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ELECTRON BEAM TEST FACILITIES FOR NOVEL APPLICATIONS

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Abstract

Delivering and tailoring high brightness electron beams for a wide range of novel applications is a challenging task in single pass accelerator test facilities. This paper will review beam dynamics challenges at single pass accelerator test facilities in Europe to generate, transport and tailor low- to medium-energy high brightness electron beams for a range of novel applications.

INTRODUCTION

Single pass test facilities delivering high brightness electron beams are being used worldwide to test new ideas and concepts in a wide range of applications. These include new radiotherapy modalities, THz radiation production and demonstration of very high accelerating gradient concepts. The proof-of-principle novel acceleration experiments at these test facilities are strongly motivated as a stepping stone for next generation light sources and energy frontier facilities. These test facilities address challenges in generation, acceleration and manipulation of high brightness beams to enable novel experiments. Additionally, these facilities provide an essential platform for testing and developing new accelerator technologies. Some of these facilities include access to high power lasers, which opens up a different class of possible experiments in the area of novel acceleration and beam manipulation. These facilities also offer a range of possibilities to apply machine learning to accelerator subsystems and to improve beam performance. When implemented, this has a promise to be a step change in all aspects of accelerator operation and beam delivery to users.

The focus in this paper is on low- to medium-energy (up to 300 MeV) high brightness electron beam test facilities in Europe which offer some form of external user access. There are a number of test facilities in Europe in this category; some are designed and built with the main goal to provide access to high quality electron beams for user experiments and novel applications (e.g. ARES@DESY [1], CLARA@STFC [2], FLUTE@KIT [3], PITZ@DESY [4]); SPARC_LAB@INFN [5] and some facilities have been repurposed, converted and upgraded into user facilities (e.g. CLEAR@CERN [6] and FLASH***lab***@PITZ [7]. This paper will review the beam dynamics challenges in generation, acceleration and manipulation of electron beams to provide user requested beam parameters at the varied experiments. The factors affecting the beam quality due to technical system performance such as stability, jitter, feedback, and so on, are not covered here.

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FACILITIES IN EUROPE

This section provides a brief description of six test facilities in Europe which use conventional RF technology to provide electron beams for novel applications. Table 1 gives an overview of electron beam parameters either available or planned to be available in near future at these facilities.

ARES (Germany)

Accelerator Research Experiment (ARES) at Short Innovative Bunches and Accelerators (SINBAD) [8] is an accelerator R&D test accelerator in the former DORIS tunnel at DESY, Hamburg, and operational from 2020 [9]. The ARES facility consists of a normal conducting 1.5-cell S-band photo-injector, followed by two travelling wave S-band linac structures providing beam energy up to 160 MeV. The beam line includes transport and focusing magnets, and a complete set of beam diagnostics, including spectrometers. A combination of velocity bunching and variable magnetic chicane facilitates provision of ultra-short bunches. An advanced, polarizable X-band Transverse Deflecting Structure (TDS) [10] is installed for beam characterisation. ARES offers three experimental areas: the first is a vacuum experimental chamber equipped with a hexapod, and also incorporates an imaging screen and a nano-wirescanner; the second is located in the dispersive arm of the spectrometer section at the end of the linac and consists of a vacuum chamber, separated from the machine vacuum by a 50 µm thick titanium foil, and is used for detector tests. The third experimental area is an in-air experimental chamber separated from the machine vacuum by a 50 µm thick titanium foil. This station is equipped with beam diagnostics, linear stages and is mainly used for medical experiments.

CLARA (U.K.)

The Compact Linear Accelerator for Research and Applications (CLARA) is a high-brightness electron beam test facility being developed at STFC Daresbury Laboratory. The front-end (FE) of CLARA comprises a 1.5-cell S-band high repetition rate RF photo-injector [11], followed by a 2 m S-band linac. The accelerated beam from the FE is merged, via an S-bend chicane, with the existing Versatile Electron Linear Accelerator (VELA) experimental beam line. The CLARA FE was commissioned with a 10 Hz 2.5-cell S-band photo-injector earlier used on VELA, and the facility has

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Table 1: Range of Parameters Available at EU Test Facilities (*not all parameters simultaneously achievable*)

Facility	**Maximum Beam Energy [MeV]**	**Bunch Charge [pC]**	**Bunch Length**	**Maximum Repetition Rate [Hz]**	**Micro-bunches per train**	**Micro-bunch Spacing**
ARES	160	0.003 - 280	0.8 fs - 1 ps[a]	50	1	N/A
CLARA	250	5 - 250	≤ 50 fs - 10 ps	100	1	N/A
CLEAR	230	5 - 3000	100 fs - 10 ps	10	1 - 150	1.5 or 3 GHz
FLUTE	41	1 - 1000	1 fs - 300 fs	10	1	N/A
PITZ	22	0.1 - 5000	100 fs - 60 ps	10	1 - 4500	0.1 - 5 MHz[b]
SPARC_LAB	180	10 - 2000	20 fs - 10 ps	10	1 - 5[c]	N/A

[a] Measured 20 fs as TDS is not fully operational
[b] Besides fixed repetition rate, the selection of individual bunches in the train is also possible
[c] Delay between bunches is 0.5 ps - 20 ns, whilst delays larger than ≈ 360 ps are achieved by injecting the bunches in different RF buckets

been made available for user experiments from 2018 [12] in two dedicated experimental runs to date. Installation of a further three 4 m S-band linacs to allow acceleration to 250 MeV is currently under way [13], and will also include the installation of: a variable magnetic bunch compressor; X-band linearising cavity for harmonic correction; and a dedicated diagnostics section including an S-band TDS and a dielectric de-chirper. A 4-dipole arc, located at the exit of the diagnostics section, transports the beam to the Full Energy Beam Exploitation (FEBE) area, located in a separate, shielded, enclosure. Access to a dedicated 100 TW laser, located on top of the FEBE hutch, will allow a variety of combined electron beam and laser experiments. The facility will be available for user experiments in early 2025.

CLEAR (Switzerland)

The CERN Linear Electron Accelerator for Research (CLEAR) is a multi-purpose facility, operating since 2017 [14], providing a high-quality electron beam up to 230 MeV to users. The facility is an adaptation of the CALIFES electron linac located in the experimental area of the CLIC Test Facility 3 (CTF3) at CERN. The facility consists of a 2.5-cell S-band photo-injector, an S-band accelerating Linac structure, used as a velocity buncher, and two 4.5 m S-band Linac structures. This is followed by a 20 m long experimental beam line which includes a diagnostics section and three test areas: (1) an in-air spectrometer/test area called VESPER (Very energetic Electron facility for Space Planetary Exploration missions in harsh Radiative environments); (2) a long section that can host several in-vacuum experiments; and (3) an in-air test stand situated just before the dump, with an additional spectrometer where most of the experiments take place [15]. Both in-air areas are extensively used for studies on medical applications and radiation hardness testing experiments. CLEAR has completed six years of user operation and the experimental parameter range available to users has been largely improved; more substantial improvement plans including a second beam line are under way.

CLEAR is currently a unique facility providing both Very High Energy Electrons (VHEE) and ultra-high dose rates for FLASH radiotherapy R&D.

FLUTE (Germany)

The Farinfrared Linac- and Test-Experiment FLUTE at the Karlsruhe Institute of Technology (KIT), developed and operated by KIT-IBPT [3], serves as an accelerator test facility for a variety of accelerator physics studies. FLUTE also provides an infrastructure for picosecond and femtosecond electron and photon beam studies to enable future application-oriented research from materials to life sciences and innovative technology solutions such as advanced electron and photon beam diagnostics. The low-energy section of FLUTE consists of an RF photo-injector providing up to 5 MeV electrons, followed by a diagnostics section including an experimental chamber and a spectrometer. This chamber is currently used for the split-ring resonator setup, an advanced streaking experiment using laser-generated THz pulses [16, 17]. In future, a 5.5 m S-band linac, accelerating the bunches to about 41 MeV, and a variable D-shaped bunch compressor will be installed to provide ultra-short electron bunches, down to a few femtoseconds, primarily for THz generation and advanced diagnostics studies. Also a dedicated THz superconducting undulator is being considered [18, 19].

PITZ (Germany)

The Photo-Injector Test facility at DESY in Zeuthen (PITZ), was originally built to test and optimise sources of high brightness electron beams for free electron lasers and linear colliders. The facility has been developing and delivering these sources to the FLASH [20] and European XFEL [21] facilities, both located at DESY Hamburg, for many years. At the PITZ facility [22], the electron bunches are produced in a 1.6-cell photo-cathode RF gun operating at 1.3 GHz with a cathode gradient of up to 60 MV/m and providing a maximum beam energy of 6.5 MeV. This is followed by an L-band booster cavity accelerating up to 22 MeV. A large number of additional instrumentation is available in the PITZ beam line for detailed control and diagnostics of the electron beam. In 2022, a world-leading high power, tunable THz-SASE-FEL was put into operation in a separated tunnel annex at PITZ after a significant

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extension of the facility [23]. Based on this, an additional beam line was added, which will be further extended to provide a platform for electron FLASH radiation therapy and radiation biology. This FLASH***lab*** [24] offers a uniquely wide parameter range for users concerning, for example, time structure of the beam and accessible doses and rates. A number of proof-of-principle experiments have already been performed.

SPARC_LAB (Italy)

The SPARC_LAB (Sources for Plasma Accelerators and Radiation Compton with Laser And Beam) facility at LNF [25] is based on the combination of the high-brightness photo-injector with the high-intensity FLAME laser. The injector consists of a high brightness 1.6-cell S-band photo-injector [26], two travelling-wave S-band and one travelling-wave C-band linacs. The maximum achievable beam energy is 180 MeV. The first linac section is also used as an RF-compressor by means of velocity-bunching [27]. Solenoid coils surrounding the first two linac sections provide additional magnetic focusing during the bunching process and control of emittance and envelope oscillations [28]. A diagnostics transfer line consisting of a spectrometer and a RF-deflector, allows for a complete 6D beam characterisation. The injector feeds three different beam lines located downstream the main magnetic spectrometer. These beam lines are used for novel user experiments including: beam-driven plasma-wakefield acceleration and FEL lasing, advanced diagnostics studies including single-shot emittance measurements, and high-power THz generation for users. The ultra-intense laser pulses are employed to study the interaction with matter for many purposes: electron acceleration through laser-wakefields (LWFA), ion and proton generation, study of new radiation sources, and the development of new electron diagnostics.

BEAM DYNAMICS CHALLENGES

A generic layout, shown in Fig. 1, illustrates the main components used in the test facilities described previously. These components include: a photo-injector, linear accelerator section(s), bunch compression (velocity bunching and/or magnetic), higher harmonic cavity for RF curvature correction (optional), dedicated diagnostics section(s), and spectrometry lines. Additional branch-lines can be included to increase experimental access for users. Below we will discuss both similarities and differences in these areas, outlining the common beam dynamics challenges across the various facilities.

Layout Constraints

Medium-energy test facilities are attractive because of their relative cost efficiency. They offer potential for the development of compact, energy-efficient accelerator facilities for future markets. Their efficiency comes at the expense of space, either when they are installed in existing buildings or when there is insufficient floor space available due to cost savings within the budget. These layout constraints impose additional difficulties on the beam dynamics of the machine, for example fewer diagnostics or smaller bending radii in arc structures. Access to user stations, whether inside the accelerator hall itself or within a separate shielded enclosure, also affects the final beam parameters due to additional transport of electron or photon beams. Where a high power laser is transported for combined experiments with electron beams, this also affects specifications of beam line components - to allow clearance for laser and photon beams envelopes, as well as laser injection and extraction mirrors.

Photo-injector

All test facilities described here use a laser driven RF electron gun because it provides both high-brightness beams and a greater flexibility in beam time structure. The beam dynamics of the photo-injector system are sensitive to a variety of parameters: the RF field strength and profile, photo-cathode laser transverse and longitudinal profile (shape and duration), photo-cathode surface characteristics and quantum efficiency (QE). In addition to all these, a particular arrangement of main and bucking solenoids around the gun is required to transport high brightness electron beams with low transverse and longitudinal emittances. There is a clear split in photo-injector cathode materials, with the majority of facilities using Cu due to their simplicity and robustness, but relatively low QE ($\sim 10^{-5}$). Facilities with requirements for high charge and/or high-current running have made the move to alkali cathodes, such as Cs_2Te, with significantly higher QE's ($1-10\%$). The range of bunch charges provided to users spans the range from fC to several nC, demonstrating a wide range of experimental requirements.

Bunch Compression & Linearisation

A second obvious division among the test facilities is the choice of bunch compression mechanisms, between velocity-bunching compression (VB), using an accelerating cavity operating near the zero-cross phase, and variable magnetic bunch compression (MC) in 4-dipole chicanes (or D-shaped chicanes, as planned at FLUTE). There are clear advantages and disadvantages between both methods: VB can maintain transverse symmetry, when coupled with solenoidal focusing, and does not suffer from the same issues of coherent synchrotron radiation (CSR) and micro-bunching (μB) phenomena as the MC case, which can limit 6D charge-densities at user end-stations. However, MC has the advantage of flexibility, which is important for facilities with a varied user community, and suppression of the incoming timing jitter from the finite R_{56}. It also offers the possibility for energy collimation utilising scrapers or apertures. However, to maximise beam quality it requires a higher-harmonic RF cavity to correct the RF curvature - adding additional space, cost and complexity, as well as introducing an additional source of timing jitter.

Diagnostics

Medium-energy test facilities provide an ideal test-bed for diagnostics development. All facilities surveyed have

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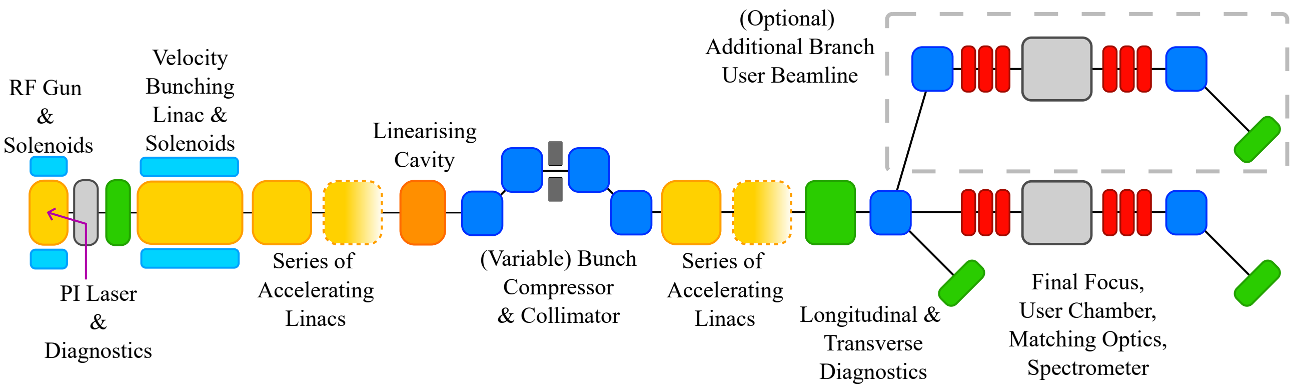

Figure 1: Schematic of a Generic Electron Beam Test Facility demonstrating the common elements seen in medium-energy electron test facilities.

an active diagnostics development program, whether for local experiments and applications or for large-scale user facilities (e.g. PITZ for FLASH and European XFEL and EuPRAXIA@SPARC_LAB). Transverse beam diagnostics studies have included scintillator screen resolution and saturation, transition radiation measurments, and novel emittance measurement methodologies. Experimental development of advanced longitudinal diagnostics include for example wakefield streakers, electro-optic (EO) bunch-profile measurements, beam generated THz diagnostics, and beam-arrival monitors.

Applications

Table 2 summarises the main areas of user applications for accelerator test facilities covered here. These are broadly similar across the continent: accelerator components and diagnostics R&D, radiotherapy (RT) via VHEE and FLASH, electron Computer Tomography (CT); beam driven novel acceleration studies via dielectric wakefield (DWA), plasma wake field (PWFA), laser wakefield (LWFA) and THz.

The extensive study of VHEE radiotherapy experiments across all of the medium-energy test facilities indicates a broad interest from the wider scientific community. These studies are well aligned with facility capabilities (sub-GeV, high-charge, flexible) and demonstrate a distinct advantage for these medium-sized facilities over larger national facilities. However, there is a case to be made that the FLASH-modality is the future of VHEE radiotherapy, and the additional high-average dose requirements (primarily driven by bunch charge and repetition rate) of $\gg 10\,\mathrm{Gy/s}$ are a limiting factor for some facilities. FLASH-VHEE may drive faster adoption of high QE alkali-metal photocathodes which, coupled with high repetition rate photo-injector lasers, can be a relatively easy way to increase facility dose-rates.

Transport and Tailoring Beam for Novel Applications

Most facilities described here advertise a table of beam parameters describing the extent of flexibility of beam operation. There is a great demand for beams with extreme parameters (high charge, short duration and low emittance)

Table 2: Main Novel Applications Delivery by Facility

Facility	Applications
ARES	Accel. components, Diagnostics R&D Medical: VHEE RT, Electron CT Acceleration: ACHIP [29]
CLARA	Accel. components, Diagnostics R&D Medical: VHEE RT Acceleration: DWA, (P/L)WFA, THz
CLEAR	High gradient acceleration, plasma lens Radiation damage, Diagnostics R&D Medical: VHEE & FLASH RT
FLUTE	Diagnostics R&D, THz Experiments Medical: FLASH RT, Detectors Machine Learning
PITZ	Min. beam emittance developments THz source development Medical: FLASH RT & dosimetry
SPARC_LAB	Acceleration: PWFA, LWFA Radiation sources: FEL, THz, betatron

for novel acceleration/deflection experiments. An iterative and collaborative dialogue with users is required to find the best beam parameter regime possible at each facility: trading off space-charge (SC) limited emittance and chromaticity limited energy spread to maximise 6D charge density.

Medical applications and irradiation experiments require high bunch charge and very low dark charge; this is achieved using varied solutions such as: dry ice cleaning of the gun; operating the gun at low field gradient (if acceptable); or the use of collimators. Careful beam transport through small apertures (e.g. collimators, beam apertures for vacuum management of gas target experiments, or harmonic correction cavities) is required to ensure full beam transport.

In most cases, user groups undertake simulation of their experiment ahead of beam time requests and a continuous dialogue with the facility team before, during and after the experiment is essential to maximise scientific outcomes and ensure users have realistic expectations on achievable beam parameters. These requirements include allowances for beam

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position jitter, trajectory repeatability, spurious dispersion, dark current, and so on, which must be measured close to the experiment.

Tailoring the beam for novel applications goes hand in hand with the best possible diagnostics that the facility can provide. For many experiments, dedicated R&D programs are required to be undertaken in collaboration with users. Users desire to know as much information about the beam as possible at the location of their experiment, which necessitates having diagnostics close to the experiment and/or the possibility of inferring this information from other sources, such as a calibrated online model and so-called virtual diagnostics. It is particularly important in these medium-energy facilities that operate in the space-charge dominated regime where beam properties are strongly charge dependant.

In order to provide multiple user stations, a number of facilities have added additional arcs or doglegs to their nominally straight-on layout. These provide achromatic but non-isochronous solutions which, combined with off-crest operation of linacs, offer the additional possibility to further (de-)compress bunches, but do need careful evaluation of the effects of higher order chromatic terms, and the addition of sextupole magnets if required (e.g. CLARA FEBE and SPARC_LAB beam lines).

Combining high power lasers with electron beams opens up novel new ideas for beam acceleration and photon generation, but achieving electron beam focus at the same longitudinal position as the laser focus needs further tight control on electron beam optics, supported by high precision diagnostics.

Start-To-End (S2E) Simulations

Most test facilities operate at the limits of achievable beam brightness, often limited by physical space leading to lower energies and limited beam manipulation. Coupled with a large amount of diagnostics, and a wide operating flexibility than traditional user facilities, this increases the requirements on beam modelling - before and during machine operation. Full S2E modelling, which is optimised to match the experimental machine conditions, is increasingly important in extracting full use of these test facilities. Each facility has a model of their machine in some form and a significant effort is currently under way to develop online models/digital twins to maximise the use of these tools. In the space-charge dominated regime, simulations are typically carried out using codes such as ASTRA [30] or GPT [31] which must be hand-tuned to accurately model space-charge and wakefield effects on the beam, as well as in-homogeneous laser profiles, cathode surfaces and RF fields. Elegant [32] is commonly used at higher energies, but must also be tuned to accurately model potential CSR and μB issues, as well as intra-beam scattering effects (IBS) in high current bunches. Benchmarking with other codes, such as CSRtrack [33] (for CSR studies), RF-TRACK [34] and OPAL [35] is essential. Integrating modelling of electron scattering in air, water and other materials is relevant for medical applications, and several groups are integrating codes such as TOPAS [36] and FLUKA [37] into their online models. Difficulties in simulating full-machines at high-speed are common issues. Optimisation tools, such as MOGA [38] and parallel Bayesian optimization help during the design phase or can find the optimum settings for different machine configurations. The use of online-models, machine-model matching and the implementation of Digital Twins are essential for tuning during operation. Machine learning-based (ML) surrogate models [39] of the accelerator provide much faster predictions of the beam properties and can serve as a virtual diagnostic or to augment data for reinforcement learning training. Integration of ML models on operating facilities is still in it's infancy, but test facilities with wide operating regimes provide ideal testing grounds.

DISCUSSION

The low- to medium-energy range facilities in Europe described here provide an excellent R&D platform to develop new tools and technologies for future large scale facilities. The beam dynamics and technical system challenges to generate, transport and tailor the beams for a range of applications at these facilities have a common set of problems with different identified solutions.

The review of facilities described here indicate that the amount of time available for commissioning and machine development varies from 10%-70% between the facilities, often depending upon maturity of the facility. The amount of time dedicated to accelerator R&D varies between 25% to 75% at these facilities, which also includes external collaborative users in some cases. All facilities confirm that close collaboration and interactions with their users is essential to optimise the beam parameters for each experiment. In some cases the machine setup has developed from an existing baseline design, and then been further refined for user experimental runs. All facilities offer some flexibility to carry out a wide range of experiments, within certain boundaries, and each facility has a unique set of features or infrastructure making it ideal for a particular set of applications. Every facility has a long wish list of additional improvements, but particularly diagnostics developments, to help deliver the highest quality beams to their users.

For the future, developing and implementing online optimisation methods and models that are available directly from the control room, along with applications of machine learning tools, is highly desirable. This will allow fine-grained control to tailor user-beams for a wide variety of novel applications.

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