Work package number	28	**Start date**	1 Jan. 2009
Activity Type	RTD		
Work package acronym	SiPM		
Work package title	Avalanche Micro-Pixel Photo-Diodes for Frontier Detector Systems		

Participant number	**Organization legal name**	**Short name**	**Activity leaders** *(in **bold** the spokesperson)*	**Person-months (total)**
9	Gesellschaft für Schwerionenforschung mbH	GSI	**H.Orth**	12
1	Istituto Nazionale di Fisica Nucleare	INFN		48
	INFN Laboratori Nazionali di Frascati	*INFN-LNF*	*C.Curceanu,*	*30*
	INFN Sezione di Pisa	*INFN-PI*	*A.Del Guerra*	*18*
2	Oesterreichische Akademie der Wissenschaften	OeAW	J.Marton	12
4	Charles University in Prague	CUNI	R.Leitner	12
14	Rheinische Friedrich-Wilhelms-Universität Bonn	UBO		12
	Universität Bonn	*UBO*	*U.Thoma*	*12*
15	Friedrich-Alexander- Universität Erlangen-Nuernberg	FAU	A.Lehmann	6
18	Justus Liebig Universität Giessen	JLU	R.Novotny	6
33	Foundation Bruno Kessler	FBK		
	FBK-irst	*FBK*	*C. Piemonte*	
37	Jagiellonian University	UJ	J.Smyrski	12
40	Institutul National de Cercetare-Dezvoltare pentru Fizica si Inginerie Nucleara – Horia Hulubei	IFIN-HH	M.Bragadireanu	60

Other involved institutions	**Activity leaders**	**Person-months**
Paul Scherrer Institut,Villigen (Switzerland)	D.Renker	3
Zecotek Photonics, Zuerich (Switzerland)	Z. Sadygov	12
Joint Institute for Nuclear Research,Dubna (Russia)	A.Olchevski	24
Petersburg Nuclear Physics Institute, Gatchina (Russia)	S.Belostotski	18
Institute for Scintillation Materials, Kharkov (Russia)	B.Gryniov	3
Institute of Nuclear Physics,Moscow (Russia)	F.Guber	6
Institute of High Energy Physics,Protvino (Russia)	V.Ammosov	12

1. OBJECTIVES

New photon detectors – Geiger mode operated avalanche micro-pixel photo sensor matrices (AMPD), also called silicon photo multipliers (SiPM)[2] – are ideally suited for future photonics systems in a broad field of basic science in physics, especially in hadron physics. They also have the potential for novel and advanced applications in many other fields. These devices combine performances of traditional phototubes like high quantum efficiency and signal amplification with extremely important features like low-cost voltage supply and electronics. Contrary to photomultipliers the device is insensitive to magnetic fields and mechanically robust thus suitable for harsh environments. Therefore, the possible applications of these devices cover space research, biology, medical diagnostics and eventually environmental technology.

The combination of the expertise of 12 European institutions and 5 from Russia will ensure a powerful collaboration to develop new matrix Geiger-mode APDs with unprecedented performance. The idea is to perform such R&D on prototypes of advanced particles detectors for hadron physics exploiting the strengths of the new photon sensor and pushing against the present deficiencies. We have chosen tree different tasks to pursue:

T1 Low-level light detection and single photon readout
T2 SiPM-coupled advanced fiber detectors
T3 Ultra-fast timing with plastic scintillators for TOF-applications.

The important tasks of investigation with the SiPM sensor are the following:

- Development and test of new SiPMs, integrated in arrays that are compatible with the demands of position sensitive detectors (e.g. single-photon detectors, scintillating fiber detectors, gamma-ray detectors using state-of-the-art crystals like LSO)
- Optimization of the timing performance with resolution below 100 ps
- Development and test of the performance as single photon counters
- Studies of damage effects due to ionizing radiation and device lifetime
- Investigation and characterization of the intrinsic and induced noise behavior
- Development of associated electronics for the supply/readout as well as data acquisition
- Assembly and installation in detector systems working in magnetic fields: characterization of the overall performances and check of the short and long time stabilities on various test beams.

2. DESCRIPTION OF WORK AND ROLE OF PARTICIPANTS

T1. Low level light detection and single photon readout with SiPM

[2] The sensor has many names in literature. In this project we term it Silicon Multiplier without allusion to any label of a producer.

Detection of Cherenkov radiation requires efficient photon sensors with fast detector response from the visible into the ultraviolet wavelength spectrum combined with single-photon sensitivity. The implementation of Particle Identification (PID in the PANDA experiment is based on the DIRC principle, where the internally reflected light is monitored at the end of the radiators) requires light sensors located in strong magnetic field with limited spatial extensions when using focusing techniques. We would like to demonstrate the feasibility of modern SiPM arrays for such detector systems. The principal difficulty of SiPM for this application is the single-photon equivalent noise that amounts to 100 kHz up to a few MHz depending on the detector type and on the operating conditions. However this noise can be overcome for the Cherenkov event, which consists of 100 to 200 coincident single- photon hits by implementing a proper majority filter. We plan to first study the majority filter technique by using a 32-sensor readout with available electronics. Then a matrix of 8 x 8 SiPM sensors (arranged in a 50 x 50 mm^2 matrix similar to a multi-pixel photomultiplier) will be constructed. Such a module will be used to study the trigger scenario for coincident few-photon events.

The leading institutions in this sub-project are GSI and OeAW. IFIN-HH will play an important role solving electronics problems, the other institutions will help in setting up the beam tests and in the analysis of the results.

This task is performed in close collaboration with WP20 (DIRCs).

T2. SiPM-coupled advanced fiber detectors

SiPM are ideally suited for the light readout of fiber detectors in medium- and high-energy physics. The different fiber techniques – inorganic crystalline fiber, organic scintillating fiber or wavelength shifting fiber require different parameters for the photo sensor: size, granularity, spectral sensitivity etc.

<u>a) Inorganic crystalline fibers:</u> The application of inorganic fibers for light transport is presently restricted to organic materials. However, energy- and in particular time-resolution of a single fiber are limited by the low yield of totally reflected luminescence. Inorganic scintillators provide higher light yield and a significantly larger interaction with electromagnetic probes due to the content of high-Z elements. Different and complementary techniques have been developed at CNRS/LPCML (a participant in HadronPhysics2) and the Institute for Solid-State Physics, Chernogolovka, Russia, which allow for the first time the production of inorganic fibers similar in diameter to the plastic ones. Fibers starting at 2 mm diameter and down to 50µm have been obtained up to 1-2 m length made of several crystals such as LSO, GSO, etc. The very high light output and the consequently excellent timing properties due to the fast decay time and high signal to noise ratio allow applications in hadronic and high energy physics.

Compact trigger, multiplicity or timing detectors can be designed by directly coupling SiPM sensors to the ends of crystalline fibers. This would provide a high photon detection efficiency, excellent timing performance and insensitivity to the magnetic environment. A feasibility study for this readout concept will be performed. An extremely interesting project well suited to develop this technique is a timing detector near the target of the Crystal Barrel spectrometer at ELSA. The leading institutions are UBonn and JLU. There will be a close cooperation with WP27 (SciFi).

<u>b) Organic scintillating fibers:</u> Scintillating fiber detector systems, when placed inside magnetic fields, which is a common situation in hadron physics experiments, need field insensitive photon sensors. The newly developed silicon photomultipliers (SiPMs) are considered to become a standard for this application. However, this technique has first to be developed. It requires: a) Accurate tests of various scintillating fibers to be read out by different SiPM sensors. b) New designs and optimization of readout electronics with DAQ. c) Special attention to precision mechanical design including alignment and optical coupling. As a first step to demonstrate the superiority of SiPMs compared to traditional solutions, a small prototype scintillating fiber detector will be designed, constructed and tested at Frascati or Bonn beams. The performance of this system will be measured using available SiPMs and different types of fibers. At all these development phases, close contact with producing firms of scintillating fibers and SiPMs will be maintained. In such a way the basic expertise for development of new types of SiPM especially designed for hadronic physics will be acquired. As a result of this study, a small prototype of the SiPM-coupled scintillating fiber detector will be delivered. The use of such detectors will be of utmost importance in the AMADEUS experiment at the DAFNE collider. The leading institutions are OeAW, INFN-LNF and IFIN-HH. The others will be involved in material research and performing the test measurements.

<u>c) Wave-length shifting fibers:</u> One of the most attractive possible applications of the new photo detectors is the electromagnetic and hadron calorimetry. The expected relatively low cost of SiPMs allows large granularity, excellent space resolution and particle separation. The large gain of an SiPM and the ability to operate in magnetic fields provide the possibility to use these devices in places where the alternative solutions often do not exist. The research in the framework of this project will concentrate on the optimization of SiPM parameters for calorimetric application. Moreover, the presently used scintillating materials do not quite fit to the spectral characteristics of SiPMs. Therefore, the participating team from the Institute of Scintillating Materials at Kharkov will contribute by searching new materials with spectral functions better suited for SiPM. The work on the project will comprise the measurement of SiPM parameters in connection with different scintillating materials (plastic and crystal). It will be used to assist WP29 (HardEx) in the construction of a prototype for the electromagnetic calorimeter of COMPASS at CERN. The leading institutions will be GSI, JINR, CUNI and INFN-PI. The others will contribute to the design and set-up of the electronics and the performance of the test program.

T3. Ultra-fast timing with plastic scintillators for TOF-applications using new SiPMs

In the future FAIR experiments PANDA and CBM, the identification of forwardly emitted particles will be performed with the time-of-flight (TOF) technique. Institutions participating in these two experiments are developing advanced TOF techniques using SiPMs. In PANDA, a TOF-wall is integrated into the Forward Spectrometer in form of large scintillator stripes 7 m downstream of the target. In this project it is proposed to replace the standard vacuum photomultipliers by the new SiPMs and to build a full-size prototype. In such an application, sufficient light is available to exploit the very fast photon response of the individual sensor pixel (< 300 ps), so that a total time resolution of better than 50 ps can be expected. We consider that the use of SiPMs will lead to an advanced and robust TOF system superior to most existing standard implementations.

The optimization of the time resolution and photon efficiency includes a full-scale Monte Carlo simulation which will be validated by experiment. Different light-guide geometries, different sizes and the spectral response of SiPMs will be tested. The design of dedicated read-out electronics is one important task of the project. Ultra-fast preamplifiers, summing amplifiers and constant fraction discriminators will be necessary.

The leading institutions will be UJ, the Petersburg Nuclear Physics Institute, Gatchina (PNPI), the Joint Institute for Nuclear Research, Dubna(JINR), and the Institute of High Energy Physics, Protvino (IHEP). The electronics and the radiation hardness test will be mainly done at PNPI. The other institutions will contribute to the construction of the prototype, to the test measurements and their evaluation

3. DELIVERABLES

The final deliverables will be well-characterized new photon sensors and sensor arrays for future detector systems in the field of hadronic physics. They are listed below:

Task	Deliverable	Month of Delivery
Single-photon readout with SiPMs	Design and construction of 64-pixel prototype matrix including readout electronics and tests.	30
SiPM-coupled advanced fiber detectors	Feasibility studies for new detectors with SiPM readout using: a) crystalline fibers, b) scintillating fibers c) Wave-length shifting fibers.	30
Ultra-fast timing for TOF-applications	Prototype. Radiation hardness and tests in beam.	30

4. EXPECTED IMPACT

From the outcome of the Silicon-Photo-Multiplier research, several fields relevant for hadronic physics will profit: readout of Cerenkov and scintillating fiber detectors for tracking devices, readout of calorimeters and of TOF-counters for particle identification.

The regime of very low light with single-photon resolution is typical for Cherenkov radiation detectors. This may be the most challenging application for the SiPM. In task T1, we propose the construction of a prototype Cherenkov photo-sensor. Important requirements are low noise, and high photon detection efficiency. A small number of pixels in the sensor matrix is sufficient since the dynamic range is not critical.

The coupling of SiPMs to fibers is addressed in task T2: The detection of low light levels exist in tracking devices, e.g. scintillating fiber detectors. The requirements to the sensor are similar to those in T1, yet not so stringent; however very good timing is of importance.

Detection of high light levels is encountered in calorimetery with efficient scintillator material adapted to the spectral response of the SiPM. Examples are inorganic and plastic scintillators, tile readout, Shashlik detectors and, very interestingly, the readout of inorganic crystalline fibers. The requirements to the sensor are the high dynamic range that translates into a large number of pixels. The dark count rate is not a crucial issue.

The very fast timing properties of the SiPMs, similar to the best vacuum phototubes, can be exploited in TOF application and will be unique in situations where the ambient magnetic fields are high, as i.e. in PANDA. Task T3 is meant to study a prototype of an advanced TOF wall module using SiPM readout.

The success of the project will have an essential impact on the design and construction of future detectors. It is thus of high importance for researchers working at the Infrastructure Institutions. The development of these techniques will also have an essential impact on medical tomographic techniques, where high segmentation and granularity are important issues, as well as on space research and on biology.

B.1.3.6 RISKS ASSESSMENT AND RELATED CONTINGENCY PLAN

We aimed at establishing a sound balance between more evolutionary, lower risk activities, typically related to networks, and higher risk developments in some of the Joint Research Activities. For each Work Package, risk owners were identified, risk controls set up, and risk retirement dates defined.

Risk owners: A hierarchy of risk owners has been established. Task leaders report to the Activity (Work Package) spokesperson, who in turn is accountable to the Management Board and Project Coordinator for the risk management of their Activity.

Risk controls: Each Activity will meet several times a year to check progress, as reported by its task leaders, with respect to the milestones set in the proposal. The Management Board and Project Coordinator will receive advanced warning, if milestones are at risk of being delayed.

Risk retirement: Risk retirement dates will be updated on a regular basis, which is particularly important for I3 components that are interdependent.

Risk mitigation: Whenever possible risk mitigation will be accomplished at the level where the risk occurred (e.g. task in Activity). If the mitigation of risks should require a redistribution of resources, the Management Board and Project Coordinator will initiate a discussion within the Consortium and negotiate with the Commission if need be.

Risks and contingency plans differ for the three types of activities:

Management of the Consortium (MGT, WP 1): The risk of failure related to the management of the Consortium is very low.

Networking (COORD, WP 2 – 9): The risk of failure is very low for all networks. At worst some milestones could be delayed in those networks that analyse incoming data, if accelerators or experiments break down temporarily.

Transnational access to Research Infrastructures (SUPP, WP 10 – 14): There is of course the typical risk of accelerators or experiments failing temporarily. However, all participating accelerator laboratories have excellent track records of reliably providing stable beam conditions with up to 6000 hours of beamtime per year. If problems should persist for a longer period of time, we would consider using another Research Infrastructure within the I3. This might, however, not always be possible.

Joint Research Activities (RTD, WP 15 – 28): Here the variation of the level of risks is larger, as detailed in the table below (Risk categories L = low, M = medium, H = high).

Work package number	***WP28***
Activity type	RTD
Work package acronym	Silicon Multiplier
Work package title	***Avalanche Micro-Pixel Photo-Diodes for Frontier Detector Systems***

(Timelines are indicate in grey, milestones with black boxes)

TASKS/Subtasks	**2009**				**2010**				**2011**			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. LOW LEVEL LIGHT DETECTION AND SINGLE PHOTON READOUT												
1.1 Study of the effect of cooling on noise for different SiPM				1								
1.2 Evaluation of timing with cooled SiPMs				2								
1.3 Setting up a majority logic with single photon threshold												
1.4 Planning a 2-dimensional array						3						
1.5 Study of light concentrator technique and construction						4						
1.6 Construction of a 64 pixel prototype matrix ($5x5cm^2$)												
1.7 Test in beam												
1.8 Planning of matrices with higher PDE >30 %												
2. SIPM-COUPLED ADVANCED FIBER DETECTORS												
CRYSTALLINE FIBERS												

TASKS/Subtasks	2009				2010				2011			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
2.1 Evaluation of available SiPMs for SciFi readout												
2.2 Tests of different fiber materials				5								
2.3 Optimization of SiPM coupling to the fibers						6						
2.4 Beam tests: Radiation hardness, aging, rates, etc.												
2.5 Data analysis and results of feasibility study												
SCINTILLATING FIBERS												
2.6 Evaluation of available SiPMs for SciFis				7								
2.7 Optimization of fiber coupling to SiPM												
2.8 Construction of small prototype												
2.9 Development of readout system						8						
2.10 Tests of small prototype detector												
2.11 Analysis of results of feasibility study												
WAVE-LENGTH SHIFTING FIBERS												
2.12 Survey and ordering of available samples of SiPM												
2.13 Optimization of SiPM and material						9						
2.14 Construction of electronics for read-out												

TASKS/Subtasks	**2009**				**2010**				**2011**			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
2.15 Test of small prototype												
2.16 Test data analysis and report												
3. ULTRA-FAST TIMING WITH PLASTIC SCINTILLATORS FOR TOF APPLICATIONS												
3.1 Monte-Carlo simulations on scintillator structure, geometry ,time resolution, etc.												
3.2 Design of fast read-out electronics and realization												
3.3 Tests with cosmics and Sr^{90} source												
3.4 Study the functionality on operating conditions (temperature, dark rate, thresholds, etc)								10				
3.5 Construction of a prototype												
3.6 Prototype tests at the PNPI 1 GeV proton beam												
3.7 Evaluation of results and report												

Milestones	
1	Report on cooling of SiPM's
2	Evaluation of timing properties of cooled SiPM's performed
3	Design of a two-dimensional array performed
4	Design of a light concentrator module performed
5	Test of different fiber materials performed
6	Efficient light coupling in small dimensions obtained
7	Evaluation of SiPM's for SciFi's performed
8	Readout system, end of development

9	Design of a small prototype module performed
10	Study of varying operation conditions performed

Work package number	WP28
Activity Type	RTD
Work package acronym	SiPM
Work package title	Avalanche Micro-Pixel Photo-Diodes for Frontier Detector Systems

WP28: Silicon Multiplier

REQUESTED EC CONTRIBUTION PER BUDGETARY ITEM AND PER BENEFICIARY

Contr. No	Contractor Acronym	Personnel (EUR)	Durables (EUR)	Consumables (EUR)	Travel and workshops (EUR)	Total direct costs (EUR)	Indirect costs (EUR)	Requested EC contribution (EUR)
1	INFN	60.000	0	20.000	6.000	86.000	51.600	137.600
	INFN-LNF	*30.000*	*0*	*10.000*	*3.000*	*43.000*	*25.800*	*68.800*
	INFN-PI	*30.000*	*0*	*10.000*	*3.000*	*43.000*	*25.800*	*68.800*
2	OeAW	0	0	46.400	3.000	49.400	0	49.400
4	CUNI	10.000	0	14.000	4.000	28.000	5.600	33.600
9	GSI	0	0	95.600	15.000	110.600	0	110.600
14	UBO	20.000	0	2.000	3.000	25.000	15.000	40.000
15	FAU	0	0	3.000	2.000	5.000	3.000	8.000
18	JLU	0	0	5.000	2.000	7.000	4.200	11.200
37	UJ	0	0	10.000	3.000	13.000	7.800	20.800
40	IFIN-HH	20.000	0	2.000	2.000	24.000	4.800	28.800
	TOTAL	**110.000**	**0**	**198.000**	**40.000**	**348.000**	**92.000**	**440.000**

WP28: Silicon Multiplier COMPLEMENTING RESOURCES PER BUDGETARY ITEM AND PER BENEFICIARY								
Contr. No	**Contractor Acronym**	**Personnel (EUR)**	**Durables (EUR)**	**Consumables (EUR)**	**Travel and workshops (EUR)**	**Total direct costs (EUR)**	**Indirect costs (EUR)**	**Total complementing resources (EUR)**
1	INFN	160.000	15.000	36.000	9.000	220.000	132.000	352.000
	INFN-LNF	*107.500*	*15.000*	*20.000*	*5.000*	*147.500*	*88.500*	*236.000*
	INFN-PI	*52.500*	*0*	*16.000*	*4.000*	*72.500*	*43.500*	*116.000*
2	OeAW	55.000		3.000	2.000	60.000	48.323	108.323
4	CUNI	14.000	0	1.000	1.000	16.000	9.600	25.600
9	GSI	55.000	20.000	5.000	2.000	82.000	11.000	93.000
14	UBO	35.000	0	1.000	1.000	37.000	22.200	59.200
15	FAU	27.500	0	3.000	1.000	31.500	18.900	50.400
18	JLU	27.500	0	3.000	1.000	31.500	18.900	50.400
37	UJ	24.000	0	1.000	1.000	26.000	15.600	41.600
40	IFIN-HH	40.000	5.000	3.000	2.000	50.000	10.000	60.000
	TOTAL	**438.000**	**40.000**	**56.000**	**20.000**	**554.000**	**286.523**	**840.523**