TauFV: a fixed-target experiment to search for flavour violation in tau decays

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Abstract

TauFV is a fixed-target experiment designed to search for Lepton Flavour Violation in tau decays, utilising a high energy, high intensity proton beam impinging on a distributed system of targets. In the baseline proposal, TauFV will be situated on the high-intensity beam line the Beam-Dump Facility of the SPS, upstream of the SHiP experiment. Its performance will rely on advanced detector technologies, currently under development for applications at future hadron-collider experiments, with excellent radiation hardness and the capabilities to provide timing information with a precision of a few tens of picoseconds. Preliminary studies indicate a sensitivity to the mode $\tau^- \to \mu^-\mu^+\mu^-$ down to branching ratios of 10^{-10}. The experiment will be able to perform searches and measurements in many other tau decays, and across a wide range of topics in kaon and charm physics.

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1. Introduction and executive summary

TauFV will probe for physics beyond the Standard Model by searching for Lepton Flavour Violating (LFV) decays of tau leptons, as well as those of charm and strange mesons, produced by a 400 GeV proton beam from the CERN SPS impinging upon a system of targets. The most suitable location for this experiment is on the high-intensity beam line of the Beam-Dump Facility (BDF) [1]. The BDF is a possible future project under consideration at CERN, whose primary purpose would be to house the proposed SHiP experiment [2, 3]. TauFV will be placed upstream of SHiP and operate synergistically, absorbing 2% of the beam and integrating 4×10^{18} protons on target (PoT) over a five-year period of operation.

TauFV will benefit from technological developments that are currently being pursued for experiments at the HL-LHC and future hadron colliders, in particular excellent timing resolution ($\mathcal{O}(10)$ ps), high rate capabilities and tolerance to extreme radiation doses. The timing resolution, together with a distributed target system and good vertexing capabilities, will be highly effective in suppressing combinatoric background, and allow for a very clean analysis environment. Excellent electromagnetic calorimetry will be invaluable in signal selection and combating specific classes of background.

The earliest start date of the experiment is 2026-27. It will be able to search for the decay $\tau^- \to \mu^-\mu^+\mu^-$ with sensitivity to branching ratios of $\sim 10^{-10}$ and probe an order of magnitude lower for modes such as $\tau^- \to e^+\mu^-\mu^-$. Corresponding world-leading performance is expected for ultra-rare decays in the charm and the kaon sector, as well as very high sensitivity in charm *CP*-violation studies for many final states, including those with neutrals.

2. Physics opportunities

The search for LFV in the charged-lepton sector has long been acknowledged as a highly sensitive probe for New Physics. Although strong constraints exist for muons, those involving the third generation are less stringent and need to be improved. Added impetus comes from the recent hints for the violation of lepton universality in B-meson decays, as this phenomenon, in general, implies LFV, with many theorists predicting effects just below the current experimental bounds [4–7]. Impressive limits come from LHCb [8], where future prospects are also promising [9, 10]. However the most stringent current bounds on tau LFV come from the e^+e^- B-factory experiments. For example, in the benchmark mode $\tau^- \to \mu^-\mu^+\mu^-$ Belle has set an upper limit of 2.1×10^{-8} [11]. Belle II expects to improve this limit by at least an order of magnitude [12], and perhaps push down into the 10^{-10} regime, provided that all background can be suppressed to a negligible level [13].

Around 10^{16} D and D_s mesons will be produced in the target system of the TauFV experiment, which will in turn give rise to a sample of 8×10^{13} tau leptons from the decay chain $D_s^- \to \tau^-\bar{\nu_\tau}$. This huge data set will allow for world-leading sensitivity in the search for LFV in decays such as $\tau^- \to \mu^-\mu^+\mu^-$, and for studies of unprecedented precision in charm *CP* violation and rare decays. The expected large signal yield at TauFV shown in Table 1, even for the ultra-low branching ratio of 1×10^{-10}, makes clear the great potential for such studies, which is also true for decays involving electrons in the final state.

Table 1: Signal yield in $\tau^- \to \mu^-\mu^+\mu^-$ decays for TauFV and other future experiments assuming a branching ratio of 1×10^{-10}. The numbers are given after preselection and, in the case of Belle II and LHCb, are extrapolated assuming the performance in the referenced publications. The TauFV yield assumes a geometrical acceptance of 50% and a preselection efficiency of 10%.

Experiment	PoT / $\int \mathcal{L}dt$	Yield	Source
TauFV	4×10^{18}	800	/
Belle II	$50\,\text{ab}^{-1}$	1	[11]
LHCb Upgrade I	$50\,\text{fb}^{-1}$	14	[8]
LHCb Upgrade II	$300\,\text{fb}^{-1}$	84	[8]

Very low branching ratios will also be accessible for LFV charm decays, such as $D \to (h)\mu^\mp e^\pm$ (where h is a hadron), and in the strange sector, where samples of $\sim 10^{19}$ kaons will allow decays such as $K^0_{\rm L}, K^+ \to \pi\mu^\mp e^\pm$ to be probed at suppressions far below the current limits of $\sim 10^{-10}$[14]. Lepton Number Violating (LNV) decays of the sort $\tau^- \to h^-h^-\ell^+$, $D^- \to h\ell^-\ell^-$, which are sensitive to the presence of heavy Majorana neutrinos, will also be searched for.

Aside from interest for LFV and LNV studies, the charm system plays a unique role in heavy-flavour physics. The virtual loops, being mediated by down-type quarks in the Standard Model, have a very different structure to those that contribute to suppressed processes in the beauty and strange sectors, and hence possess a complementary sensitivity to possible New Physics contributions. The charm yields at TauFV will be 10^5 larger than at Belle II [13], and an order of magnitude above even the enormous samples foreseen at LHCb Upgrade II [9, 10]. Hence the experiment has great potential in the search for, and eventual study and characterisation of, *CP* violation in charm, which is known to be very small in the Standard Model, but may be enhanced by New Physics contributions. The particular strengths of the experiment, discussed in Secs. 3 and 4, namely an excellent control of combinatoric background, and a good efficiency for soft neutrals, will give it complementary physics reach to LHCb in the charm domain. Targets will include *CP*-violation studies of radiative and electroweak Penguin decays [15, 16] and D decays involving π^0 mesons. Another goal is the observation of the decay $D^0 \to \gamma\gamma$, for which the current limit is 8.5×10^{-7} at the 90% confidence level [17]. Measurement of the branching ratio of this channel, expected to be $\mathcal{O}(10^{-8})$ [18], most likely lies beyond the capabilities of Belle II, and yet is necessary to constrain the long-distance contribution to the New Physics sensitive 'golden mode' $D^0 \to \mu^+\mu^-$, the search for which will itself be another important task of the experiment.

3. Experiment overview and location

The target system of TauFV will consist of a set of thin blades, made of tungsten alloy or some other high-density material. These blades will be matched to an elliptical beam profile of vertical size ~ 1 mm, each separated by ~ 2 cm and distributed over a length of 10-20 cm (see Fig. 1, left). This layout will ensure that interactions will be well spread both longitudinally and transversally, which is desirable for background rejection. Furthermore, the majority of the tau leptons will decay in free space, and there will be a low probability of a decay track passing through a downstream target.

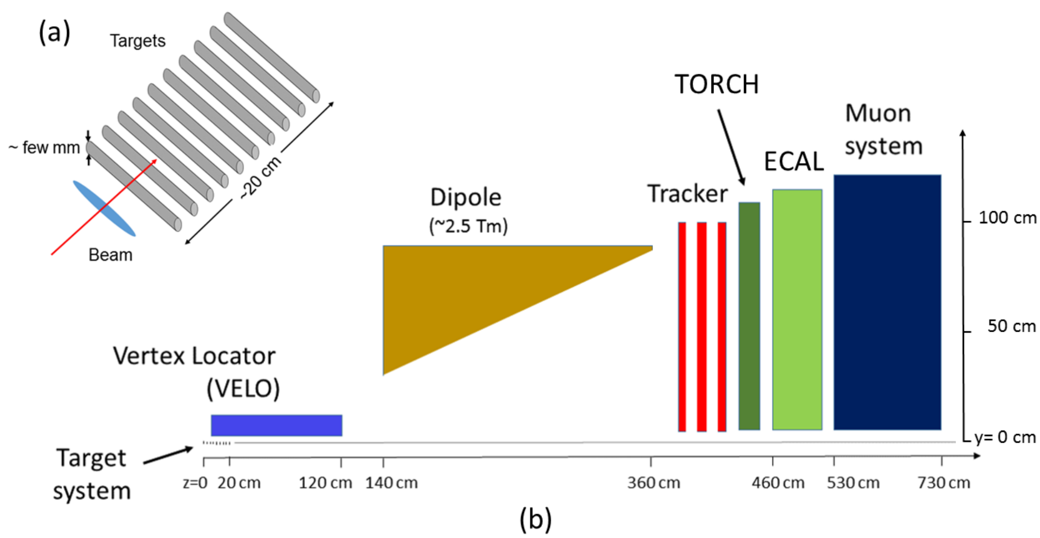

Figure 1: (a) TauFV target system. (b) half-view schematic of the spectrometer.

The spectrometer design (see Fig. 1, right) has an acceptance in polar angle between 20 and 260 mrad, and length of around 7 m. A Vertex Locator (VELO), comprising planes of silicon-pixel detectors broadly similar to the LHCb VELO, interleave the target system, and continue downstream of it. Bending of charged tracks is provided by a dipole of integrated field of ~ 2.5 Tm, which is followed by a tracker, a TORCH (Timing Of internally Reflected CHerenkov light) detector [19], a high performance ECAL and a muon system. All sub-detector components will have fast-timing capabilities, good radiation hardness and high granularity. More information on the most critical sub-detectors can be found in Sec. 5

Several locations can provide the required beam conditions and the beam drift space to accommodate the detector along the new 200 m transfer line between the TDC2 switch-yard cavern and the BDF target station, without either affecting the location of the BDF experimental area or requiring significant changes to the beam-line configuration. The choice is instead driven by considerations related to the civil engineering in the vicinity of the existing installations, radiological protection, and access and transport requirements, both above ground and underground. Lateral space is required on both sides for shielding in order to limit the radiation exposure of the surrounding underground area to levels typical for the rest of the beam line.

The currently preferred location is situated 100 m upstream of the BDF target bunker. A dedicated experimental area, including detector bunker, bypass tunnel, and an access and service building at the surface will be implemented.

By a modest reconfiguration of the beam elements in the baseline BDF design, a beam spot of $\sigma_x = 6.8\,\mathrm{mm}\ \times \sigma_y = 0.3\,\mathrm{mm}$ will be achievable, and a drift space of 20 m made available to implement the detector and the shielding. The experimental dipole necessitates the addition of a compensator magnet. The downstream dilution system, which is required to sweep the beam in a circle on the BDF target to dilute the beam power, will have to be twice as strong in this configuration.

An initial evaluation of the characteristics of the proposed target configuration and beam-induced effects on the material has revealed no show-stopper. The target and the VELO will share a common closed volume containing a circulating inert gas to prevent radiation-induced corrosion and to provide external cooling of the target.

A preliminary FLUKA study of the radiological aspects has been performed. It confirms that the radiation environment will be challenging for the detectors. Remote handling will be required to move the detectors out of their data-taking position into an adjacent shielded service space for interventions. No access will be allowed underground during operation. A first optimization of the shielding behind the detector has been performed to suppress radiation for downstream elements of the beam line. At a later stage of the project further improvements of the shielding configuration will be investigated. Additional detailed studies will be performed to ensure that the facility respects the environmental limits and the fluxes in neigbouring underground areas at the North Area.

4. Preliminary studies of physics performance

The capabilities of TauFV are best illustrated though a study of its capabilities in the search for $\tau^- \to \mu^-\mu^+\mu^-$. Here the signal must be separated from two sources of contamination: firstly, combinatoric background, being the random association of muon candidates from different proton-target interactions; secondly, specific background arising from same-topology decays of D^- and D_s^- mesons.

Pythia is used to generate 10^6 protons on target, which corresponds to $1.25\,\mu$s of operation. The beam is smeared horizontally, corresponding to the expected profile, and ten targets are simulated, each separated by 2 cm. Muon candidates are selected within the spectrometer acceptance, and include contributions from the decays of resonances and heavy flavours, decays in flight, and misidentified pions that are randomly chosen assuming a 1% fake rate. Two-muon combinations are constructed, on which loose cuts are imposed, after which tau candidates of three muons are made. It is assumed that the location of each inelastic interaction will be well reconstructed. Each track in the tau candidate is required to be compatible with a common close-lying interaction, and further requirements are placed on other quantities such as vertex quality and flight distance, which must be greater than 1.5 mm. All cuts applied assume tolerances that are modest with respect to the expected knowledge on the track parameters reconstructed by the VELO. The surviving candidates are found to be overwhelmingly dominated by particles from different interactions.

Tau candidates are then retained if they lie within a mass window of $\pm 50\,\mathrm{MeV}$, which is more than three times wider than the foreseen resolution. With ten targets a total of seven candidates are reconstructed (studies with lower number of targets show a larger number of candidates; *e.g.* a single target leads to an order of magnitude increase). A time resolution of 15 ps is expected to suppress this number by 1.4×10^{-10}, giving a total background yield of around 4000 in five years of operation. Such a level of contamination will not limit the measurement, even at branching ratios of 10^{-10}. Furthermore it may be possible to operate the BDF in a mode where the spill length is doubled to 2 s, while keeping the total number of PoT unchanged, which would increase yet more the impact of the precise timing information.

The largest same-topology background is the mode $D_s^- \to \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu_\mu}$, which has a visible branching fraction of $\sim 10^{-5}$. Other dangerous channels, listed in order of abundance, include $D_s^- \to \phi(\mu^+\mu^-)\mu^-\bar{\nu_\mu}$, $D_s^- \to \eta'(\mu^+\mu^-\gamma)\mu^-\bar{\nu_\mu}$, $D^- \to \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu_\mu}$, $D^- \to \omega(\mu^+\mu^-)\mu^-\bar{\nu_\mu}$ and $D^- \to \rho(\mu^+\mu^-)\mu^-\bar{\nu_\mu}$, where the latter mode yields around 20 times fewer decays than $D_s^- \to \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu_\mu}$.

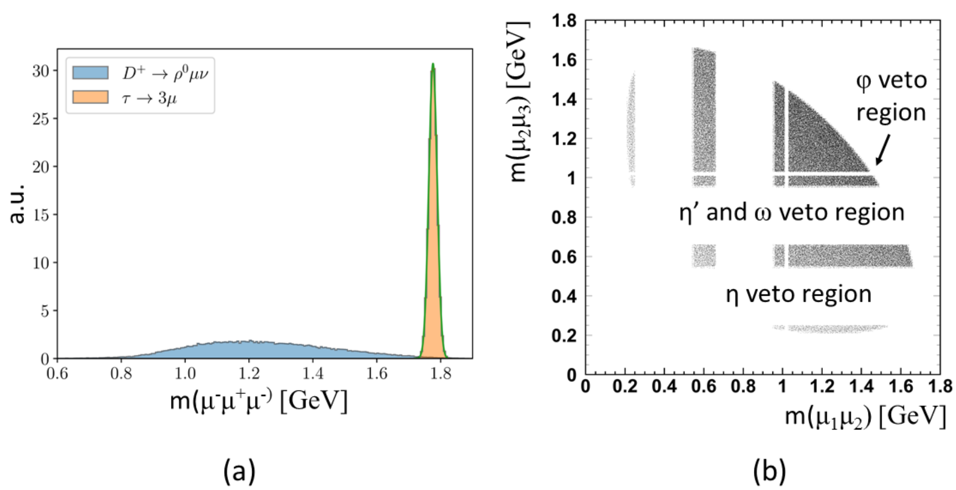

Figure 2: (a) Invariant mass of three-muon system in $D^- \to \rho(\mu^+\mu^-)\mu^-\bar{\nu_\mu}$ and $\tau^- \to \mu^-\mu^+\mu^-$ decays. (b) phase space of $\tau^- \to \mu^-\mu^+\mu^-$ decays, showing possible veto regions.

The primary weapon in combatting all same-topology backgrounds is the invariant mass requirement on the tau candidate. By way of example, the spectrum for $D^- \to \rho(\mu^+\mu^-)\mu^-\bar{\nu_\mu}$ is shown in Fig. 2(a), together with the signal distribution. A wide window placed around the signal suppresses this source of background by two orders of magnitude. As most of the background channels involve a narrow dimuon resonance there also exists the option to place vetoes on the invariant mass of the $\mu^+\mu^-$ combinations. Figure 2(b) shows the $m(\mu_1\mu_2)$ vs. $m(\mu_2\mu_3)$ space of the dimuon combinations, with vetoes imposed that are sufficient to eliminate essentially all these narrow backgrounds, whilst still retaining around 25% of the signal, when assuming a $\tau^- \to \mu^-\mu^+\mu^-$ decay that is uniform in phase space. However, such an approach introduces model dependence into the interpretation, as the precise kinematics of $\tau^- \to \mu^-\mu^+\mu^-$ decays will depend on the New Physics driving the process. Other discriminants will be the identification of soft photons from background decays involving $\eta^{(\prime)} \to \mu^+\mu^-\gamma$, kinematic variables relating the momentum vector of the candidate with its production and decay vertices, and the tagging of soft photons in the chain $D_s^{*-} \to D_s^-\gamma$, which will enable all D^- backgrounds to be heavily suppressed. In practice, all these approaches will be combined together in a multivariate analysis, but preliminary studies involving a cut-based analysis indicate that sufficient suppression can be attained to provide discovery potential down to 10^{-10}. Even better sensitivity will be achievable in modes of the sort $\tau^- \to e^+\mu^-\mu^-$, which have no sources of same-topology background.

5. Candidate detector technologies and R&D

R&D is beginning on the most critical elements of the detector, which are the VELO, the TORCH and the ECAL. Here there is very close synergy with the requirements of Upgrade II of LHCb [9, 10], in particular the emphasis on radiation hardness and high-resolution time measurements.

5.1. VELO

The VELO will consist of a sequence of rectangular stations placed around the beam. The first stations will be interspersed with the targets, with a precise arrangement that is still subject to optimisation. One possible layout is shown in Fig. 3. The general arrangement is similar to that used in LHCb, but is mechanically more straightforward, as there is no need to 'open' and 'close' the stations between data-taking periods, and there is no RF foil or secondary vacuum.

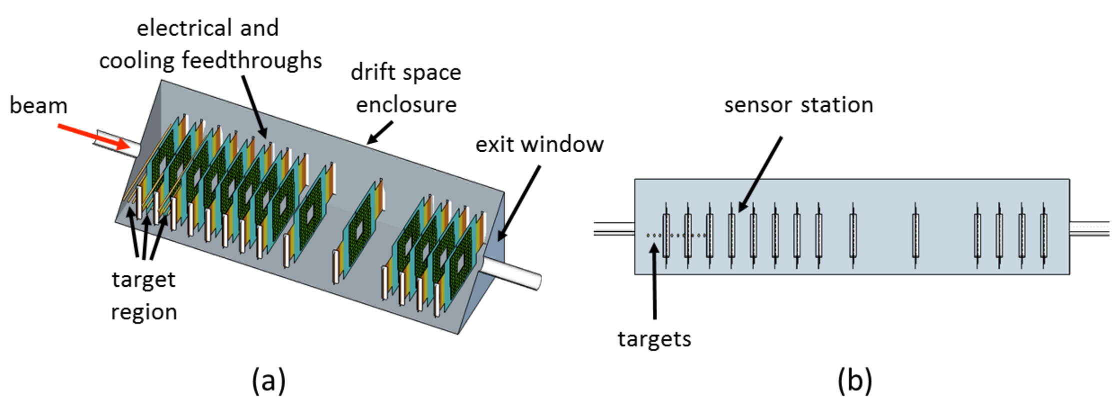

Figure 3: (a): possible layout of the VELO and target region. (b) sideways view.

The modules will be constructed of hybrid-pixel sensors, similar to those being prepared for installation in LHCb Upgrade I. These are lightweight and compact, and benefit from state-of-the-art microchannel CO_2 cooling. Further progress will be required in terms of radiation hardness, data rates, and fast-timing capabilities, but these attributes are largely in common with those foreseen for LHCb Upgrade II. In particular a new ASIC readout chip will be required, which must provide time information with a resolution of 50 ps or better, in order to expedite VELO pattern recognition and seed tracks for association to the TORCH. The development trajectory matches well the plans of LHCb, who are already working with chip designers of the Medipix collaboration. Within this context the VeloPix ASIC has recently been produced, to address the ultra-high rates and radiation-hardness requirements of the LHCb Upgrade I. The Timepix4 ASIC, which has many features in common and targets an in-pixel time resolution of 200 ps, is currently in development. These chips are valuable precursors of the TauFV ASIC, concerning which informal discussions with members of the Medipix collaboration have already begun.

5.2. TORCH

The TORCH [19] is a detector system for ultra-precise time-of-flight (TOF) measurements over a large area. Cherenkov photons, emitted and then internally reflected in a thin quartz plate, are imaged by micro-channel plate (MCP) photodetectors with a time resolution targetted to be 70 ps. The detection of around 30 photons from each charged particle then permits a time resolution per track of 10-15 ps, significantly better than has been achieved in any other TOF detector. The purpose of the TORCH within TauFV is to provide fast timing to suppress combinatoric background, and to supply $\pi - K$ separation for momenta up to around 10 GeV/c, which will enhance the experiment's capabilities in charm physics.

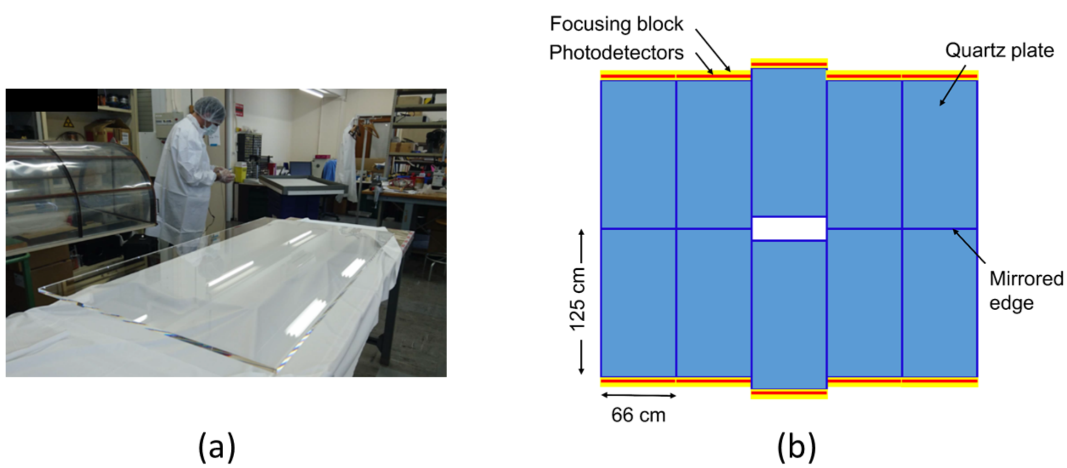

Figure 4: (a): quartz radiator plate for the TORCH prototype mode. (b) schematic of a possible layout of the TORCH detector for TauFV, comprising ten modules.

The TORCH proof-of-principle has been established with a small demonstrator module ($12 \times 25 = 420\,\mathrm{cm}^2$), equipped with MCPs developed in collaboration with industry. A time resolution approaching 80 ps per photon has been achieved, close to the design value [20]. Recently, a large-scale prototype of dimensions $66 \times 125 = 8250\,\mathrm{cm}^2$ has been constructed (see Fig. 4(a)) and is currently under evaluation in a beam test [21].

Much of the TORCH R&D until now has proceeded with a possible future application in LHCb in mind, and the large-scale prototype is half the size required for a module in that experiment. However, the dimensions of the prototype already match very well the requirements of TauFV, and only ten such modules would be required in the final detector (see Fig. 4(b)). Further improvements will be required on the photodetectors. A recent achievement has been to manufacture square detectors of $53 \times 53\,\mathrm{mm}^2$, containing 4906 readout pads, but higher granularity readout will most likely be required for TauFV, together with improved lifetime and rate capabilities.

5.3. ECAL

Efficient electron, photon and π^0 reconstruction is required for many of the important physics studies envisaged at TauFV. The very high particle flux necessitates a small Molière radius and the ability to provide timing information with a resolution of a few tens of picoseconds. In addition, the ECAL must be able to withstand a radiation dose of several hundred Mrad. Simulation and detector R&D is ongoing to ascertain whether these goals are best met by a homogeneous crystal calorimeter, which would provide exceptional energy resolution, or a sampling device with tungsten-alloy absorber, which is optimal in terms of shower size. For both solutions GAGG crystal ($Gd_3Al_2Ga_3O_{12}$ co-doped with Ce, Mg and Ti) is an attractive choice for the scintillating element.

We have performed studies of the radiation hardness and time response of GAGG and obtained very promising results. Figure 5(a) presents the optical transmission of a crystal, and shows almost no degradation at the scintillation wavelength 520 nm after exposure to $3.1 \times 10^{15}\,p/\mathrm{cm}^3$, which is equivalent to $\sim$100 Mrad[22]. The light pulse is measured to last 36 ns (73%) / 120 ns (27%), with a rise time of <3 ps.

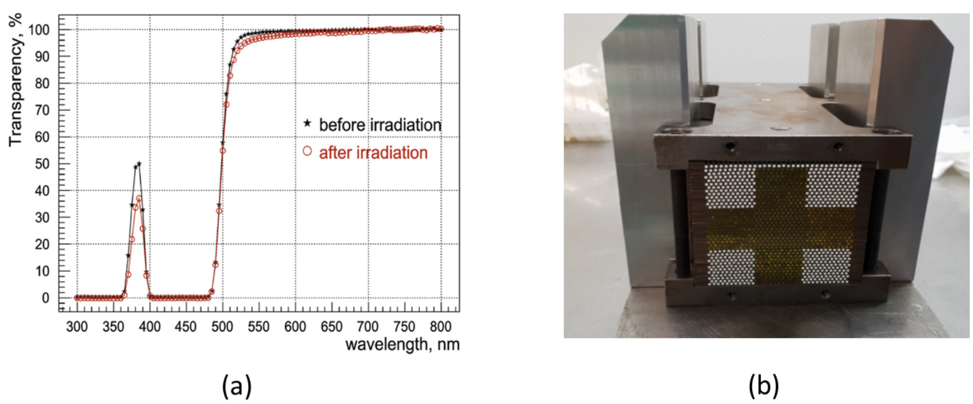

Figure 5: (a): optical transmission of GAGG crystal before and after irradiation of 100 Mrad. (b) prototype SPACAL module, comprised of cells with various scintillators, including GAGG (middle).

Recently, we have studied a SPACAL design as a possible option for the sampling GAGG calorimeter, with a W(75%)/Cu(25%) absorber. The crystal fibres in the SPACAL both function as the active element and also transport the light, thus removing the need for WLS fibres, for which radiation tolerance is a concern. A prototype module has been constructed, comprised of cells made with different fibre materials, including GAGG (see Fig. 5(b)). For a beam centred on the GAGG cell a sampling term can be obtained in the range of $5 - 10\%/\sqrt{E[\mathrm{GeV}]}$, with fibre-to-fibre distance of 1.4 to 1.8 mm. These results are compatible with simulation expectations. In addition, studies indicate that a time resolution of 30 ps can be achieved; this will be validated in future beam tests. Similar performance is expected for the homogeneous crystal design.

6. Timeline

The two principal factors that will determine the start date of TauFV are the schedule for the BDF construction, and the time required to develop the sub-detector technology, in particular the front-end ASICs. The current BDF planning would allow for the TauFV experimental hall to be prepared in 2026-27, which would also represent the earliest opportunity to install the experiment. As this would be a few years before Upgrade II of LHCb, with which a significant part of the detector R&D is coupled, it might be that LS4 in 2030 is a more realistic goal. In this case it would still be possible to install a demonstrator experiment at the earlier date, either at the BDF or in another beam line, to establish proof-of-principle for many of the key aspects of the project, and to perform first physics measurements.

In order to reach the most interesting sensitivities it is foreseen that data taking should last for five years. Even then it is quite possible that many analyses would remain statistics limited. Given that the sample sizes are not constrained by the beam intensity there could in future be a strong case for an upgrade to the experiment which would integrate significantly more PoT. This future development would require further advances in ASIC and detector technology.

7. Conclusions

If, as many New Physics models suggest, the mode $\tau^- \to \mu^-\mu^+\mu^-$ lies close to current experimental reach, TauFV will be able to collect significantly more signal decays than any other current or foreseen facility, which will be invaluable in characterising the underlying dynamics. The experiment will be equipped with state-of-the-art detector technologies, already being developed for future hadron-collider applications, that will provide excellent control of background. In particular, precise time resolution, together with the distributed target system, will ensure very high suppression of combinatoric contamination. TauFV will have discovery potential for branching ratios of $\sim 10^{-10}$, far beyond current limits, and better than the expectations of the Belle II experiment, which operates in a very different environment. Even higher sensitivity will be accessible in decays such as $\tau^- \to e^+\mu^-\mu^-$, where same-topology backgrounds are absent. The experiment will also have powerful capabilities in the search for rare or forbidden charm and kaon decays, and in studies of *CP* violation in the charm system.

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