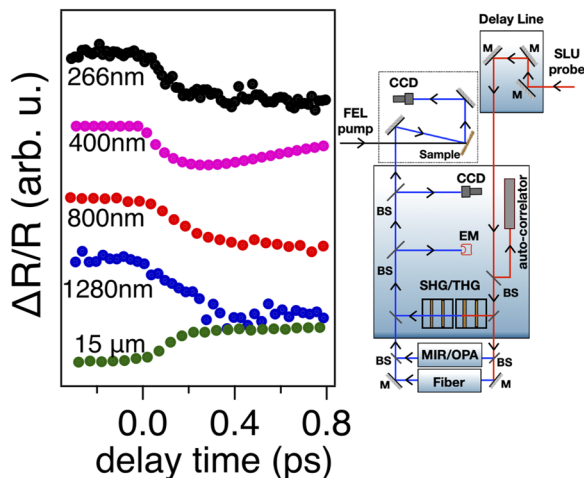


FIG. 4. Temporal overlap: (left panel) relative change in the transient reflectivity ($\Delta R/R$) of a single crystal of silicon measured at different probing wavelengths as a function of the delay time between the FEL pump and the SLU probe pulses and (right panel) the optical scheme for fine time zero measurements. M denotes reflecting mirrors, BS: beam splitter, EM: energy meter, and SHG/THG: second (400 nm)/third (266 nm) harmonics generation. The ($\Delta R/R$) signal is collected by a CCD camera with an Infinity K2 Distamax.

TABLE V. Experimental SLU and FEL parameters for fine time zero measurements. SLU is used as a probe with almost comparable pulse energy (0.5 μJ) for all wavelengths.

SLU		FEL	
λ (nm)	Pulse energy (μJ)	λ (nm)	Pulse energy (μJ)
800	0.5	3.86	9
400		16.64	13
266		4.32	20
1 280		18.69	5
15 000		16.20	11

conditions. The experimental FEL (pump) and SLU (probe) parameters are tabulated in Table V. The detailed dynamics after the pump arrival depend on both pump and probe colors. In order to make a proper estimate of the time overlap, it is enough to consider the trace up to 500 fs. The behavior of the system after such a time scale is out of the scope of this discussion. In particular, the transient reflectivity of silicon single crystals measured at 1280, 800, 400, 266 nm, and mid-IR (15 μm) is reported.

V. BEAMLINE CONTROL AND DATA ACQUISITION

The control system of the FERMI facility³⁰ has the demanding task of acquiring and correlating in real-time the characteristics of the electron and photon beams (both FEL and SLU), and the output of the end-station instrumentation, within a time window compatible with the 50 Hz FEL repetition rate. Such a task requires an infrastructure of synchronization and data transmission spanning the whole facility, from the injector to the end-stations. Moreover, the acquired data must be efficiently directed toward a data storage system and made available at once for possible in-time online processing and analysis.

The backbone of the control system is an Ethernet network connecting all types of devices. Standard instrumentation is controlled by VME-based front-end computers (Equipment Controllers – EC) equipped with Emerson MVME-7100 PowerPC boards running the Linux operating system. Instruments requiring special hardware interfaces or proprietary software are controlled and acquired by Intel-based rack-mount servers. In addition, a system made of Programmable Logic Controller (PLCs) is devoted to instrumentation protection.³¹

The synchronization between devices is performed by means of a dedicated Ethernet network running a real-time software protocol called Network Reflective Memory (NRM),³² which allows transparent data sharing among connected computers. Moreover, a real-time server is in charge of distributing an increasing counter called “bunch number,” which is then used by each acquisition computer to uniquely time-tag the data acquired shot-by-shot. EC computers also host an Event Receiver (Micro-Research EVR) that receives the machine bunch trigger via a fiber optics infrastructure, making it available for synchronizing the data acquisition of the instrumentation.

The Data Acquisition (DAQ) software³³ of the MagneDyn beamline, based on the Tango framework,³⁴ gathers the data collected by the instrumentation pertaining to each bunch number and

organizes them into HDF5 (Hierarchical Data Format) archives.^{35,36} The software architecture is based on two layers of Tango device servers: the low-level layer is devoted to single instruments control, while the high-level is in charge of carrying out the experiment, gathering the data, performing online processing/reduction, writing the HDF5 archives, and uploading them into the storage system. The latter is composed of a temporary fast-access, beamline-specific storage area (*scratch4magnedyn*), and a stable redundant storage space (*online4magnedyn*) that is accessible by all the participants in that specific experiment, also remotely through the scientific computing portal of the Virtual Unified Office (VUO).³⁷ Finally, the portal also allows remote control of the experiment and provides programming tools for online analysis of the experimental data, mainly based on the Jupyter platform.³⁸

VI. EXPERIMENTAL END-STATIONS

A schematic layout of the experimental area of MagneDyn is illustrated in Fig. 5. The main experimental end-station presently installed at MagneDyn is dedicated to magnetic scattering experiments. The second user experimental area hosts a setup for time-resolved resonant x-ray scattering experiments.

A. Sample stage

The sample is mounted on a four-axes manipulator with stepper motors for precise sample adjustment. The sample can be moved in the scattering plane (Y- and X-directions), along the vertical (Z-axis) and around the θ . These adjustments can be done with an accuracy of $1\ \mu\text{m}$ and 0.1° . An additional rotation stage can be also installed on the sample holder for the azimuthal rotation. Sample surface scanning is enabled by the X-Z movement of the manipulator, while the Y movement permits to align the sample surface to the beam path or adjust the offset of different thicknesses of the samples.

The sample holder can be shaped and machined based on the experiment scattering configuration and sample typology. Two

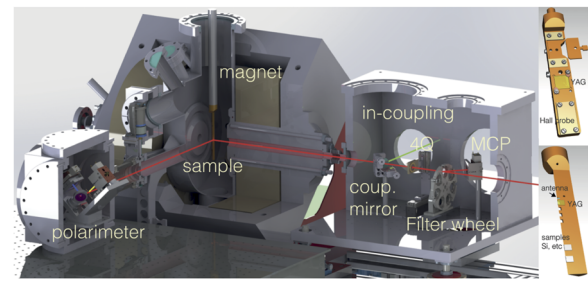


FIG. 6. View of the magnetic chamber. The focused FEL beam propagates through the in-coupling chamber where the beam is filtered and its intensity is monitored. The FEL beam enters the magnetic chamber through the magnetic expansion and impinges on the sample mounted on the shaft of a closed-cycle cryostat. Quasi-collinear to the FEL path, the optical beam is driven to the sample through an in-coupling mirror. The FEL reflected beam is then collected by the polarimeter. Directly reflected optical beams are collected through a side viewport by means of a telemicroscope (not shown) that is part of the focused imaging and the time-zero diagnostics. A schematic of the two sample holders available at MagneDyn is also shown. The sample holders are equipped with standard tools such as an antenna, YAG, Si sample, etc., for temporal and spatial overlaps, temperature, and magnetic field readings.

sample holders are available: (a) a copper shaft where multiple samples can be mounted and are equipped with clearances for transmission experiments and (b) a copper socket where a single removable copper plaquette specifically designed for air-sensitive samples that must be loaded in the magnetic chamber while preserving the vacuum conditions, shown in Fig. 6.

Both sample stages are equipped with a Ce:YAG polished crystal for the control of the spatial overlap, a broad-band antenna with a naked tip for coarse time-zero overlap, a Si crystal for fine time-zero overlap (see Sec. IV A), and a Si diode sensor and a Hall sensor for controlling the temperature and the magnetic field, respectively. The sample can be cooled down by means of a helium closed-cycle cryostat and a radiation shield (ARS, Model CS-204AF-DMX-20B³⁹) allowing the control of the sample temperature between 25 K and

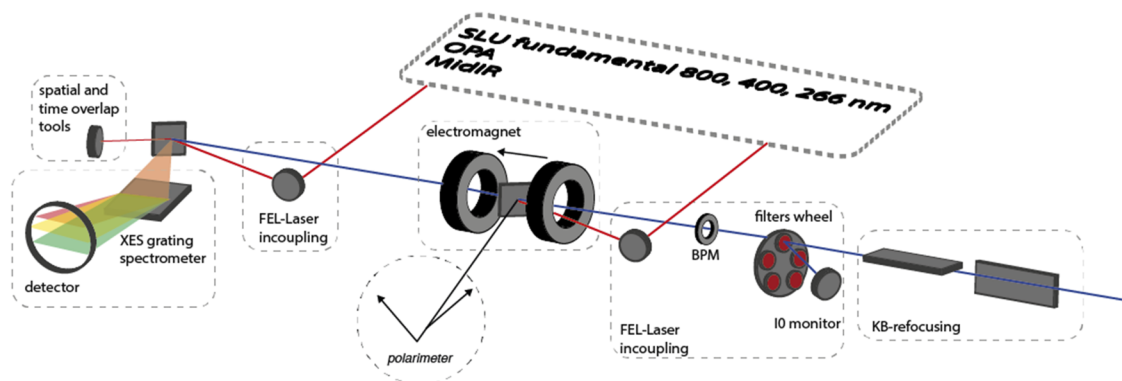


FIG. 5. Optical layout of the experimental area of MagneDyn. From the right: the FEL beam can be focused and shaped along the beam direction in either the magnet or the RXES chambers by the KAOS refocusing mirror system. The SLU is manipulated in a dedicated optical breadboard and then driven into the experimental chambers through two dedicated in-coupling high-vacuum chamber where piezo-motorized collecting mirrors are placed. In the first in-coupling vessel, a beam positioning monitor, two solid state filter wheels, and an I_0 detector are installed. The electromagnet is coupled to an XUV polarimeter.²⁷ The RXES chamber has an XES355 spectrometer²⁸ available.

room temperature. A specially adapted heating stage can heat the sample up to 450 K.

B. Magnet chamber and the EUV polarimeter

A layout of the magnet chamber is displayed in Fig. 6. The magnet end-station of MagneDyn consists of a UHV in-coupling chamber, a UHV chamber customized with a GMW⁴⁰ electromagnet that is capable of generating a 1.6 T magnetic field collinear to the FEL beam direction, and the Wollaston polarimeter for X-ray FEL sources (TONIX). The polarimeter is equipped with pairs of high reflective Nb mirrors and multilayers suitable for covering the photon energy range relevant to transition metal M-edges and rare-earth N-edges (see Fig. 7). The working scheme and the performances of the polarimeter are reported by Caretta *et al.*^{27,41} The focused FEL beam propagates through the in-coupling chamber where it is filtered by solid-state filters before arriving in the magnet scattering chamber. The beam reflected from the sample is then recollimated and analyzed by the polarimeter. Three collection angles of incidence are available: 37.5°, 45°, and 52.5°. A scattering scheme for measurements in the transmission is also possible. A set of demonstrative time-resolved element-specific Kerr rotation and relative change in magnetization taken on a Ni₈₀Fe₂₀ permalloy as a function of time and photon energy are reported in Fig. 8.

The experiment is performed in a pump-probe mode with the FERMI FEL pulses tuned at the Ni M_{2,3} (67 eV) and Fe M_{2,3} (55 eV) edges, respectively. The sample is excited with a laser pump pulse at 1.56 eV (800 nm) with a fluence of 32 mJ/cm². The same FEL experimental parameters are listed in Table VI. The XUV reflected pulse is collected by the polarimeter in order to measure the polarization state. As shown in Figs. 8(a) and 8(c), it is possible to reconstruct the reflectivity ($\Delta R/R$) and the magnetic ($\Delta M/M$) response of the material after the laser pump excitation. The demagnetization dynamics for both elements shows a sub-picosecond decay, followed by a slower recovery time. The $\Delta M/M$ curves fitted using a double-exponential fit function suggest that the demagnetization occurs within 150 fs for Ni and within 190 fs for Fe, respectively. Figure 8(b)

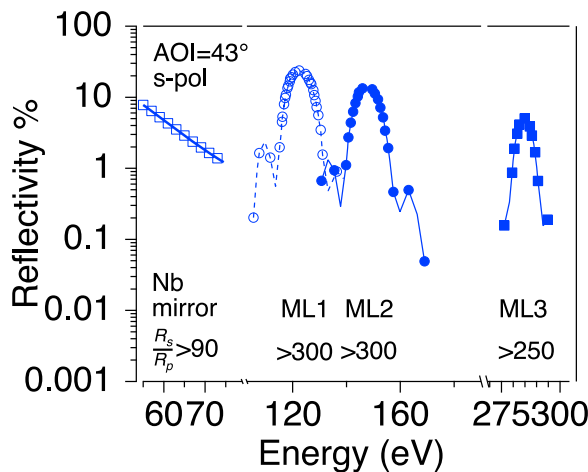


FIG. 7. Nb mirror and multilayers (ML) s-polarization reflectivities (R_s) at a fixed angle of incidence of 43° in the range 60–300 eV.

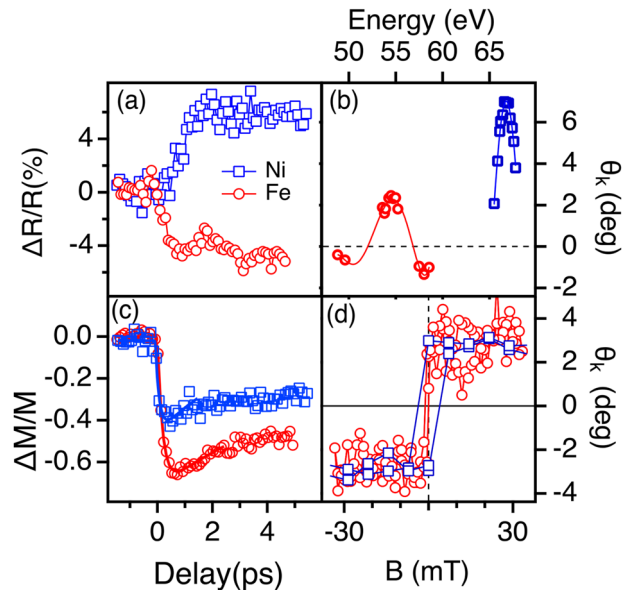


FIG. 8. (a) Element resolved relative change in the sample reflectivity as a function of time delay between the pump optical pulse and the FEL probe pulse tuned at Ni M_{2,3} (67 eV) and Fe M_{2,3} (55 eV) edges, respectively. (b) Element resolved Kerr rotation of the light polarization as a function of the photon energy (solid lines are guide to the eye). (c) Demagnetization signals at the Ni and Fe M_{2,3}-edges. (d) Element resolved unpumped magnetic hysteresis.

shows the experimentally measured photon energy dependence of the Kerr rotation angle for Fe and Ni spanning their M edges. In Fig. 8(d), the static Kerr rotation at the Ni and Fe M_{2,3} edge energies was measured by applying a magnetic field of the order of 50 mT in longitudinal MOKE geometry. Kerr rotation shows a hysteresis curve confirming the ferromagnetic nature of both the elements in permalloy.

TABLE VI. Relevant experimental FEL parameters for typical measurements of time-resolved MOKE and time-resolved RXES FERMI MagneDyn beamline. The data reported in this table are measured at Ni and Fe M-edges on a Ni₈₀Fe₂₀ thin film, the Si L-edge on a Ni/Si thin film, and a carbon K-edge of graphite.

	Fe M _{2,3} ^a	Ni M _{2,3} ^a	Si L _{2,3} ^b	C K
Average incident energy at the sample (μJ)	0.3	0.25	0.08	0.02
Average of photons per pulse	2.6×10^{10}	2.2×10^{10}	5×10^9	2×10^7
Repetition rate (Hz)	50	50	50	10
Pulse length (fs)	60	60	70	70
Spot size on the sample (1/e ² diam. μm)	50	60	60	40
Fluence per pulse (mJ/cm ²)	4	2.5	1.2	0.05

^aData taken from Ref. 27.

^bData taken from Ref. 42.

C. Time-resolved RXES chamber and spectrometer

The second experimental area hosts a chamber for pump-probe RXES/RIXS experiments with a sub-eV energy resolution. This end-station is an upgraded version of the time-resolved RIXS setup already developed and installed at FERMI.⁹

A schematic of the chamber is sketched in Fig. 9, top panel. The incoming FEL beam is scattered by the sample and then the radiation is collected by the spectrometer placed at 90°.

The scattering angle of incidence can be varied between 0° and 90°, while the in-plane X-Y directions are used to adjust the sample on either the FEL and spectrometer foci.

The spectrometer consists of three spherical gratings in Rowland geometry set in the plane of the horizontal FEL polarization.²⁸ The main parameters of the three gratings are reported in Table VII, while the gratings transmittivities as a function of the photon energy are reported in Fig. 9, bottom panel. Dedicated ray-tracing tools and energy calibration procedures are also available and reported elsewhere.⁴³

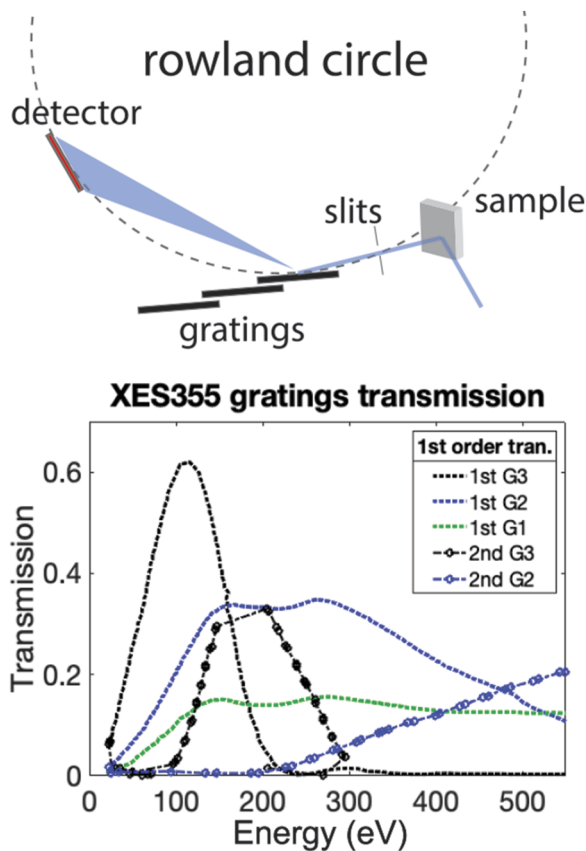


FIG. 9. Top panel: the FEL light scattered by the sample is collected by the spectrometer through a pair of collimating slits and dispersed over the solid-state detector. Scienta XES 355 can be described as three spectrometers merged into one single stack by having a common entrance slit and a detector that can be aligned to the focal curve (Rowland circle) of the selected grating. Bottom panel: first and second order transmittivities of the three gratings.

TABLE VII. The Scienta XES 355 spectrometer gratings parameters mounted on the Rowland circle geometry.

Standard gratings	G1	G2	G3
Groove density (lines/mm)	1200	600	400
Incident angle	88.1	87.43	84.6
Energy range in first order (eV)	130–700	55–600	>20
Optimized energy (eV)	540	275	100
Resolution at optimized energy with 10 μm entrance slit (eV)	0.39	0.20	0.07

The spectrometer has an overall resolution of ~ 100 meV at 70 eV up to ~ 600 meV at 300 eV. The resolution is defined by either a pair of slits or the vertical dimension of the FEL focus in a slitless configuration. The radiation is collected by a 2-D detector containing a multi-channel plate double stack, activated for UV and x rays by CsI, and read out by a resistive anode, which is then imaged by a CCD.

The sample stage consists of the system already described in Sec. VI A. The full capabilities of the optical laser system of MagneDyn and the spatial- and time-overlap tools are available.

A demonstrative set of pump-probe RXES data taken at the carbon K-edge of a HOPG (Highly oriented pyrolytic graphite) sample are shown in Fig. 10. The carbon sample has been pumped by a

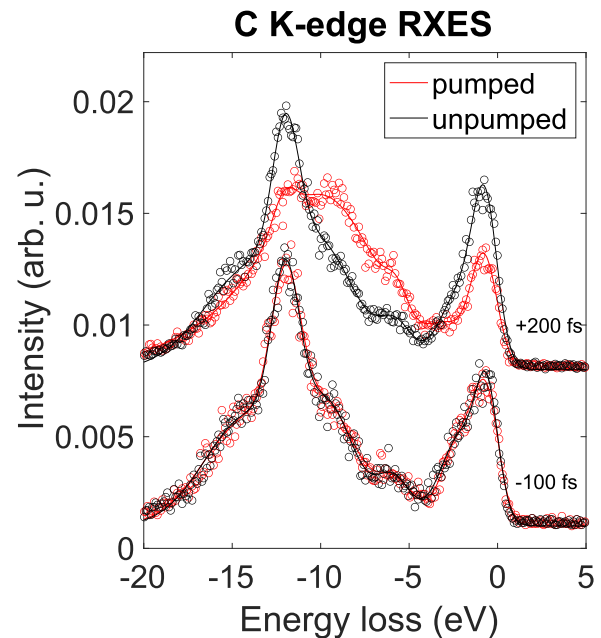


FIG. 10. The pumped (red dotted curve) and unpumped (black dotted curve) RXES spectra at positive (+200 fs) and negative time delays (−100 fs) taken at the carbon K edge (incident photon energy $h\nu = 295$ eV) of an HOPG sample are shown. The normalized intensity of the RXES spectra is plotted vs the photon energy loss.

266 nm optical pulse and probed with a FEL photon energy tuned at 295 eV resonant to the C K ($1s \rightarrow 2p_\pi$) edge. The pump and probe fluences were 30 and 0.5 mJ/cm², respectively.

The static (black dotted curve) and pumped (red dotted curve) RXES spectra have been measured at negative (−100 fs) and positive (+200 fs) pump–probe time delays. The energy resolution was set to 600 meV. The acquisition time of each spectrum is ~20 min.

The RXES spectra span from 0 eV down to −20 eV energy loss and map the p_π - and p_σ -symmetry projected valence bonding orbitals of carbon below the Fermi energy.

The main spectral features originate from either the momentum-dependent $2p_\pi$ and $2p_\sigma$ orbital components of the valence band in the Brillouin zone or the dipolar matrix elements that couple the valence electronic states and the C 1s core-hole.

The physical origin of the observed large spectral change in the pumped spectra will be the subject of forthcoming work.

VII. CONCLUSIONS

The MagneDyn beamline has been designed to provide the User community with advanced experimental capabilities exploiting the FERMI FEL light to carry out time-resolved XUV MOKE and time-resolved RXES/RIXS experiments.

The feasibility of time-resolved XUV MOKE experiments on solid samples has been demonstrated at FERMI by means of the MagneDyn beamline, combining a XUV Wollaston-like polarimeter with tunable photon energy polarized FEL pulses and a synchronized optical laser system in a pump–probe scheme.

The combination of the high transmittivity of the TONIX polarimeter, the variety of the available sample environments in terms of magnetic field and temperature as well as sub-picosecond time resolution, clearly makes magneto-dynamical studies of systems composed of 3d transition metals and 4f rare earth elements possible.

The feasibility of time-resolved RXES/RIXS on solid samples with sub-picosecond time resolution and ≤ 1 eV energy resolution has been demonstrated utilizing a high throughput spectrometer in combination with the pump–probe facilities available at MagneDyn permitting the recording of spectra with a sufficient signal to noise ratio in a reasonable amount of time. Spatial and temporal overlap between FEL and optical laser can be efficiently established down to 10 μm and to the femtosecond level, respectively, using the diagnostics at the end-station.

We would like to mention that a major upgrade of the FEL2 source is planned, extending the photon energy range to the water window and up to $L_{2,3}$ edges of transition metals.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Marco Malvestuto: Conceptualization (lead); Methodology (lead); Supervision (lead); Writing – original draft (lead); Writing – review & editing (lead). **Antonio Caretta:** Conceptualization (equal); Investigation (equal); Methodology (equal). **Richa Bhardwaj:** Data curation (equal); Investigation (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Simone Laterza:** Data curation (supporting). **Fulvio Parmigiani:** Methodology (equal). **Alessandro Gessini:** Methodology (equal). **Matteo Zamolo:** Methodology (supporting). **Fabio Galassi:** Methodology (supporting). **Rudi Sergo:** Methodology (supporting). **Giuseppe Cautero:** Methodology (supporting). **Miltcho B. Danailov:** Methodology (equal). **Alexander Demidovic:** Methodology (equal). **Paolo Sigalotti:** Methodology (equal). **Marco Lonza:** Methodology (supporting). **Roberto Borghes:** Software (equal). **Adriano Contillo:** Software (equal). **Alberto Simoncig:** Methodology (equal). **Michele Manfreda:** Methodology (equal). **Lorenzo Raimondi:** Methodology (equal). **Marco Zangrando:** Methodology (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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