CERN
CH-1211 Geneva 23
Switzerland

the
Large
Hadron
Collider
project

LHC Project Document No.
FCC-ST-0001

CERN Div./Group or Supplier/Contractor Document No.
TE/BE/EN/PH

EDMS Document No.

Date: 2005-06-15

Work Package Description

FUTUR CIRCULAR COLLIDER

SPECIAL TECHNOLOGIES

Abstract

This document describes the FCC Special Technologies Work Package. The objective of this WP was to identify the challenges, the showstoppers and look towards opportunities for technology breakthroughs.

Indeed, this last argument will complement perfectly the Physic Cases to get an approval for the next step of the FCC Study.

This document compiles the sub-WP items with definition of scope, deliverables and milestones. CERN resource impact has been evaluated in order to provide feedback to potential international partners.

Prepared by :	***Checked by :***	***Approval Leader :***
Jose Miguel JIMENEZ (CERN) Jose.miguel.jimenez@cern.ch **Olivier BRUNNER (CERN)** Olivier.brunner@cern.ch	Francis PEREZ (ALBA-SPAIN) Laurent TAVIAN (CERN) Brennan GODDARD (CERN) Francesco BERTINELLI (CERN) Davide TOMMASINI (CERN) Wolfgang HOFLE (CERN) Roberto LOSITO (CERN) Rhodri JONES (CERN) Paolo CHIGGIATO (CERN) Mar CAPEANS (CERN) Andrzej SIEMKO (CERN)	**Michael Benedikt** Michael.benedikt@cern.ch **Franck Zimmermann** Franck.zimmermann@cern.ch

Approval List :

History of Changes

Rev. No.	*Date*	*Pages*	*Description of Changes*
0.0	2015-03-24	All	Initial submission

Table of Contents

1 EUROCIRCOL WP4

1.1 CRYOGENIC BEAM VACUUM SYSTEM CONCEPTION

Participant	CERN	KIT	INFN	ALBA	CIEMAT	STFC
Person months	**84**	**15**	**94**	**100**	**54**	**96**
Type	All types					

Objectives

1) Evaluate the impact of the arc design on technology requirements
2) Develop an overall, integrated design for the cryogenic beam vacuum system consisting of (1) beam screen, (2) proximity cryogenics, (3) magnet cold bore and (4) vacuum system
3) Determine the needs for advancing individual technologies to meet the requirements
4) Study synchrotron radiation heat load absorption and mitigation of the photo-electrons generation
5) Consider novel mitigation techniques, e.g. based on frequent discrete photon absorbers

Description of Work

The cryogenic beam vacuum system for the arc dipoles will be designed in close iterative interaction with the magnet cold bore conceptual design. The functional and performance requirements need therefore to be continuously re-evaluated and refined. Relevant aspects include beam-induced heat loads including synchrotron radiation, vacuum stability, mechanical performance, beam screen cooling concept, dynamic effects such as electron cloud multipacting and photo-electrons generation by synchrotron radiation. Image current continuity and impedance are assumed to significantly affect the accelerator and magnet design. Optimisation has large performance improvement and cost reduction potentials.

Task 4.1: Work Package Coordination (ALBA)

ALBA with the assistance of CERN coordinates the work of all other tasks of this work package to ensure consistency of the work according to the project plan and to coordinate the WP technical and scientific scope with the tasks carried out by the other WPs. Coordination duties include the organization of WP internal steering meetings, setting up of proper reviewing, reporting to project management and distribution of the information within the WP as well as to the other work packages. The task covers the organization the annual meeting sessions dedicated to the WP activity review and possible workshops or specialized working sessions, implying the attendance of invited participants from inside and outside the consortium. In particular this WP requires coordination with other WPs on the following subjects:

- WP 2 (arc design and lattice integration): Task 4.2 relies on layout and design parameters for modelling and creating a conceptual design of the cryo-photon absorbers. Task 4.6 provides input on adjusting the overall beam parameters based on the measurement results.
- WP 5 (accelerator magnet design): Task 4.2 needs to ensure compatibility between the conceptual design of the cryo-photon absorbers and the accelerator magnet design. Task 4.4 provides well aligned ranges for the operating temperature for the accelerator magnet and the beam-screen.

Task 4.2: Study beam-induced vacuum effects (ALBA, CERN)
ALBA will model and compute the cryogenic beam vacuum system, both in static and in time-constant (so called "dynamic") modes based on the input provided by CERN (D-4.4). CERN will contribute to the implementation of the time-constant modelling, providing expertise and training. The model will include synchrotron radiation effects. In a second stage, ALBA, in close correlation with CERN, will evaluate options to implement cryo-photon absorbers and will propose a conceptual design for these absorbers, which are compatible with the accelerator magnet design and accelerator layout.

Task 4.3: Mitigate beam-induced vacuum effects (STFC, CERN)
STFC will study different coatings to mitigate beam-induced electron cloud and ion instabilities on flat samples and on beam-screen prototypes provided by CERN. Compatibility of these coatings with cryogenics temperatures has to be demonstrated, in particular sticking and flaking of coatings after several cool down and warming up cycles. CERN will review the testing conditions, results and analysis and will provide the beam-screen prototypes. This work flows into the engineering design (D-4.3).

Task 4.4: Study vacuum stability at cryogenic temperature (INFN, CERN)
INFN Frascati will determine vacuum stability and adsorption isotherms at different cryogenic beam screen operating temperature ranges (D-4.1). It will perform complementary studies on beam-induced stimulated desorption phenomena by photons, electrons and ions. These studies rely mainly on experimental samples and require beam--screen prototypes supplied by CERN.

Task 4.5: Develop conceptual design for cryogenic beam vacuum system (CERN, CIEMAT)
CIEMAT will closely collaborate with CERN on the mechanical design of the cryo-magnet beam screen, ensuring compatibility with fast magnetic transitions and cryogenic cooling concepts (D-4.3). CIEMAT and CERN will study and determine beam image current continuity and impedance issues on vacuum engineering and review the buckling safety factor accordingly. CERN will manufacture the beam-screen prototypes and qualify them in one of its magnet test stands at different beam screen temperatures. CIEMAT will assist CERN with instrumentation, measurements and qualification of the beam-screens.

Task 4.6: Measurements on cryogenic beam vacuum system prototype (KIT, INFN, CERN)
ANKA at KIT will be responsible for the "beam qualification" of the beam-screen prototype supplied by CERN (D-4.2). The goal is to determine synchrotron radiation heat loads and photo-electrons generation inside the beam-screen prototype. This beam-screen will be qualified with beam by installing the CERN COLDEX36 experiment in the synchrotron ring and expose the beam-screen prototype to significant levels of synchrotron radiation, comparable to the operation conditions at the hadron collider. CERN delivers to ANKA premises the COLDEX experiment together with all documents required to define and create the machine-COLDEX interfaces. ANKA will assist for the installation and integration of COLDEX carried out by CERN and INFN. INFN will commission the experiment and perform the measurements under CERN advice.

Deliverables	**Month**
D4.1: Analysis of vacuum stability at cryogenic temperature Description of simulation environment and assumed input parameters. Description of samples and existing prototypes used as baseline. Documentation of vacuum stability and adsorption isotherms at different beam screen operating temperature ranges from simulations and laboratory tests.	**M22**
D4.2: Measurements of vacuum chamber at light source Description of the test setup and the measurement conditions including any aspects that may have an impact on the quality of the raw data and analysis. Set of raw data, associated calibration data and relevant environment operation data. Preliminary summary of the analysis, discussion of the results and conclusions.	**M28**
D4.3: Preliminary beam screen and beam pipe engineering design Drawings of the beam screen and surrounding beam pipe mechanical design as produced for the measurements at the light source. Description of the materials and manufacturing processes used to produce the test element.	**M29**
D4.4: Analysis of beam-induced vacuum effects Description of the simulated effects and comparison to the analysis of measurement data taken at the light source. Discussion and conclusion of the effects and description of efficacy, risks and potential impacts of mitigation measures. Suggestion for implementation and future work.	**M36**

2 CRYOGENICS CHALLENGES

2.1 MAGNETIC REFRIGERATION FOR SC RF CAVITIES

Participant	CERN	CEA				
Person months	**0.5**	3				
Type	STAFF	STAFF				

Objectives

Feasibility study on magnetic refrigeration allowing reaching temperature down to 1.6 K with a continuous refrigeration capacity of 5 kW.

Description of Work, Tasks with associated milestones

Based on its recent development for space applications, CEA/DSM/INAC-SBT will carry a feasibility study on magnetic refrigeration allowing reaching temperature down to 1.6 K with a continuous refrigeration capacity of 5 kW.

Task 1: Deliver a study report on new architectures and technologies for innovative superfluid helium refrigeration at 1.6 K based on magnetic refrigeration.

Deliverables	**Month**
D1. Deliver a study report on new architectures and technologies	**M30**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**0.5**
FELL/PJAS	**0**
PhD	**0**
CERN Resources (Material) [kCHF]	
Travels	**10**

2.2 PROXIMITY CRYOGENICS FOR FCC-HH

Participant	CERN					
Person months	**39**					
Type	All types					

Objectives

Conceptual design of the proximity cryogenics for the:

a. Superconducting magnets (FCC-hh)
b. Beam Screen (FCC-hh)

Description of Work, Tasks with associated milestones

Large cryogenic systems must be conceptually designed for the cooling of a 100-km circumference superconducting hadron collider. This collider will be mainly constituted of superconducting bending dipole and focusing quadruple magnets which will produce magnetic fields in the 16-20 T range. The operating temperature of these superconducting magnets is not defined yet and an operating temperature of 4.5 K or 1.9 K must be considered. For each operating temperature, specific cooling and distribution schemes must be defined and optimized. In addition, the collider will be sectorized and the cryogenic power must be transported over distances of up to 7-10 km.
Another important parameter which strongly impacts the cryogenic system is the beam synchrotron radiation which will deposit a specific power of up to 44 W/m in the cryogenic system on dedicated beam screens operating at a temperature around 50 K. For the whole accelerator, the total synchrotron radiation power will reach about 5 MW. Helium or neon has to be considered as cooling fluid of these beam screens.

Task 1: Deliver the PhD thesis on the conceptual design the cooling schemes of the superconducting magnets operating at 4.5 or 1.9 K and of the beam screens, to compare the different cooling and distribution schemes in terms of energetic efficiency and of piping dimensions. **Delivery milestone: 30.09.2016.**

Deliverables	**Month**
D1. Deliver the PhD thesis on the conceptual design	**M36**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**3**
FELL/PJAS	**0**
PhD (Claudio Kotnig)	**36**
CERN Resources (Material) [kCHF]	
Travels	**10**
Material budget for PhD Student	**30**

3 BEAM TRANSFER CHALLENGES

3.1 KICKER GENERATOR WITH SOLID STATE SWITCH TECHNOLOGY

Participant	CERN	KEK	ISL?	HDL?	Lisbon Univ.	
Person months	**45**					
Type	All types					

Objectives

1. Define key parameters for FCC injection and extraction kickers
2. Investigate individual solid state switch characteristics
3. Design and prototype a solid state inductive adder generator for fast rise time, short kicker pulses

Contributors

CERN	Coordination, overall system design, prototype design, construction and tests
KEK	Magnetic materials, switch over-current protection
ISL	Individual device characterisation, SiC, radiation resistance
HDL	High-current feedthroughs, transmission lines
Lisbon	Topologies, Marx generator concepts

Description of Work

Solid state switch technology will be needed for FCC kicker generators for reasons of high reliability, modularity, cost, radiation resistance and maintainability.

Most existing kicker systems at CERN rely on technologies which include thyratron switches and pulse-forming networks/lines (PFN/PFL). For thyratrons, long-term availability is a real concern: an alternative fast-switch technology is required. PFNs are complex devices built of many discrete components, difficult to adjust for optimisation of pulse-shapes, and PFLs rely on difficult-to-source cable for the highest voltage (~80 kV) kicker systems. Technologies and topologies such as the inductive adder (adapted from CLIC R&D) or Marx generator permit the series and parallel connection of power semiconductor switches to achieve high pulse power designs, and the inductive adder stores energy in capacitors, instead of PFN/PFLs.

The modularity of the inductive adder concept allows the same design to be used with different specifications.

The proposed Work Package addresses the questions of specifications of a system representative for FCC, and aims at the development of a prototype to illustrate feasibility and investigate the open questions. It is worth noting that there are possible applications in present ABT systems, to replace thryratron switches with such inductive adders.

The study would cover several R&D topics, but each with a rather tight focus for the chosen parameter set. The main topics would need to be:

- Switch stacking topologies,
- Magnetic materials,
- Individual SiC and Si semiconductor device characteristics,
- Overcurrent protection,
- Modularity in the design,
- Optical triggering,
- Stability,
- Radiation hardness,
- Droop compensation.

The Work Package has been broken down into a number of Tasks:

Task 1: Complete detailed proposal (objectives, timeline, identify lab space, secure resources, secure budget, and establish formal collaborations).

Task 2: Study overall concepts and kicker system options, and define key parameters for FCC injection and extraction kicker generators.

Task 3: Test and select individual components (switches and magnetic materials for cores), design of the prototype: technical report of tests and measurements on materials, and design report for prototype.

Task 4: Construct the prototype system (generator, transmission lines, load): hardware for test and measurements.

Task 5: Test the prototype: test bench; report of tests and measurements.

Task 6: Document results and CDR write-up.

Deliverables	**Month**
D1: Detailed proposal	**M2**
D2: Concepts and parameters	**M6**
D3: Components and design	**M24**
D4: Construct prototype	**M36**
D5: Test prototype	**M42**
D6: Document results	**M48**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**9**
FELL/PJAS	**36**
PhD	**0**
CERN Resources (Material) [kCHF]	
Total budget estimate for prototype Inductive Adder with 26 layers	**400**
Year1	*60*
Year2	*140*
Year3	*140*
Year4	*60*

3.2 KICKER MAGNET R&D

Participant	CERN	KEK?				
Person months	**46**					
Type	All types					

Objectives

1. Define key parameters for FCC injection kicker magnets;
2. Determine shielding required for anticipated FCC beam spectrum;
3. Develop the beam screen to achieve:
    a. adequately low, broadband, beam coupling impedance;
    b. fast field rise-time;
    c. acceptable high voltage behaviour.
4. Develop means of adequately cooling the ferrite yoke

Contributors

CERN	Coordination, overall system design, prototype construction and tests
KEK	Magnetic materials, impedance calculations

Description of Work

Kicker magnets with fast field rise/fall time will be required for injection into the FCC collider. A system with similar parameters will be needed for extraction from the 3.3 TeV High Energy Booster.

When the magnet is installed in a circular machine with high beam intensity circulating for many hours, the kicker magnets can experience significant beam induced heating of the magnet yoke, as the power spectrum of the beam generated by the longitudinal bunch structure is coupled via the kicker impedance to the structure.
Shielding of the magnet yoke from the circulating beam is a compromise of achieving fast rise/fall times, good high voltage behaviour and compatibility with vacuum.
The individual bunch population for FCC (1e11 p+) is similar to the present LHC, but beam induced heating is strongly dependent upon bunch-width and the frequency lines in the beam spectrum. In addition, the smaller FCC aperture means that the magnet will have smaller gaps, lower current and eventually faster rise time, all other constraints being equal.

The goals of Work-Package are to:

1. Define key parameters for FCC injection kicker magnets, in parallel with the specification of the generators;
2. Determine shielding required, for anticipated FCC beam spectrum, to achieve a beam induced heating which does not require significant developments in the area of ferrite yoke cooling and provides adequate margin for reliable operation;
3. Develop the beam screen to achieve:
    a. adequately low, broadband, beam coupling impedance;
    b. fast field rise-time;
    c. acceptable high voltage behaviour.
4. Develop means of adequately cooling of the ferrite yoke.

Developments are of course required in other areas for the kicker magnet but, at present, no fundamental show-stoppers have been identified.
A strong synergy exists with the studies and upgrades needed for the MKI injection kickers of the LHC for the HL-LHC project, and the possibility exists to share

manpower resources for several common themes, including impedance and thermo-mechanical simulations and measurements.

The Work Package has been broken down into a number of Tasks:

Task 1: Complete detailed proposal (objectives, timeline, identify lab space, secure resources, secure budget, and establish formal collaborations).
Task 2: Study overall concepts and kicker system options, and define key parameters for FCC injection kicker magnets.
Task 3: Simulation and optimization of beam screen geometries.
Task 4: Studies to design and implement improved cooling.
Task 5: Construct a prototype beam screen for installation in existing magnet (MKI?).
Task 6: Test the prototype in the laboratory: beam impedance measurements and high voltage tests.
Task 7: Document results and CDR write-up

Deliverables	**Month**
D1: Detailed proposal	**M2**
D2: Concepts and parameters	**M6**
D3: Beam screen design	**M30**
D4: Ferrite cooling design	**M30**
D5: Construct prototype screen	**M36**
D6: Test prototype	**M42**
D7: Document results	**M48**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**10**
FELL/PJAS	**0**
PhD	**36**
CERN Resources (Material) [kCHF]	
Total budget estimate for cooling design study and prototype beam screen development *Year1* *Year2* *Year3* *Year4*	**220** *10* *30* *120* *60* *0*

3.3 SEPTUM MAGNET R&D

Participant	CERN	Wigner	GSI	BNL		
Person months	**46**					
Type	All types					

Objectives

1. Define key parameters for FCC injection and extraction septum magnets;
2. Perform design study for Super Conducting extraction septum;
3. Perform magnetic and mechanical design for high field Lambertson and massless septa;
4. Construct and test one short prototype septum magnet

Contributors

The study as proposed relies for the construction of the small-scale prototype on the successful establishment of a collaboration with an outside institute to cover the required drawing efforts, as well as some manufacturing. Testing is expected to take place at CERN.

CERN	Coordination, overall system design, Lambertson and massless septum design, prototype tests
Wigner	Mechanical drawings, component production and assembly for prototype
GSI	Superconducting septum design study
BNL	Massless septa design study

Description of Work

In the framework of the beam transfer studies for the FCC challenging requirements will be defined for the extraction equipment. Integrated septum fields of between 100 and 400 T.m are defined as necessary for injecting and extracting the FCC beam, which with today's technology would mean extraction septa installations of around 400 m long, about 75 individual septum magnets in series.

A more compact septum system will provide serious economies in the installation cost and complexity, reliability and complexity; in addition, power consumption in all new facilities must be a primary consideration in the overall cost optimisation. But most importantly, a compact (high field) septum will allow much more flexibility in the design of the injection and extraction insertions, which will be essential to overcome some of the other major challenges associated with the FCC beams, such as the stored energy and machine protection considerations during beam injection and extraction. Alternatively, the concept of the 'massless' septum with no active coil or yoke material directly in the beam path between zero- and high-field gap may also allow new concepts for dealing with mis-steered or swept injected or extracted beams.

For these reasons, a Work-Package is proposed to investigate advanced septum designs, with a design study of the superconducting septa, and the realisation of at least one prototype for the normal conducting alternatives (massless or high-field Lambertson). A high-induction Lambertson with a superconducting coil (superferric Lambertson) should also be considered as a means of reaching maximum field and reducing power consumption.

The three threads in the study would cover many common R&D topics:

- field range and maximum obtainable field;
- main gap field homogeneity limits;
- relative leak field limits;

- septum thickness with respect to gap height;
- magnetic length with respect to system length;
- magnetic material properties;
- dynamic limitations.

The goals of Work-Package are to:

1. Define key parameters for FCC injection and extraction septa, in parallel with the specification of the kickers (options for Lambertson, massless and SC septa);
2. Perform magnetic and mechanical designs for Lambertson AND massless septa prototypes
3. Construct and test one prototype Lambertson OR massless septum
4. Complete design study for SC septum

The Work Package has been broken down into a number of Tasks:

Task 1: Complete detailed proposal (objectives, timeline, identify lab space, secure resources, secure budget, and establish formal collaborations).
Task 2: Study overall concepts and septa options, and define key parameters for FCC injection and extraction septum magnets.
Task 3: Literature survey and design study for cross-section of SC septum.
Task 4: Survey and selection of magnetic material for high-field Lambertson septum.
Task 5: Simulations and magnetic designs for massless and Lambertson.
Task 6: Evaluation of options and construction of one prototype short septum magnet.
Task 7: Test the prototype in the laboratory: field quality, insulation, vacuum, cooling.
Task 8: Document results and CDR write-up.

Deliverables	**Month**
D1: Detailed proposal	**M2**
D2: Concepts and parameters	**M6**
D3: SC septum design study	**M18**
D4: Magnetic material selection	**M18**
D5: Magnetic design	**M30**
D6: Build prototype	**M36**
D7: Test prototype	**M42**
D8: Document results	**M48**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**10**
FELL/PJAS	**0**
PhD	**36**
CERN Resources (Material) [kCHF]	
Total budget estimate for design studies, materials tests and prototyping *Year1* *Year2* *Year3* *Year4*	**380** *10* *70* *220* *80*

3.4 FAST ELECTRONICS, TRIGGERING AND SWITCH CONTROLS

Participant	CERN	Univ. of Manchester			
Person months	**44**				
Type	All types				

Objectives

1. Investigate mitigation measures for radiation to electronics close to beam
2. Develop concepts for compact fast control electronics close to magnets
3. Develop ultra-high-reliability triggering and synchronisation concepts for highly segmented systems

Contributors

CERN intends to seek contributions from collaborators. Each participant will supply specific expertise, technology or facilities.

CERN	Coordination, overall system design, prototype construction and tests
Manchester Univ.	Electronics design, reliability studies.

Description of Work

The FCC will potentially require a large number (several hundred) of individual fast-pulsed magnets in a highly segmented and modular system, for beam injection and extraction. This number of separate modules will require control electronics that are extremely reliable and performant, to provide the required machine safety and availability. Moreover, the physical scale of the FCC collider and the associated travel times to the equipment demands equipment with built-in redundancy. The redundant equipment should be hot-swappable, meaning that a remote operator can disable a malfunctioning part and activate its redundant part.

For these reasons R&D studies are required on technologies for controls, triggering and proximity electronics with the following themes:

1. Effects of the radiation on complex trigger and diagnostic electronics in close proximity to the beam Spontaneous trigger rates and failures need to be estimated, and mitigating technologies and techniques need to be developed.
2. Physical integration of electronics with the high voltage pulse generators. The large number of individual magnet systems modules will impose economies of scale and physical limits to the size of the control systems. These can be best achieved by reducing the size of the electronic sensors & circuits and bringing them closer to the equipment (switch, PFN, magnet etc.). A fieldbus, if possible wireless to reduce cabling, should connect the network of sensors and the processing power (CPU, FPGA, PLC etc.). This fieldbus should be centralised and provide redundancy. Remote software changes and firmware flashing should be possible.
3. Solutions found for other inaccessible devices (e.g. satellites, Mars rover and remote submersibles) should be investigated to identify possible applications to low-accessibility FCC control electronics.
4. The classification of an asynchronous beam dump for FCC as a ‘not allowed’ failure mode will require significant changes to the triggering concepts and architecture presently used in the LHC. In addition technological solutions to the difficult problem of always firing the dump, but never out of synchronisation with the abort gap(s) will need to be found.

The Work Package has been broken down into a number of Tasks:

Task 1: Review of current technologies; cooperate with other groups at CERN with radiation hardened electronics experience.

Task 2: Study and test possible solutions to mitigate degradation by radiation.

Task 3: Develop smaller sized sensors, interconnect them and centralise the computing power, which has to be redundant.

Task 4: Proposition of new ultra-high-reliability triggering and synchronisation technologies.

Task 5: Document results and CDR write-up

Deliverables	**Month**
D1. Technical report	**M12**
D2. Radiation mitigation	**M18**
D3. New sensor pilot project	**M30**
D4. Triggering and synchronisation test bench	**M42**
D5. Document results	**M48**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**8**
Fellow/PJAS (from mid-2015)	**36**
PhD	**0**
CERN Resources (Material) [kCHF]	
Total budget estimate for test bench, PCBs, components and FSU	**200**
Year1	*20*
Year2	*60*
Year3	*60*
Year4	*60*

4 MANUFACTURING TECHNOLOGIES

4.1 HIGH VELOCITY FORMING OF SUPERCONDUCTING RF STRUCTURES

Participant	CERN	Bmax (FR)				
Person months	**56**					
Type	All types					

Objectives

1. Thorough understanding of the electro-hydraulic forming process applied to copper and niobium geometries for Superconducting RF structures.
2. Characterisation and modelisation of copper and niobium for fast forming.
3. Production of a niobium functional structure.

Description of Work

Superconducting RF (SRF) structures are traditionally fabricated from sheet metal formed using a wide range and combination of techniques: spinning, deep drawing, necking and hydroforming. The metals involved are pure niobium as well as Oxygen free OFE copper typically used for preliminary trials. Geometries used for SRF cavities can be axisymmetric (e.g. LHC, ILC, SPL) or non-axisymmetric (e.g. HL-LHC crab cavities). Electron-beam welding is typically used to join formed structures to obtain the final geometry.

The possible forming techniques can be compared along different characteristics of merit: complexity of set-up, equipment and dies, precision of formed geometry, regularity of formed thickness, metallurgy, reproducibility of results, cost.

High-velocity forming is a potentially alternative process. It involves a high-strain rate deformation, through a process lasting a few milliseconds, that allows reaching higher formability (larger plastic deformation, smaller springback). Applications to copper and niobium have only recently been started using electro-hydraulic forming (EHF). Advantages are expected in metallurgy, geometrical precision, reproducibility, suitability for economic, large series production.

The project proposal aims to study and apply this technology initially for the application to HL-LHC crab cavities, combining the competences at CERN of EN/MME (the Engineering Department / Mechanical and Materials Engineering Group) and BE/RF (the Beams Department/Radio-Frequency Group) with the industrial partner Bmax (in Toulouse, France). EHF could allow the design of the crab cavity – as well as developing Future Circular Collider (FCC)-type SRF structures - to be optimised using fewer parts and welds positioned in lower field areas.

EN-MME, will use its internal resources in:

- Engineering and mechanical design
- Numerical modelling and simulation of the EHF process relying on the experience gained with explicit FEM methods and hydrocodes like LS-Dyna and Autodyn.
- Materials, metallurgy, SEM/FIB analysis

- Mechanical testing including high-strain rate characterization of the materials (possibly exploiting the agreement between CERN and Politecnico di Torino which is leader in this field).
- CMM metrology
- Machining and sheet metal forming
- Electron beam welding to assemble the final structure

EN-MME would work closely in collaboration with BE-RF physicists and engineers.

Bmax would also perform advanced simulation and modelling work, and contribute their specific know-how in electro-hydraulic forming.

The result of the study is expected to be a thorough understanding of the process and the identification and influence of its parameters on copper and niobium, as well as a complete HL-LHC crab cavity prototype (in copper and/or niobium). In particular, the development of microstructure and of physical (e.g. Residual Resistivity Ratio, RRR) and mechanical properties induced by the regime of strain rates associated to the EHF process will be investigated as a function of the process parameters in the whole temperature range relevant for the application.

It should allow to introduce high velocity forming as a qualified, referenced alternative for the forming of accelerating structures throughout laboratories world-wide.

Task 1: learning period, first simple EHF tests on copper and simple geometries
Milestone 1: Identification of key project issues and required contributions.
Deliverable 1: Report on the state of sheet metal forming for SRF applications, potential of EHF, state-of-the-art, detailed project plan for numerical simulation, forming, testing.

Task 2: project programme
Milestone 2: production of simulations and formed components
Deliverable 2: Report covering EHF tests, comparisons with numerical simulations, testing and qualification of produced structures in copper and niobium.

Task 3: application of know-how to structural components
Milestone 3: production of a functional, complex geometry SRF component in niobium
Deliverable 3: Final structural component, summary report of findings.

Deliverables	**Month**
D1. First simple EHF tests	**M6**
D2. Project programme	**M24**
D3. Application of know-how to structural components	**M6**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF 5 PM/year	**20**
FELL/PJAS (starting mid-2015)	**36**
PhD	**0**
CERN Resources (Material) [kCHF]	
Total budget estimate for test bench, PCBs, components and FSU	**275**
Year1	*50*
Year2	*50*
Year3	*100*
Year4	*75*

4.2 ADDITIVE MANUFACTURING FOR RF STRUCTURES

Participant	CERN	3T RPD (UK)	SST (DE)		
Person months	**56**				
Type	All types				

Objectives

1. The results will enable the introduction of AM as a qualified, referenced alternative for the production of RF accelerating structures throughout laboratories world-wide.
2. To provide much needed data into the properties of copper and niobium parts manufactured by laser and electron beam sintering, as well as identifying a pathway for developing and introducing new powders for the AM process which will be useful across industry sectors. The innovative concept of the research includes the unusual materials, and the need for good conductivity and UHV properties.
3. Production of a niobium functional structure.

Description of Work

Metal additive manufacturing (AM) allows the fabrication of complex geometries with functional characteristics, in high-quality fields including medical and aeronautical. AM is particularly relevant for prototypes or small series of parts, and for geometries difficult to fabricate with conventional processes. AM processes are attractive for accelerator applications, such as radiofrequency (RF) components and beam instrumentation, due to the design freedom and ability to personalise individual parts.

By using AM technology RF physicists could explore entirely novel geometries and structures to be exploited in developing accelerators such as the Future Circular Collider (FCC). These structures could be either thin-walled (cavities, waveguides) or bulk (ancillaries like tuners or couplers), in a range of sizes. Currently the most popular AM materials include steels, aluminium and nickel alloys, and titanium; however there is increasing demand from different industries to expand the material scope. RF components require the use of high quality Oxygen free OFE copper and/or pure niobium powders, neither of which is common within the AM industry.

AM technology can either use laser sintering, which is more wide-spread in industry, or electron beam sintering, that being based on a vacuum environment potentially should yield purer metals.

The project aims to design, optimise and build complex RF parts in copper and/or niobium, using Additive Manufacturing by combining and exploiting the expertise in CERN of EN-MME and BE-RF, 3T RPD and SST.

CERN/EN-MME in collaboration with BE-RF physicists and engineers, with expertise in:

- Engineering and mechanical design.
- Electron beam welding and operation.
- Materials, chemical analysis, metallurgy, powder characterisation.
- Analysis techniques including SEM/FIB, micro-optical observations, image analysis, CMM metrology.
- Mechanical property testing, including conductivity and characterisation of residual resistivity ratio (RRR) across different temperatures.
- Vacuum-thermal treatment (for powders, semi-finished and finished parts).

3T RPD (3T), with expertise in:

- Designing for additive manufacture.
- AM Material development.
- Optimisation of direct metal laser sintering (DMLS) parameters.
- Manufacturing and post-processing of complex parts.
- Analysis of DMLS powders.

SST, with expertise in:

- Electron beam welding and delivery technology.
- Powder delivery systems.
- Control of electron beam displacements.

Initial work on manufacturing with these powders has started at CERN, supported by the Knowledge Transfer (KT) fund. The project will therefore continue the characterisation of copper and niobium started under the KT Fund, focusing on the direct metal laser sintering method. The main project deliverables are the development, production, characterization, testing and documentation of proof-of-principle samples with high electrical conductivity, good mechanical properties and suitability for Ultra High Vacuum (UHV) applications. The samples include those for tensile testing, RRR measurements and for assessing the suitability for UHV and RF applications, in both copper and niobium. Specific attention would be dedicated to identification of suitable powders and optimisation of their characteristics. Finally prototype RF structures with complex geometries will be produced in copper and niobium.

Task 1: *Definition of powder specification and property requirements for optimised parts - report based on a literature review and discussion with industry.*

Task 2: *Fabrication of test parts.*
  - *Design and fabrication of test parts for analysis of mechanical, conductivity, RRR and UHV properties.*
  - *Each parameter could be analysed individually allowing for a steady flow of test pieces.*

Task 3: Selection of design and fabrication parameters for optimised part.
  - *Pieces will be built incorporating the learnings from previous milestones.*
  - *Various simple shapes will be built and tested.*

Task 4: Fabrication of final part.
  - *Final complex geometry component built with optimised properties.*

Deliverables	**Month**
D1. Report: mechanical properties of copper parts (mechanical, conductivity).	**M24**
D2. Report: mechanical properties of niobium parts (mechanical, conductivity).	**M24**
D3. Report: suitability of parts for UHV applications.	**M36**
D4. Dissemination of results through journal paper(s) and conference presentation(s).	**M48**

CERN Resources (Manpower) [Person.Months (PM)]	
STAFF 5 PM/year	**20**
FELL/PJAS (starting mid-2015) 2 FTE / year for a more complete programme.	**36**
PhD	**0**
CERN Resources (Material) [kCHF]	
Total budget estimate for test bench, PCBs, components and FSU	**300**
Year1	*25*
Year2	*75*
Year3	*100*
Year4	*100*

4.3 NOVEL MATERIALS FOR THE HIGH-ENERGY FRONTIER

Participant	CERN	GSI	Politecnico di Torino	Brevetti Bizz	BNL?	Other industry(ies)
Person months	**158**					
Type	All types					

Objectives

1. Explore and review physical limits of existing materials for Beam Interacting Devices under extreme energy deposition.
2. Research, develop, characterize and model novel materials with the potential to approach or meet FCC challenges for accelerator devices interacting with the particle beam.
3. Adapt and extend state-of-the-art simulation methods to the FCC high energy frontier.
4. Maximize testing capability in HiRadMat and explore complementary testing methods overcoming HiRadMat beam energy and intensity limitations.

Description of Work

The introduction of new, extremely energetic particle accelerators brings about the need for advanced cleaning and protection systems, such as collimators, in order to safely increase the energy and intensity of particle beams to unprecedented levels. Beam Interacting Devices (Collimators, Dumps, Absorbers etc.) must adopt materials able to withstand the extreme conditions (temperatures, pressures and densities) induced by the impact of particle beam pulses; on top of outstanding thermal shock resistance, these materials are usually required a number of additional relevant properties, such as high electrical conductivity, geometrical stability and resistance to radiation damage. These requirements are set to become by far more challenging when the energy and intensities of the Future Circular Collider are taken into account.

Within EN/MME, highly valuable experience and competencies have been built over more than ten years in the investigation and simulation of the interaction of highly energetic beams with matter, also relying on state-of-the-art hydrodynamic codes (e.g. LS-Dyna and Autodyn), in the characterization and testing of material samples and complete systems (including several experiments performed and planned at CERN HiRadMat facility) and in the research, development and processing of novel advanced materials, possessing a unique combination of thermo-physical and mechanical properties (with the support of the Knowledge Transfer fund; international patent pending).
A consolidated network focused on these topics has been established with a number of international partners, including laboratories, universities and industries, as well as with other relevant groups at CERN.

Building upon this experience (particularly developed in the frame of the LHC Collimation project) and on international collaborations such as EuCARD, EuCARD2, and HiLumi, a new program is proposed to investigate and develop novel materials and their manufacturing technologies, to simulate their behaviour in scenarios relevant for the FCC, as well as to characterize and test both materials specimens and full components under extreme conditions (high strain rates, high temperatures, high pressures and radiation doses) approaching those expected in the FCC.

Beyond the relevance for high-energy physics, the development and characterisation of new materials may be of interest for other applications where equipment may be exposed to high intensity radiation, high-density energy deposition and large temperature excursion such as thermal management for electronics, high temperature space applications, and fusion and fission reactors.

EN-MME will use its internal resources and expertise in:

- Engineering and mechanical design
- Numerical modelling and simulation of the interaction between particle beams and matter relying on implicit and explicit FEM methods and on hydrodynamic codes like LS-Dyna and Autodyn.
- Thermo-physical characterization exploiting in-house facilities (LFA, DSC, high temperature dilatometry).
- Metallurgy, SEM/FIB analysis, non-destructive (NDT) and destructive (DT) testing.
- Mechanical testing including high-strain rate and high-temperature characterization of the materials (in collaboration with Politecnico di Torino).
- Machining, EB welding, assembling.
- CMM metrology.

Additional groups implied include BE-ABP, TE-MPE and EN-STI.

Task 1: characterization campaign of existing materials used for Beam Interacting Devices (mostly carbon-based) to define their limits against FCC parameters, relying on thermo-physical measurements, metallurgical investigations, quasi-static and dynamic mechanical testing, radiation damage assessment.

Task 2: building upon results gathered during the HL-LHC Collimation project and collaboration programs (EuCARD, EuCARD2 and HiLumi), continue the development of a new class of materials (such as metal-catalysed highly ordered graphite), optimizing their manufacturing processes, exploring robust and shock-resistant coatings, increasing their thermal, mechanical, electrical, radiation-damage and UHV performances. Additionally, study novel design solutions embarking such materials, particularly for collimators, in view of FCC challenges.

Task 3: interaction of 50 TeV proton beams with matter entails extreme and little explored phenomena like high intensity shock waves, extensive changes of material density, explosions, spalling, hydrodynamic tunnelling, plasma generation etc. To simulate such events, one must resort to state-of-the-art explicit finite element techniques and hydrodynamic codes. In order to get reliable results, relevant scenarios must be provided by Beam Dynamics simulation tools while an efficient coupling with energy deposition codes, such as FLUKA, must be established; furthermore, accurate constitutive models for materials, both traditional and innovative, must be built. This task will focus on the optimization of simulation algorithms, comparing results of complementary tools, such as Autodyn, LS-Dyna and BIG2 (in collaboration with TE-MPE group and GSI, developer and proprietary of BIG2 code) for extreme cases and on the development of material constitutive models (equations of state, strength models, failure models …), partly in the frame of international collaborations.

Task 4: controlled tests under high intensity particle beams are of paramount importance to validate and qualify any component directly exposed to beam interaction. CERN HiRadMat facility offers a unique opportunity to perform such experiments. A large expertise has been built up in recent years in the design of extensively instrumented test-benches allowing to acquire, mostly in real time, the effects induced on material specimens and full components (such as LHC Collimator jaws) by intense beam pulses. This task aims at the improvement and optimization of future experiments in HiRadMat, allowing to collect even more information on material and structure response, to be used to compare simulation results and improve simulation techniques. In order to further extend experimental capabilities, reaching conditions closer to those encountered in the FCC, complementary test setups such as high energy laser ablation facilities may be explored in collaboration with European laboratories.

Deliverables	**Month**
D1. Detailed Proposal (specification, timeline, resources, collaborations setup …)	**M4**
D2.Characterization campaign of existing materials	
D2-1. Data analysis of performed experimental tests and literature review	**M18**
D2-2. Report on existing materials	**M24**
D3. Research and development of novel materials	
D3-1. Optimize manufacturing processes of advanced materials	**M18**
D3-2. Explore and test advanced coating concepts	**M24**
D3-3. Design proposal for advanced collimators	**M36**
D3-4. Develop and characterize novel graphitic materials	**M48**
D4. Simulation methods for the high energy frontier	
D4-1. Identify suitable numerical tools for simulations of extreme phenomena	**M12**
D4-2. Consolidate database on constitutive models for existing materials	**M18**
D4-3. Coupling between FLUKA and Autodyn for extreme cases	**M24**
D4-4. Simulate and benchmark extreme cases with alternative hydrodynamic codes	**M36**
D5. Experimental methods and tests	
D5-1. Perform experiment in HiRadMat on multi-material test-bench	**M18**
D5-2. Thermo-physical and metallurgical testing of existing materials	**M18**
D5-3. High strain-rate, high temperature mechanical testing of advanced materials	**M36**
D5-4. Explore and perform alternative testing methods with high energy facilities	**M48**

CERN Resources (Manpower) [Person.Months (PM)]	
STAFF (only EN/MME) 12 PM/year	**50**
FELL/PJAS (starting mid-2015)	**72**
PhD (with TE/MPE)	**36**
CERN Resources (Material) [kCHF]	
Total budget estimate for R&D studies, material tests and characterization	**950**
Year1	*150*
Year2	*350*
Year3	*250*
Year4	*200*

5 NORMAL CONDUCTING MAGNETS

5.1 RAD-HARD PLUGGABLE NORMAL CONDUCTING COILS AND ANCILLARIES

Participant	CERN	JPARC	BINP	COCKCROFT	DANFYSIK	FRAUNHOFER
Person months	**42.5**					
Type	All types					

Objectives

1. Develop coil insulation materials and schemes for accelerator normal conducting magnets capable of withstanding operational voltages of up to 5 kV after having been exposed to radiation doses of 300 MGy, in presence of humidity and possibly of ozone.
2. Develop fast connectable radiation resistant hydraulic and electrical joints
3. Integrate the above mentioned connection in global solution to enable the construction of “plug-in” magnet units, which would possibly be remotely handled and aligned.

Contributors

Each of the participants will be in charge of a specific theme, with CERN assuming the role of coordinator. The technologies developed here shall be applicable both for dipole and for quadrupole magnets, and shall take into account the requirements anticipated in “description of work”.

KEK-JPARC	reference person Kazuhiro Tanaka kazuhiro.tanaka@kek.jp Integration and alignment
BINP	reference person Anatoly Utkin A.V.Utkin@inp.nsk.su MgO technology, including electrical and hydraulic connections
COCKCROFT	reference person Jim Clarke jim.clarke@stfc.ac.uk Electrical and hydraulic connections for impregnated coils
Danfysik	reference person Frank Ebskamp febs@danfysik.dk Impregnated coils (cyanate ester and/or other radiation resistant resin with fiber-glass or mica)
FRAUNHOFER	Irradiation tests in the BGS facility

Description of Work

High collision luminosity and particle beam energy, as targeted by HL-LHC and FCC, will increase significantly the radiation dose to equipment, and generate “hot” areas creating issues for the access of personnel for maintenance and repair. As an example, in case of HL-LHC it is estimated that the environmental radiation levels around point 7 (collimators), after 6 months of cooling at 40 cm from the magnets, will be of the order of several mSv/h, with a peak of about 10 mSv/h at the most exposed location. Values at least as high can be expected for FCC.

The work proposed here addresses both material and access/operation and aims at the development of magnets with the following features:

a) built with materials withstanding radiation doses of about one order of magnitude higher than what typically considered as reference of state of the art technologies, taking into account the number of load cycles for an expected life time of 20 years
b) integrated in a such a way that their inspection, possible connection/disconnection and alignment can be performed within a few minutes, possibly remotely.

To achieve this scope we target the study to:

1. develop materials and manufacturing processes for “super radiation hard coils”. In this frame it is to be underlined that a qualification and testing program is already starting in the frame of the LHC Consolidation Project and of the HL-LHC Project and therefore the work to be carried out will be in synergy and in complement to the work programmed in the above mentioned projects.
2. develop technologies and design for reliable, radiation hard, fast electrical fittings, compatible with remote handling
3. develop technologies and design for reliable, radiation hard, fast hydraulic fittings, compatible with remote handling
4. develop suitable mechanical systems to allow fast or remote handling, alignment, connection and disconnection.

For each of these points we can schematically distinguish the following tasks:

Task 1: Review of present technologies: performance, limitations and potential for development

Task 2: Set-up of an experimental program to complete the information where necessary

> For example there is little or no information about degradation of high performance organic materials at radiation doses above 10-30 MGy, for both mechanical and dielectric properties, possibly including combined effects of humidity and presence of oxygen.

Task 3: Identify and design one or several solutions potentially fulfilling the scope

Task 4: Set-up an experimental program to validate the above solutions

Deliverables	**Month**
D1: Coil Insulation (Complement to activities in the frame of LHC Consolidation and HL-LHC)	
D1-1: Review of the available information and identification of the 2-3 most interesting technologies, proposal of a detailed test plan (radiation mechanics and electric) D1-2: Test of the selected technology in the virgin state D1-3: Result of 1st tests after low number of fatigue cycle and low radiation dose D1-4: Result of 2nd tests with full number of fatigue cycle and high radiation dose	**M12** **M18** **M24** **M36**
D2: Hydraulic fittings	
D2-1: Review of the state of the art, proposals of technologies and related test plan D2-2: Results of the test campaign on virgin samples D2-3: Results of the test campaign on samples submitted to the relevant life cycle	**M12** **M18** **M24**
D3: Electrical connections	
D3-1: Review of the state of the art, proposals of technologies and related test plan D3-2: Results of the test campaign on virgin samples D3-3: Results of the test campaign on samples submitted to the relevant life cycle	**M12** **M18** **M24**
D4: Proposal of a solution integrating the alignment, electrical connection and hydraulic fittings for fast assembly	**M48**

CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**10.5**
FELL/PJAS (needed as from beginning 2016)	**24**
PhD	**0**
CERN Resources (Material) [kCHF]	
Total budget estimate for test bench, PCBs, components and FSU	**500**
Year1	*50*
Year2	*50*
Year3	*250*
Year4	*150*

5.2 COMPACT MAGNETS & AIR COOLED WINDINGS

Participant	CERN					
Person months	**39**					
Type	All types					

Objectives

1. Compact magnets, decrease costs and footprint, may result in energy efficiency
2. Air-cooled windings, low current density for reduced energy consumption

Description of Work

Compact magnets, decrease costs and footprint, may result in energy efficiency

Task 1: Small aperture, requires high precision and tight tolerances (impact on manufacturing and measurement methods) – this work is relevant to CLIC.
Task 2: Alternative yoke materials (Fe-Co) to increase saturation level, reduce the yoke dimensions and weight – this work is relevant to medical applications (TULIP)

Air-cooled windings

Task 3: Study low current density for reduced energy consumption

Deliverables	**Month**
D1. Small aperture, requires high precision and tight tolerances	**M36**
D2. Alternative yoke materials (Fe-Co)	**M36**
D3. Study low current density for reduced energy consumption	**M36**

CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**3**
FELL/PJAS	**36**
PhD	**0**

CERN Resources (Material) [kCHF]	
Total budget estimate for test bench, PCBs, components and FSU	**200**
Year1	50
Year2	100
Year3	25
Year4	25

6 TRANSVERSE FEEDBACK SYSTEMS

6.1 TRANSVERSE FEEDBACK (TFB)

Participant	CERN					
Person months	**40**					
Type	All types					

Objectives

1. FCC-hh: focus on specification using CERN LHC ADT experience
   a. coupled bunch feedback with options for 5 ns and 25 ns bunch spacing (driven by resistive wall instability ☐ fast instability rise times)
   b. bandwidth up to 100 MHz for 5 ns option to cover all CBMs
   c. injection damping ☐ kicker waveform a challenge (ripple), aperture
   d. feasibility of intra-bunch GHz feedback (TMCI), R&D in SPS
   e. use of feedback for abort gap and injection cleaning ☐ waveform a challenge (see LHC)
   f. transverse blow-up to counteract synchrotron radiation damping ☐ new
   g. needed R&D for the technology for kicker and power systems
   h. 100 MHz for the 5 ns option, likely base-band with flatter frequency response than LHC
   i. TMCI feedback option with GHz technology.
2. FCC-ee: focus on technology using B factory experience
   a. coupled bunch feedback with options of down to 20 ns spacing and lower ?
   b. beam pick-ups for high frequencies, best frequency and scheme for bunch motion detection
   c. signal processing for short bunches, fast ADCs, DACs and processing
   d. challenges: feedback algorithms for fast growth times
   e. Is TMCI instability an issue?

Description of Work

Cover LHChh and LHCee. The following deliverable have been identified:
Task 1: Freeze machine parameters for study.
Task 2: Input from ABP and ABT to feedback design.
Task 3: Coupled bunch feedback conceptual design frozen.
Task 4: SPS TMCI feedback study completed sufficiently to conclude
Task 5: Decision on need and implementation of a TMCI feedback.
Task 6: Detailed work.

Deliverables	**Month**
D1. Freeze machine parameters for study	**M6**
D2. Input from ABP and ABT to feedback design	**M12**
D3. Coupled bunch feedback conceptual design frozen	**M15**
D4. SPS TMCI feedback study completed sufficiently to conclude	**M18**
D5. Decision on need and implementation of a TMCI feedback	**M24**
D6. Detailed work	**M36**

CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**6**
FELL/PJAS	**0**
PhD	**32**

CERN Resources (Material) [kCHF]	
Total budget estimate for test bench, PCBs, components and FSU	**100**

7 COLLIMATORS & DUMPS

7.1 BEST MATERIALS FOR COLLIMATORS AND DUMPS?

Participant	CERN					
Person months	**30**					
Type	All types					

Objectives

Study of energy deposition
Identification of candidate materials

Description of Work

The study of energy deposition in materials at 100 TeV requires some work of benchmarking with literature data and eventual update of some models. The bulk of the work described in this work package is however related to the evaluation of energy deposition scenarios in the most critical elements of a hadron collider, in order to select a range of candidate materials on which to concentrate the efforts in material characterisation in extreme conditions. The work and the respective resource levels will be synchronised with the activity performed by the collimation team within the FCC-hh study group.

Task 1: Provide a reliable account of the radiation shower at the target beam energy.
Task 2: Calculate thermal load and structural damage for a material palette.

Deliverables	**Month**
D1. Provide a reliable account of the radiation shower	**M12**
D2. Calculate thermal load and structural damage	**M24**

CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**6**
FELL/PJAS	**24**
PhD	**0**

CERN Resources (Material) [kCHF]	
Total budget estimate for computing resources and travels for and to collaborators	**50**
Year1	25
Year2	25
Year3	
Year4	

7.2 BEAM INDUCED DAMAGE AND HYDRODYNAMIC TUNNELLING

Participant	CERN					
Person months	**42**					
Type	All types					

Objectives

Study of the limits

Description of Work

New materials have to be studied and characterised for the stress/radiation levels to be encountered in the FCC. A test methodology has to be developed including dynamic stress measurement, fatigue behaviour, creep, extreme temperature effects, impact studies in HiRadMat, post irradiation analysis.

Task 1: Identify partners for material characterisation for wide ranges of temperature, strain rates, irradiation levels and vacuum. Establish protocols for tests of innovative materials (e.g. Si).
Task 2: Test candidate materials in HiRadMat. Design a re-usable vessel/test-bench to allow repeated HiRadMat tests. Select and characterise specific instrumentation for temperature and displacement/vibration measurements in HiRadMat tests.

Deliverables	**Month**
D1. Identify partners for material characterisation	**M12**
D2. Test candidate materials in HiRadMat	**M36**

CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**8**
FELL/PJAS	**0**
PhD	**36**

CERN Resources (Material) [kCHF]	
Total budget estimate	**400**
Year1	50
Year2	200
Year3	150

7.3 REMOTE HANDLING IMPACT ON ACCELERATOR DESIGN & INFRASTRUCTURES

Participant	CERN					
Person months	**69**					
Type	All types					

Objectives

1. Evaluate the compatibility of the LHC integration with remote handling and propose a new concept of acceleration-infrastructure interface which will ease this remote handling.
2. Development of radiation tolerant positioning systems including actuation and position sensing with submicrometer accuracy and repeatability.
3. Development of a remote handling concept allowing the maintenance and repair of collimators and other activated systems from the control room using telemanipulators.

Description of Work

- Inter-alignment: if the hierarchy of different collimators depend on micrometer or submicrometer alignment from collimator to collimator is necessary, it will be necessary to further develop position measurement and control solutions based on new technologies (piezo, optical, etc…). Also the radiation level will increase with respect to the LHC and all the ancillaries (motors, position sensors, switches etc...) have to be qualified with respect to higher integrated doses. 300 MGy might be assumed as reference dose, a more justified level will be provided by studies conducted in WP 7.1. Radiation tests of the presently used equipment and eventual market survey of new resins and fillers are envisaged.
- Investigation on operational aspects: how often will we have to change the collimators? Radiation issues? Can we develop "remotely disposable" collimators (quick and fully automated collimator replacement). What could be the optimal telemanipulator and how to transport it to the faulty equipment in a reasonable time (e.g. less than 3 hours). How to connect from the control room (wired or wireless).
- Establish basic functional specifications to perform an integration study to reserve the necessary space in the accelerator tunnel.

Task 1: Development of the remote handling concept, including:
  - Determination of the optimal dimension and allowable payload.
  - Study of best communication carrier (wired/wireless).

Material resources: 150 kCHF.

Task 2: Integration study for the remote handling/manipulation
  - Integrate the remote handling/telemanipulators in the tunnel cross section to reserve space.
  - Determination of allowable downtime following a failure.
  - Determination of the optimal number of telemanipulators based on allowable downtime. Discuss garage position along the tunnel
  - Study of best communication carrier (wired/wireless).

Material resources: 60 kCHF.

Task 3: Irradiation test of present equipment. Eventual development of radiation tolerant equipment up to 300 MGy.
  - Motors, switches position sensors

- Optical position sensors
- Piezo actuators

Material resources for radiation tests: 400 kCHF.

Task 4: Development of the concept for an easily disposable collimator. Based on the present design, improve all aspects of remote maintenance (replacement of faulty motors/sensors, connection/disconnection of vacuum flanges, remote bake-out).

Material resources for prototyping: 300 kCHF.

Task 5: Study of disposal options, optimisation of radioactive wastes from collimators.

Material resources for prototyping: 50 kCHF.

Deliverables	**Month**
D1. Development of the remote handling concept	**M12**
D2. Integration study for the remote handling/manipulation	**M36**
D3. Irradiation test of present equipment	**M36**
D4. Development of the concept for an easily disposable collimator	**M24**
D5. Study of disposal options	**M24**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**9**
FELL/PJAS	**60**
PhD	**0**
CERN Resources (Material) [kCHF]	
Total budget estimate for test bench, PCBs, components and FSU	**960**
Task 1	*150*
Task 2	*60*
Task 3	*400*
Task 4	*300*
Task 5	*50*

8 BEAM INSTRUMENTATION

8.1 BEAM LOSS MONITORS (BLM) FOR FCC-HH

Participant	Univ. Liverpool?	Australian Synchrotron?	SR Taiwan?	SPRING8?		
Person months						
Type	All types					

Objectives

Find a viable technology for a large distributed beam loss monitoring system, providing maximal machine coverage and localisation better than 1m.

Description of Work

The current LHC beam loss monitoring system is based on ~4000 ionisation chambers located throughout the machine. While a similar system can be envisaged for FCC-hh, this implies either a significant increase in the number of channels or a reduction in the overall beam loss coverage. Alternative technologies are therefore to be investigated in order to optimise the number of channels and overall coverage.

Task 1: Review of present technologies: performance, limitations and potential for development
Task 2: Set-up of an experimental program to investigate the feasibility of using fibre based technology (already being studied in the context of CLIC).

Deliverables	**Month**
D1: Report on existing technologies	**12**
D2-1: Setting an experimental program	**24**
D2-2: Results of the experimental program	**36**

CERN Resources (Manpower) [Person.Months (PM)]	
All manpower to come from collaboration	**0**

CERN Resources (Material) [kCHF]	
No request	**0**

8.2 BEAM SIZE MEASUREMENT FOR FCC-HH

Participant	Australian Synchrotron ?	Univ. Liverpool?	SR Taiwan?	SPRING 8?	Diamond Light Source	SPEAR
Person months						
Type	All types					

Objectives

1. Show the feasibility of using synchrotron radiation for absolute beam size measurement in FCC-hh.

Description of Work

Non-invasive beam size measurement for the calculation of emittance is essential for any high energy collider. Already difficult for the current LHC, this will be one of the main beam instrumentation challenges for FCC-hh. The only viable candidates to date are:

- Gas based detectors
    - Ionisation profile monitors
    - Beam-gas vertexing
    - Gas jet or gas sheet monitors
- Synchrotron light diagnostics

All of the gas based detection systems are already under study within the framework of HL-LHC or CLIC, but all require gas injection systems. The only truly no-invasive technique is synchrotron light detection, for which the main challenge is to image without being diffraction limited. For the FCC-hh this implies X-ray imaging.

Task 1: Calculation of the best wavelengths to use for beam size measurement using synchrotron radiation throughout the FCC-hh acceleration cycle.
Task 2: Conceptual design of an extraction system and imaging optics for these wavelengths

Deliverables	**Month**
D1: Result on best wavelength	**12**
D2: Conceptual design	**36**

CERN Resources (Manpower) [Person.Months (PM)]	
All manpower to come from collaboration	**0**

CERN Resources (Material) [kCHF]	
No request	**0**

8.3 BEAM INSTRUMENTATION (OTHERS)

Participant	CERN					
Person months	**6**					
Type	All types					

Objectives

Produce a feasibility study for all beam diagnostic instruments required for the FCC-hh and FCC-ee options

Description of Work

In addition to the BLM and Beam size measurements mentioned in 8.1 and 8.2 respectively, both the FCC-hh and FCC-ee options will require a whole suite of standard beam instrumentation:

- Beam orbit measurement system (BPM) for FCC-hh and FCC-ee
- Beam intensity monitors (BCT) for FCC-hh and FCC-ee
- Polarimeters for FCC-ee
- Longitudinal profile measurement for FCC-hh and FCC-ee
- Luminosity monitors for FCC-hh and FCC-ee
- Tune measurement for FCC-hh and FCC-ee
- Chromaticity measurement for FCC-hh

This work package will summarize the feasibility of using existing technologies for achieving the necessary specifications for both machines.

Task 1: Produce a feasibility study for all beam diagnostic instruments required for the FCC-hh and FCC-ee options.

Deliverables	**Month**
D1: Publication of feasibility study	**M24**
CERN Resources (Manpower) [Person.Months (PM)]	
Staff	**6**
FELL/PJAS	**0**
PhD	**0**
CERN Resources (Material) [kCHF]	
No request	**0**

9 BEAM VACUUM

9.1 FCC HH VACUUM CHALLENGES

Participant	CERN	LNF	BESSY2?			
Person months	**20**	60-150?	10?			
Type	All types	All types	SR?			

Objectives

1. Find out the best materials and surface coatings for the FCC-hh arcs beam pipe (and/or) beam screen in terms of performance, feasibility, and costs.
2. Provide inputs for instability simulations (Secondary electron Yield, Reflectivity & Photon Yield) for all material and material coatings at all relevant temperatures.
3. Validate full compatibility of chosen materials with all vacuum issues, impedance and other relevant aspects.

Contributors

CERN	Coordination, sample design, construction, Vacuum tests and characterizations
LNF	SEY, XPS AFM, STM spectroscopy on small prototypes, SR experiments (at Bessy2) and Vacuum experiments (at CERN).
BESSY2?	Beamtime and help (after an official agreement) to measure with SR, R and PY of the different prototypes.

Description of Work

The study aims at analyzing surface properties of various candidate materials for the FCC-hh Vacuum chambers (with emphasis onto the dipole magnet Beam screen). Electron – photon –(eventually ion) interaction with the different candidates material will be analyzed as a function of material coatings macro- as well as microscopic surface conditions, temperature, surface contaminants, adsorbates, etc. Part of this work may benefit from the use of LNF facilities for surface spectroscopy, XPS, UPS, SEY and Low energy SEY at variable temperature, different growing techniques, Micro Raman analysis, variable Temperature AFM and STM (to be integrated to serve the project).

Part of the foreseen tasks implies the use of “ad hoc” developed state ‘of the art’ Synchrotron Radiation beamline and experimental station to measure Reflectivity and PY. One of the very few existing facilities suitable to this task is the “Optical beamline” at BESSY2, Berlin. The experience with synchrotron radiation facility and laboratory source developed at Bessy and LNF will be integrated in this study (if resource allows). Electron cloud mitigation methods will be also addressed by this work package and partners’ previous experience will be considered and utilized to this purpose.

The Work Package has been broken down into a number of Tasks:

Task 1: Validate beam screen material and material coatings, their compatibility with static as well as dynamic vacuum issues, impedance and other relevant aspects. (if co- funded) .

Task 2: Identify and measure surface properties like SEY, R and PY to be used as input parameters in instability simulation codes (if co-funded) and a collaboration agreement is signed with BESSY2.

Task 3: Analyze the potentiality offered by reflecting away from dipole region the very high SR power, as a cost sustainable constructive option.

Task 4: Document results and CDR write-up.

Deliverables	**Month**
D1: Detailed proposal	**M3**
D2: formalize economic aspects of proposal	**M6**
D3: Define access to Synchrotron Radiation at BESSY 2	**M24**
D4: Production and mechanical analysis of test samples	**M36**
D5: experimental work on test samples	**M42**
D6: Document results	**M48**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**6**
FELL/PJAS (MC simulations)	**0**
PhD (Technical student is requested) (shared with HL-LHC activities)	**12**
CERN Resources (Material) [kCHF]	
Prototypes & Material for Labs	**250**

9.2 FCC EE VACUUM CHALLENGES

Participant	CERN	KEK?				
Person months	**68**					
Type	All types					

Objectives

Find out the best vacuum system for the FCC-ee arcs and experimental regions in terms of performance, feasibility, and costs.

Description of Work

The study aims at designing the vacuum system of the arcs and of the interaction regions. Several solutions will be studied while keeping the optimisation of the costs as a mandatory aspect. Of particular importance are photon adsorption and shielding: distributed and localised photon absorption will be both taken into account. The experience collected with synchrotron radiation facility and B factories will be integrated in this study, notably the super-KEKB and the Photon Factory accelerators. Electron cloud mitigation methods will be also addressed by this work package. Here again, the previous experience will be considered. The study will be concluded with the calculation of pressure profiles and estimation of the costs for the different solutions.

Task 1: At least 3 different design studies will be presented; the first consists on a scale up of the LEP, the second take into account localised absorbers, and the third considers the extensive application of NEG coating.

Task 2: The costs of the proposed technical solutions will be evaluated.

Task 3: A prototype dipole beampipe will be produced and tested by the synchrotron light of the Photon Factory at KEK.

Deliverables	**Month**
D1-1: Scale-up from LEP	**12**
D1-2: Option with localised absorbers	**18**
D1-3: Option with extensive use of NEG coatings	**24**
D2: Cost evaluation of 3 options	**30**
D3-1: Prototype of dipole	**30**
D3-2: Prototype of dipole tested under SR	**36**

CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**8**
FELL/PJAS (MC simulations)	**36**
PhD (Technical student is requested)	**24**

CERN Resources (Material) [kCHF]	
Prototype of dipole	**75**
Prototype of dipole tested under SR	**25**

9.3 HTS COATING TECHNIQUES FOR IMPEDANCE MITIGATION

Participant	CERN	Industry (?)	SPIN (I)			
Person months	**44**					
Type	All types					

Objectives

Feasibility study of HTS coatings for the reduction of the beampipe impedance of FCC-hh

Description of Work

In the FCC-hh the most probable range of temperature for the beam screen is 40-60 K. At such temperatures the resistivity of copper, the metal facing the beam, would unduly contribute to the global impedance. A possible solution would be to coat the beam screen with HTC thin films and benefit of the very low electrical resistance. Though simple, this proposal is a technological challenge both in term of feasibility and implementation. This work package aims at investigating if HTS films can be coated in long and confined structure like the beam screen. Pulsed laser deposition would be the first technique to be considered. In parallel, the physical and chemical properties of this special layer would be analysed. For example SEY, electron and photon induced desorption, together with resistance to radiation would be measured.

Task 1: Find out the best deposition technique in cylindrical geometry.

Task 2: Measure electronic properties of the films (Tc, SEY at RT and 40 K, impedance at the FCC-hh dipolar magnetic field and at the beam E-M frequency).

Task 3: Evaluate the vacuum properties of the film: outgassing and degassing induced by particle impingement.

Task 4: Evaluate the radiation damage of the film, in particular on its superconducting properties.

Deliverables	**Month**
D1: Identify best deposition techniques	**24**
D2: Measurement of electronic properties	**30**
D3: Vacuum performances of coatings	**36**
D4: RadTol of the coatings in particular superconducting properties	**36**

CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**8**
FELL/PJAS	**0**
PhD	**36**

CERN Resources (Material) [kCHF]	
	125

10 INSULATION VACUUM

10.1 HELIUM LEAKS MITIGATION

Participant	CERN					
Person months	**16**					
Type	All types					

Objectives

Study the feasibility of an alternative/complementary pumping in the insulation vacuum of the FCC-hh, for example pumping by cryosorption.

Description of Work

The insulation vacuum of the LHC is permanently pumped by turbomolecular pumps, which are installed to ensure the pumpdown and provide helium gas evacuation in case of leak in the cryogenic pipes. If scaled up to the FCC-hh, such a pumping would have a massive impact on the costs and the reliability of the whole installation. The number of pumps would be 4 times higher, which implies also more cables and higher maintenance costs. In addition, the number of suppliers for such pumps is limited because of the required radiation resistance, which in turn affect the cost. It is proposed that, after the pumpdown by mobile turbomolecular groups and the cold-mass cooling, the insulation vacuum is permanently pumped by adsorbers suitably installed in the system and cooled at the lowest possible temperature. The main role of the adsorbers would be the pumping of helium gas.

Task 1: Investigate previous work on the subject and write a literature review.

Task 2: Investigate and propose adsorbers suitable for installation in the insulation vacuum and their interference with the cryogenic system (active or passive cooling).

Task 3: Produce a prototype of adsorber and measure adsorption isotherms for helium.

Deliverables	**Month**
D1: Literature review on similar topic	**6**
D2: Proposal of adsorbers materials	**12**
D3-1: Prototype of adsorber available	**24**
D3-2: Prototype of adsorber measured	**36**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**4**
FELL/PJAS	**12**
PhD	**0**
CERN Resources (Material) [kCHF]	
	25

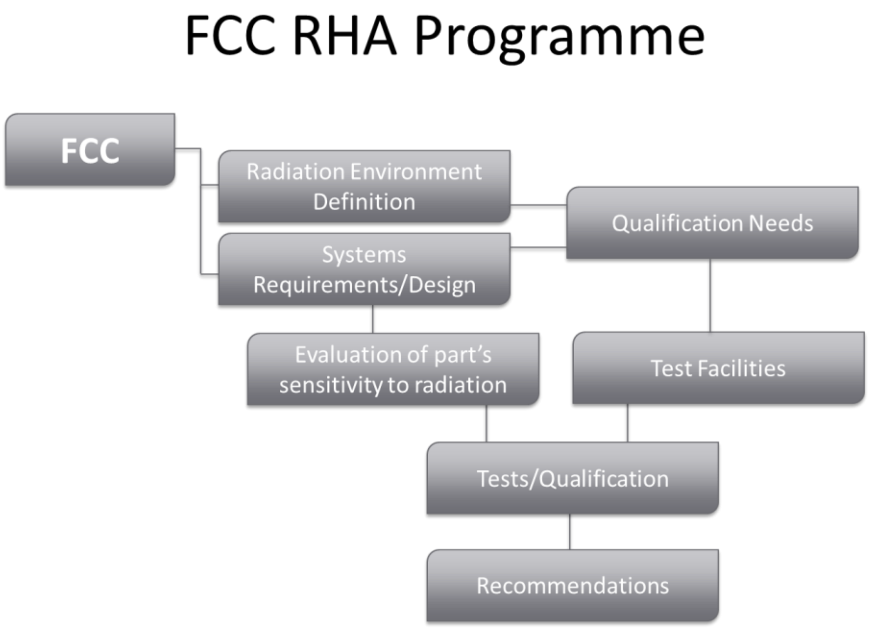
11 RADIATION HARDNESS OF ELECTRONICS

11.1 RADIATION HARDNESS ASSURANCE (RHA)

Participant	CERN					
Person months	**144**					
Type	All types					

Objectives

1. FCC will need a **massive amount of electronic systems** in the accelerator tunnel, the Particle Detectors, and in the side galleries to control and monitor the various infrastructures and systems such as power converters, vacuum, cryogenics, RF systems, etc.
    a. One challenge for control and powering systems of the FCC will be linked to the size of the installation, thus requiring: (i) high availability of systems; (ii) alternative powering and communication technologies; (iii) long-distance maintenance options.
    b. Radiation levels at FCC will roughly scale with energy and, as LHC has shown, **degradation of components under radiation** can become a major showstopper.
2. Two parallel and complementary approaches are needed: reduce equipment dose by developing shielding for service electronics, and **develop electronics and equipment radiation resistant to FCC radiation levels.**
3. The FCC R&D on Radiation Hardness Assurance (RHA) deals with the last aspect, and in particular:
    a. RHA consists of all activities undertaken to ensure that the electronics and materials developed for FCC perform to their design specifications after exposure to the FCC radiation environment.
    b. RHA deals with environment definition, part selection, part testing, radiation tolerant design, and FCC subsystems requirements.



Description of Work

Background Work

Task 1: Field conditions and radiation levels at FCC

Task 2: Qualification Protocols: Define FCC qualification requirements (safety factors, sample size, procedures) for components and systems, including particle detectors and FE electronics. Evaluation of current irradiation facilities and testing infrastructure at CERN and available worldwide; proposal of upgrade programs for facilities at CERN, if needed.

Task 3: Equipment needs for the accelerator, particle detectors and service systems. Identification of technologies used at FCC and radiation levels they will be exposed to: propose strategies for RHA taking into account maintenance, reliability and remote operation. Catalogue of critical equipment (technology, supplier, function, etc.) and possible common developments.

Task 4: State of the art and development efforts on rad hard components for HL-LHC.

Intensive work is ongoing in terms of radiation hardening of electronics, components, materials and detectors in the framework of R2E, RD50, RD51, RD53, presently with a main focus on HL-LHC. Cost optimization for electronic systems will most likely have to consider the use of components of the shelf (COTS), thus a respective early technology analysis will be key throughout the development process. Assuring the continuity of these research projects will guide us towards the FCC and assure that expertise in radiation testing/hardening is kept, testing facilities are kept operational and state-of-the-art as well as forefront development electronics is tested and radiation hardened at any point in time. Evaluate HL-LHC VS FCC needs, identify common versus specific developments.

Experimental Work

Task 5: Technologies: define needed developments linked to technologies: wireless communication, miniaturization, optical transmission, compactness, on-chip optical/electrical, packaging, new materials…

  - Example: i) establish a program to develop miniaturized prototypes, ii) develop prototypes, iii) test prototypes at irradiation facilities to define threshold for miniaturization with respect to radiation hardness

- **Specific system development and qualification:**
  - Radiation monitoring systems (for detector and accelerator areas)
  - Luminosity monitors
  - Radiation-hard sensors and readout for environmental monitoring (P, T, H) for detector and accelerator equipment
  - Interconnection technologies reliability
  - High density assemblies on PCB
  - New materials for electronics

Deliverables	Month
D1-1. Evaluation of FLUKA models' needs (environment and effects)	**M6**
D1-2. FLUKA tuning for FCC (operational/layout options/requirements)	**M12**
D1-3. Agreement on FCC target radiation field/levels	**M14**
D2-1. Define overall FCC qualification requirements as input to RHA	**M12**
D2-2. Evaluation of current irradiation facilities and testing infrastructure	**M20**
D3-1. Identification of technologies used at FCC with their expected radiation levels	**M14**

D3-2. Catalogue of critical equipment (technology, supplier, function, etc.)	**M18**
D4.1 Evaluate HL-LHC VS FCC needs of rad hard components	**M20**
D5.1 Prototype status and definition of needed developments linked to technologies	**M20**
D5.2 Radiation tester of advanced components/systems	**M36**
D5.3 Radiation sensor	**M40**

CERN Resources (Manpower) [Person.Months (PM)]

Projects needing injection of resources 2015-2017

- FLUKA/TCAD/Spice model development in order to study future electronic technologies enabling a strategic decision process (focus simulation and benchmarking platform, with a specific technology example e.g., new materials for power devices)
    - Resources: 1 PJAS or fellow 2-3y, 50kCHF for materials
- Evaluation of irradiation and testing infrastructure requirements and development, allowing for component and system tests in representative radiation environments and operation conditions (low temperatures, etc.) at CERN (IRRAD, CHARM, GIF)
    - Resources: engineering support (PJAS or FSU) for 2y, and outsourcing of development of temperature/humidity control stations, in collaboration with outside institute
- Development of a radiation tester of advanced components/systems in representative radiation fields: hardened FPGA based platform allowing to test complex and fast components
    - Resources: 1PJAS or fellow, 60kCHF material cost and outsourcing of module construction.
- Development of radiation sensor focus on mixed-radiation environment and an integrated sensor allowing for TID/DD/SEE relevant measurements, possibly to be combined with larger setup in order to deduce also radiation hardness factors
    - Resources: PJAS or fellow 2-3y, 100kCHF material costs, In collaboration with outside institute.
- R&D on materials radiation damage: tests of new materials/components complemented with the understanding of damage mechanisms. hardness factors
    - Resources: PJAS or fellow 2-3y, 50kCHF material costs, in collaboration with outside institute.

CERN Resources (Manpower) [Person.Months (PM)]

STAFF	**24**
FELL/PJAS	**120**
FLUKA/TCAD/Spice model	*30*
Development of a radiation tester	*30*
Development of radiation sensor	*30*
R&D on materials radiation damage	*30*
PhD	**0**

CERN Resources (Material) [kCHF]

Total budget estimate:	**470**
FLUKA/TCAD/Spice model development	*50*
Evaluation of irradiation and testing infrastructure requirements	*210*
Development of a radiation tester	*60*
Development of radiation sensor	*100*
R&D on materials radiation damage	*50*

12 MAGNETS & MACHINE PROTECTION

12.1 POWERING, PROTECTION ARCHITECTURE FOR HIGH FIELD CIRCUITS

Participant	CERN					
Person months	**81**					
Type	All types					

Objectives

Propose architectures and technologies for the protection of high field circuits. Towards future accelerators, opportunities are immediate and shall include operational aspects, for example, remote controls to minimise First Line interventions and maintenances.

Description of Work

Quench detection/protection of the main ring (LTS) is a challenge because of:

- Large stored energy density (a factor 3 larger than in LHC)
- Large operating current density (same as in LHC, at half of the copper fraction)
- Large circuit inductance (at least 3 times the LHC?)

Task 1: Analyse the LHC concept in view of removing electronics form the accelerator tunnel and centralizing them in underground infrastructures or preferably to surface infrastructures.

Energy extraction of all high current and high energy circuits.

Task 1: Extrapolate existing technologies and systems for the new requirements and propose circuit layout configurations compatible with FCC scale.
Task 2: Propose new concept for energy dump system, optimising energy recovery.

Local magnet protection system(s)

Task 1: Analyse the existing magnet protection technologies and evaluate applicability of alternative technologies like Coupling-Loss Induced Quench (CLIQ). Optimisation of the system, implementation at the design stage of the magnets. Report on feasibility based on HL-LHC experience, specify potential implications for subdivision of magnet coils,
Task 2: Evaluate the existing LHC magnet diode bypass assembly and propose required diode parameters in connection with the powering architecture of the magnets.

Deliverables	Month
D1. Analyse the LHC concept	**M18**
D1. Extrapolate existing technologies and systems for the new requirements	**M12**
D2. Propose new concept for energy dump system	**M24**
D1-1. Report on feasibility based on HL-LHC experience	**M24**
D1-2. Tests delivery	**M36**
D2. Propose required diode parameters	**M24**

CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**9**
FELL/PJAS	**36**
PhD	**36**
CERN Resources (Material) [kCHF]	
Diode prototyping	**250**

12.2 CONCEPT, ARCHITECTURE OF MACHINE PROTECTION & INTERLOCKS

Participant	CERN					
Person months	**45**					
Type	All types					

Objectives

Develop the architecture of the machine protection and interlock system for a larger accelerator scale as compared to LHC.

Description of Work

Task 1: The study of these new options of architecture must be linked to the machine availability concepts.
Task 2: Based on the outcome of the task 1, review LHC concepts and propose new architecture of protection systems to assure machine component protection and optimised availability.

Deliverables	**Month**
D1. Analyse the LHC availability and extrapolate to the FCC accelerator	**M24**
D2. Preliminary design report	**M24**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**9**
FELL/PJAS	**36**
PhD	**0**
CERN Resources (Material) [kCHF]	
Prototypes	**50**

12.3 HTS MAGNET PROTECTION						
Participant	CERN					
Person months	**45**					
Type	All types					

Objectives
Study and propose a detection method applicable for hybrid magnets with HTS inserts, including cold powering systems (links and current leads).
Description of Work
Quench detection of the HTS insert (very high field option) is so far unresolved: • Existing Voltage detection based on a threshold possibly too slow/not sufficiently sensitive • Develop alternative voltage instrumentation (high sensitivity), and detection method, based on precursors and pattern recognition (catch a quench before it starts) • Develop alternative detection principles (optical fibers, magnetic, acoustic, radio-frequency) **Task 1:** Analyse what exist and identify the limitations for this type of applications. **Task 2:** Study and develop prototypes of alternative voltage instrumentation. **Task 3:** Study alternative detection concepts and systems.

Deliverables	**Month**
D1. Preliminary report	**M12**
D2. Prototype of system	**M24**
D3. Preliminary report of feasibility	**M36**
CERN Resources (Manpower) [Person.Months (PM)]	
STAFF	**9**
FELL/PJAS	**0**
PhD for tasks 1 & 3	**36**
CERN Resources (Material) [kCHF]	
Prototypes	**300**

ANNEX A: MANDATE OF FCC SPECIAL TECHNOLOGY WP

The mandate of the FCC Special Technologies Work Package has been defined as follow:

- Study the special technologies including conceptual aspects required for the FCC accelerator and identify the possible design and performance limitations for the accelerator.
- Identify challenges, opportunities for technological breakthroughs and set the R&D program.
    - Understand impacts of technologies
    - Prioritize R&D topics
    - Define scope, schedule, cost guidelines
    - Reporting on Specific Technologies R&D Programs
- Set up collaborations to address standard FCC issues and R&D opportunities

- The R&D activities will then be followed in the frame of the Accelerator R&D Work Package which is sub-divided in three Sub-Work Packages:

    - High field Magnet Program
    - Superconducting RF Program
    - Special Technology Program (all except Magnet and RF)

ANNEX B: SPECIAL TECHNOLOGIES WBS STRUCTURE (DRAFT)

To ease understanding the organisation of the diffenret items, the WBS struture has been rearraged accordingly:

Energy driven
- Beam transfer elements requirements and conceptual design

Power driven
- Collimation systems and absorber requirements and conceptual design
- Dump and stopper requirements and conceptual design

Beam driven
- Vacuum system requirements and conceptual design
- Proximity cryogenics for superconducting magnets and RF
- Beam diagnostics requirements and conceptual design

Reliability driven
- Machine protection system requirements and conceptual design
- Quench protection and stored energy management requirements and concepts

Radiation driven
- Shielding
- Normal magnet requirements and element conceptual design

Accelerator driven
- Machine detector interface system needs and conceptual design
- RF system requirements and conceptual design
- Power converter requirements and conceptual design
- Control system requirements
- Element support, survey and alignment requirements and concepts

ANNEX C: CERN REFEREES FOR DIFFERENT ITEMS

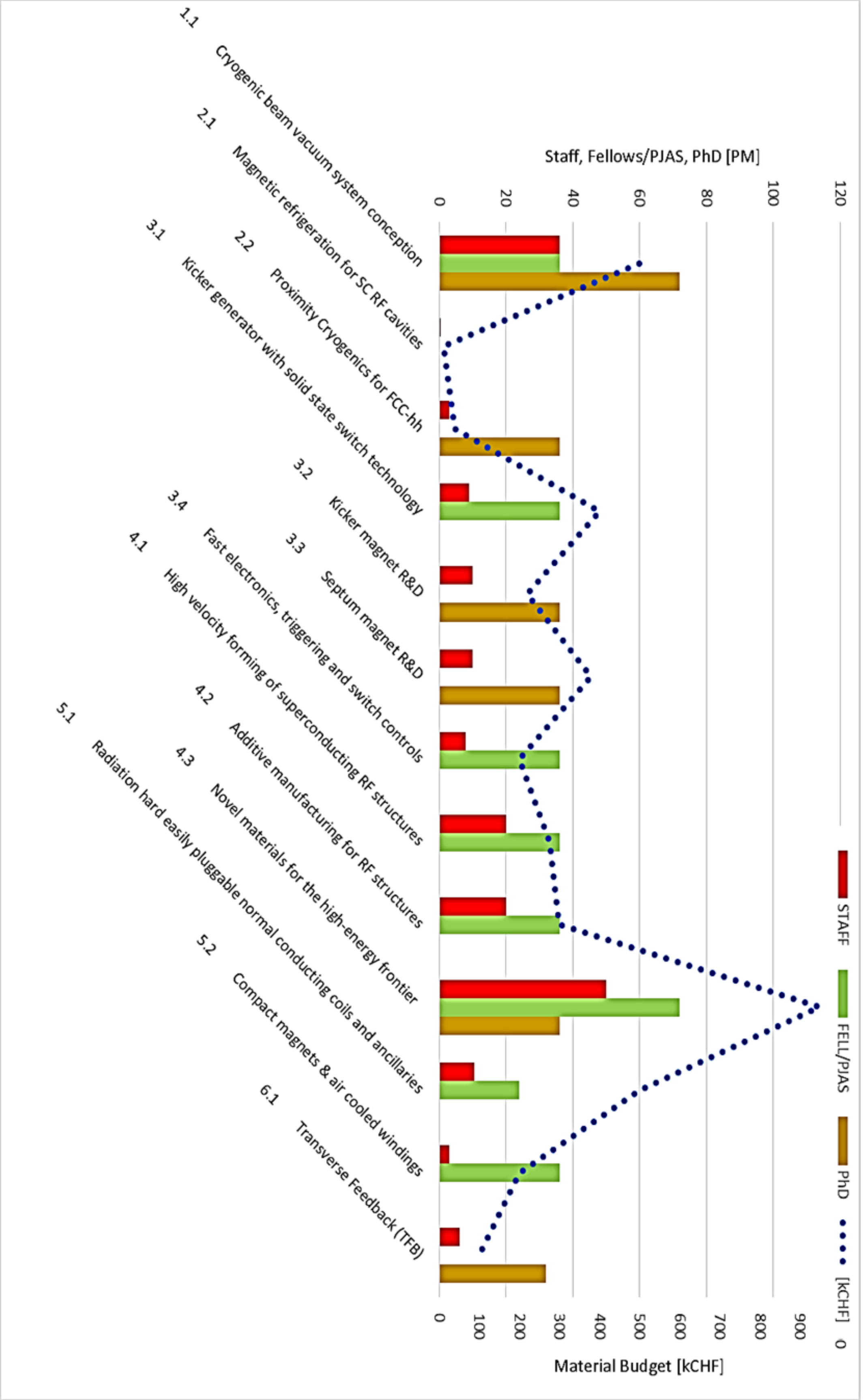
The following Table aims at easing contacts with CERN Sub-Tasks Coordinators

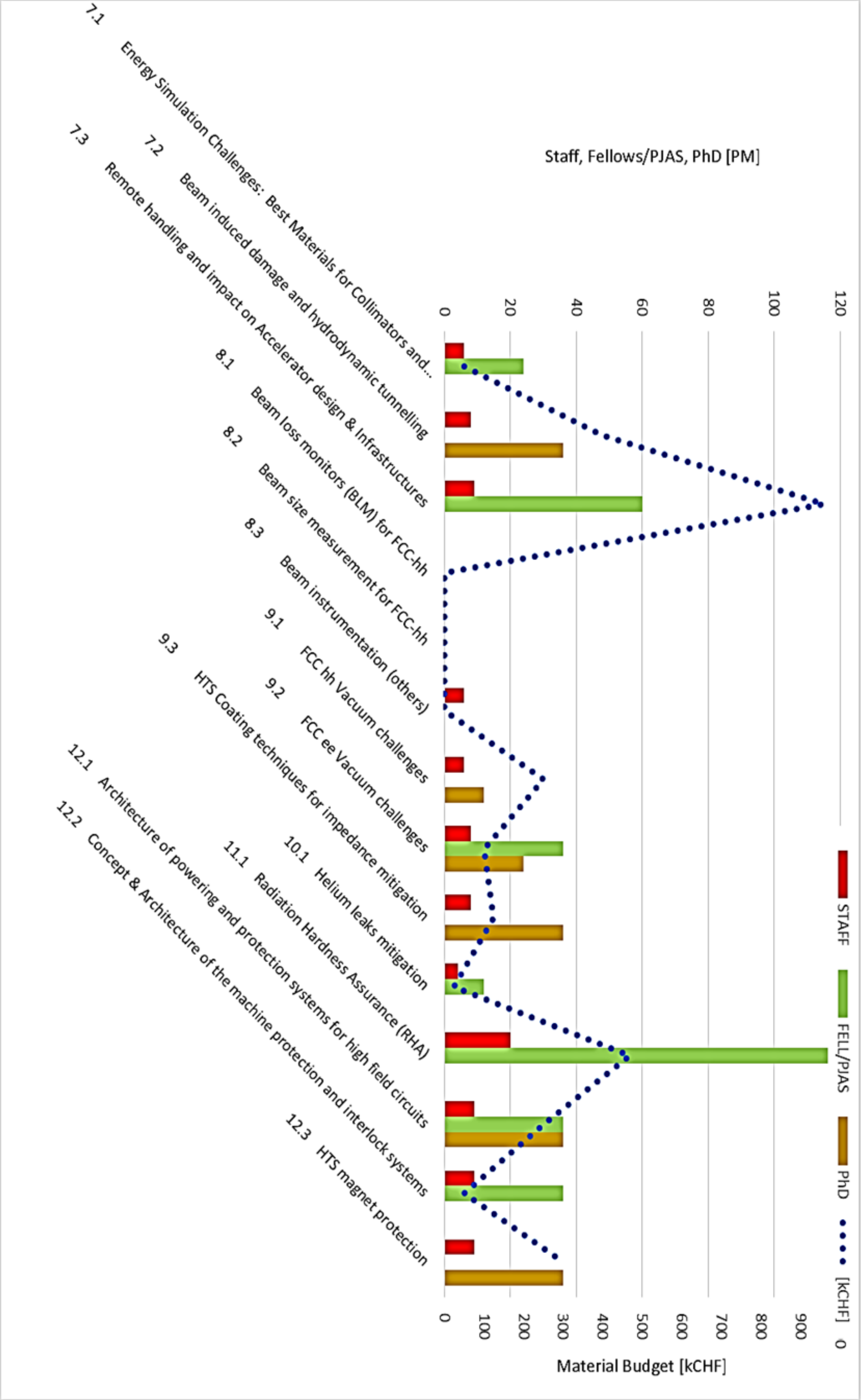
WP #	Description	Contact Person
1	EuroCirCol WP4	Francis PEREZ (ALBA-SPAIN)
2	Cryogenic Challenges	Laurent TAVIAN (CERN)
3	Beam Transfer Challenges	Brennan GODDARD (CERN)
4	Manufacturing Technologies	Francesco BERTINELLI (CERN)
5	Normal Conducting Magnets	Davide TOMMASINI (CERN)
6	Transverse Feedback Systems	Wolfgang HOFLE (CERN)
7	Collimators & Dumps	Roberto LOSITO (CERN)
8	Beam Instrumentation	Rhodri JONES (CERN)
9	Beam Vacuum	Paolo CHIGGIATO (CERN)
10	Insulation Vacuum	Paolo CHIGGIATO (CERN)
11	Radiation Hardness of Electronics	Mar CAPEANS (CERN)
12	Magnets & Machine Protection	Andrzej SIEMKO (CERN)

ANNEX D: CERN RESOURCES (PERSONNEL & MATERIAL)

	CERN Resources (Manpower) [PM]			CERN Resources (Material)
	STAFF	FELL/PJAS	PhD	[kCHF]
1 EuroCirCol WP4 proposal [ALBA & TE-VSC]				
1.1 Cryogenic beam vacuum system conception	36	36	72	500
2 Cryogenics challenges [by Laurent TAVIAN (TE-CRG)]				
2.1 Magnetic refrigeration for SC RF cavities	0.5	0	0	10
2.2 Proximity Cryogenics for FCC-hh	3	0	36	40
3 Beam Transfer challenges [by Brennan GODDARD (TE-ABT)]				
3.1 Kicker generator with solid state switch technology	9	36	0	400
3.2 Kicker magnet R&D	10	0	36	220
3.3 Septum magnet R&D	10	0	36	380
3.4 Fast electronics, triggering and switch controls	8	36	0	200
4 Manufacturing technologies [by Francesco BERTINELLI (EN-MME)]				
4.1 High velocity forming of superconducting RF structures	20	36	0	275
4.2 Additive manufacturing for RF structures	20	36	0	300
4.3 Novel materials for the high-energy frontier	50	72	36	950
5 Normal Conducting magnets [Davide TOMMASINI (TE-MSC)]				
5.1 Radiation hard easily pluggable normal conducting coils and ancillaries	10.5	24	0	500
5.2 Compact magnets & air cooled windings	3	36	0	200
6 Transverse Feedback systems [by Wolfgang HOFLE (BE-RF)]				
6.1 Transverse Feedback (TFB)	6	0	32	100
7 Collimators & Dumps energy simulations [by Roberto LOSITO (EN-STI)]				
7.1 Energy Simulation Challenges: Best Materials for Collimators and Dumps?	6	24	0	50
7.2 Beam induced damage and hydrodynamic tunnelling	8	0	36	400
7.3 Remote handling and impact on Accelerator design & Infrastructures	9	60	0	960

	CERN Resources (Manpower) [PM]			CERN Resources (Material)
	STAFF	**FELL/PJAS**	**PhD**	**[kCHF]**
8 Beam Instrumentation [by Rhodri JONES (BE-BI)]				
8.1 Beam loss monitors (BLM) for FCC-hh	0	0	0	0
8.2 Beam size measurement for FCC-hh	0	0	0	0
8.3 Beam instrumentation (others)	6	0	0	0
9 Beam Vacuum [by Paolo CHIGGIATO (TE-VSC)]				
9.1 FCC hh Vacuum challenges	6	0	12	250
9.2 FCC ee Vacuum challenges	8	36	24	100
9.3 HTS Coating techniques for impedance mitigation	8	0	36	125
10 Insulation Vacuum [by Paolo CHIGGIATO (TE-VSC)]				
10.1 Helium leaks mitigation	4	12	0	25
11 Radiation Hardness of Electronics [Mar CAPEANS (PH-DT)]				
11.1 Radiation Hardness Assurance (RHA)	20	120	0	470
12 Magnets & Machine protection [by Andrzej SIEMKO (TE-MPE)]				
12.1 Architecture of powering and protection systems for high field circuits	9	36	36	250
12.2 Concept & Architecture of the machine protection and interlock systems	9	36	0	50
12.3 HTS magnet protection	9	0	36	300


Staff, Fellows/PJAS, PhD [PM]
0
20
40
60
80
100
120
Material Budget [kCHF]
0
100
200
300
400
500
600
700
800
900
0
STAFF
FELL/PJAS
PhD
[kCHF]
1.1 Cryogenic beam vacuum system conception
2.1 Magnetic refrigeration for SC RF cavities
2.2 Proximity Cryogenics for FCC-hh
3.1 Kicker generator with solid state switch technology
3.2 Kicker magnet R&D
3.3 Septum magnet R&D
3.4 Fast electronics, triggering and switch controls
4.1 High velocity forming of superconducting RF structures
4.2 Additive manufacturing for RF structures
4.3 Novel materials for the high-energy frontier
5.1 Radiation hard easily pluggable normal conducting coils and ancillaries
5.2 Compact magnets & air cooled windings
6.1 Transverse Feedback (TFB)


Staff, Fellows/PJAS, PhD [PM]
0
20
40
60
80
100
120
7.1 Energy Simulation Challenges: Best Materials for Collimators and...
7.2 Beam induced damage and hydrodynamic tunnelling
7.3 Remote handling and impact on Accelerator design & Infrastructures
8.1 Beam loss monitors (BLM) for FCC-hh
8.2 Beam size measurement for FCC-hh
8.3 Beam instrumentation (others)
9.1 FCC hh Vacuum challenges
9.2 FCC ee Vacuum challenges
9.3 HTS Coating techniques for impedance mitigation
10.1 Helium leaks mitigation
11.1 Radiation Hardness Assurance (RHA)
12.1 Architecture of powering and protection systems for high field circuits
12.2 Concept & Architecture of the machine protection and interlock systems
12.3 HTS magnet protection
STAFF
FELL/PJAS
PhD
[kCHF]
0
100
200
300
400
500
600
700
800
900
Material Budget [kCHF]