MuCol WP6:

RadioFrequency Systems

(CEA, INFN, UROS, Uni. Lancaster, CERN, Uni. Strathclyde)

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MUCOL Workpackages

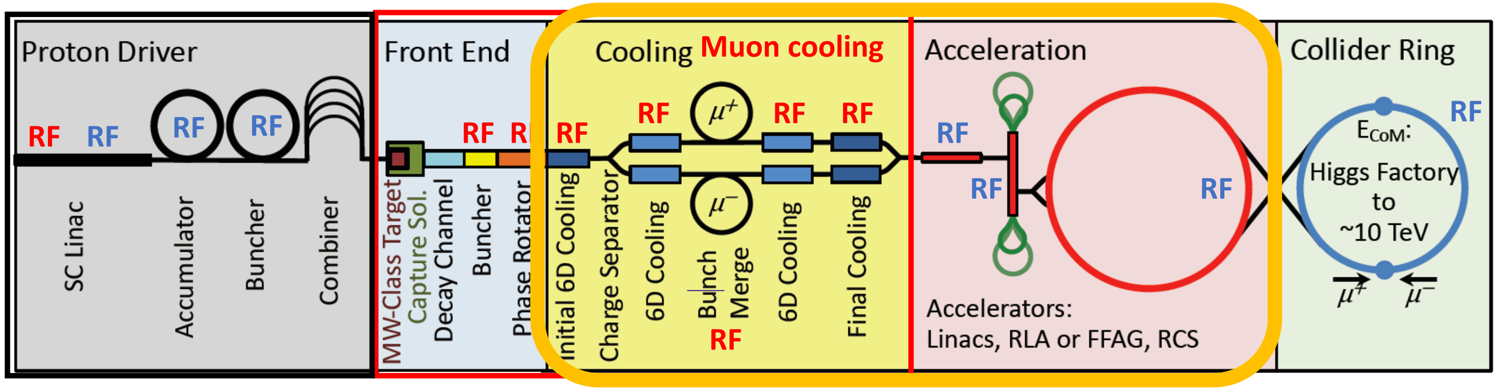
1. Coordination and Communication: CERN
2. Physics and Detector Requirements: UNIPD, INFN, CEA, DESY, UOS, LIP, CERN

   Accelerator chain:

3. Proton Complex: ESS, UU, CERN
4. Muon Production and Cooling: UKRI, Imperial, UWAR, CERN
5. High-energy Complex: CEA, INFN, CERN

   Critical technologies:

6. RF Systems: CEA, ULA, UROS, INFN, CERN, Strathclyde
7. Magnet Systems: CERN, CEA, INFN, SOTON, TUDa, UTWENTE, UMIL
8. Cooling Cell Integration: UMIL, INFN, Imperial, UKRI, CERN



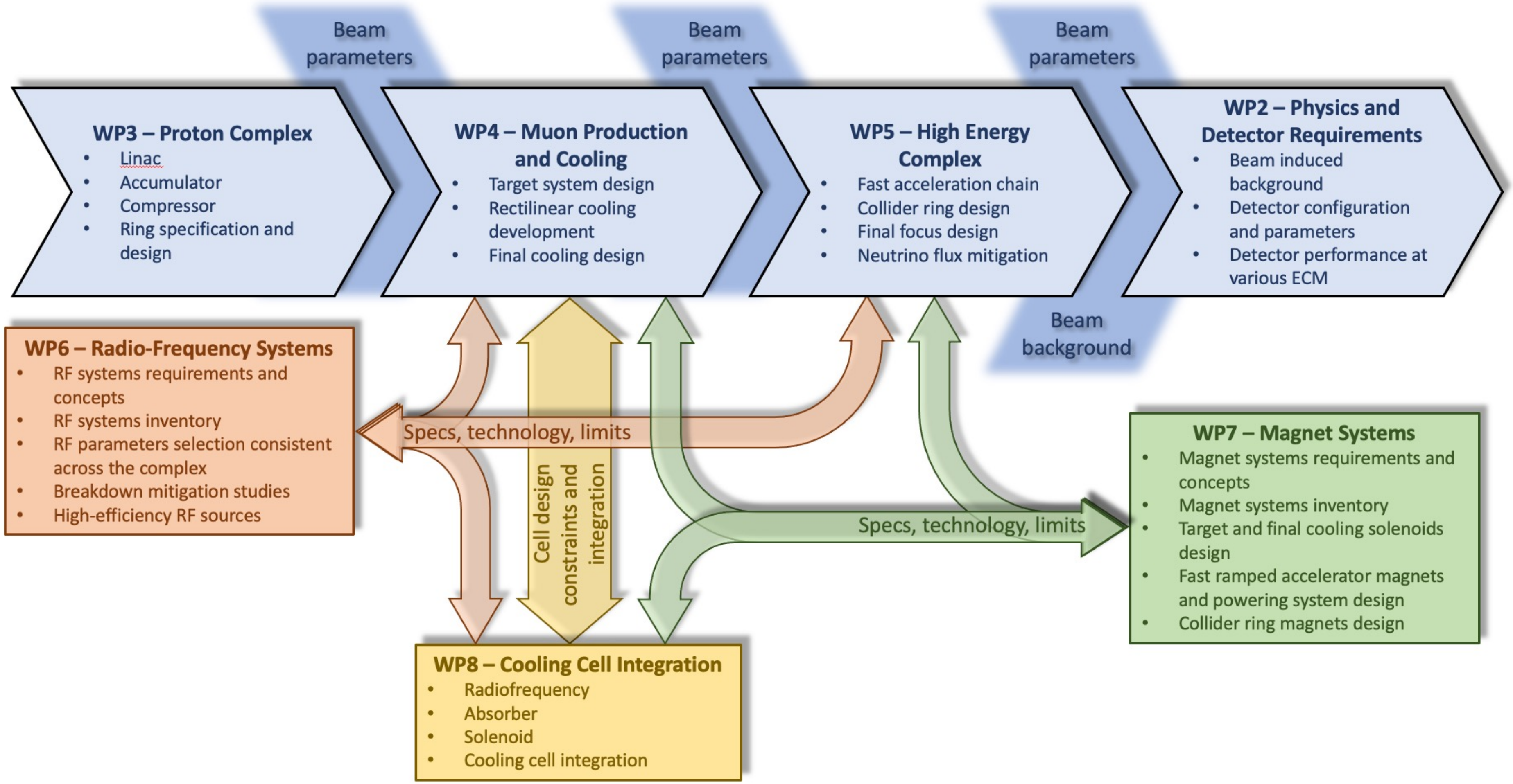
- **WP6 objectives:**

The objective of this work package is to assess crucial feasibility issues and technological challenges of the RF systems. The study will concentrate on the two most challenging sections, the Muon Cooling Complex (MCC), and the muon acceleration stage of the High Energy Complex (HEC), for which a baseline concept of most critical RF components will be outlined based on inputs from WP4, WP5 and WP8 (cavities and RF sources).

- **WP6 tasks and connection to LDG R&D challenges:**

- Task 6.1: Baseline concept of the RF system for acceleration to the High Energy Complex -> LDG 3.5.1 SRF & 5.6.5
- Task 6.2: Baseline concept of the RF system for the Muon Cooling Complex -> LDG 3.5.2 NC RF & 5.6.4
- Task 6.3: Break down mitigation studies for cavities of the muon cooling cells -> LDG 3.5.2 NC RF
- Task 6.4: Baseline concept of high efficiency and high-power RF sources for the muon collider
  -> LDG 3.5.3, 8.2 Sustainability-Energy efficient technologies-Efficient RF sources

Interfaces between MUCOL WP's



Coordination of work for WP6

- **Regular meetings for each task to coordinate work and present updated status**
  - **On a bi-monthly basis:** https://indico.cern.ch/category/12831/

RF systems for acceleration to high energy (MuCol 6.1)	5 événements
SRF technology for muon accelerators	vide
RF systems for muon cooling complex and demonstrator (MuCol 6.2)	2 événements
High gradient RF in strong magnetic field (MuCol 6.3)	3 événements
RF power sources for muon collider RF systems (MuCol 6.4)	vide

Task 6.1: Concept of RF systems for acceleration to HEC (RCS's) (UROS, INFN Milano, CERN, *CEA*)

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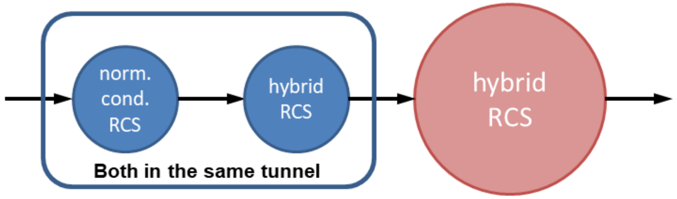
- Chain of rapid cycling synchrotrons, counter-rotating μ^+/μ^- beams
  $\rightarrow$ 63 GeV $\rightarrow$ 0.3 TeV $\rightarrow$ 0.75 TeV $\rightarrow$ 1.5 TeV



$\rightarrow$ Fast acceleration to increase muon survival rate
- Acceleration time only in ms range or less (few 10s of turns)
- Repetition rate ~15 Hz, one pulse every ~67 ms

Example RF parameters of RCS chain

		Unit	RCS-LE	RCS-ME	RCS-HE
Injection energy	E_{inj}	[TeV]	0.063	0.3	0.75
Ejection energy	E_{inj}	[TeV]	0.3	0.75	1.5
Circumference	$2\pi R$	[km]	**6**	**6**	10.7
Stable phase	ϕ_s	[°]	45	45	45
RF voltage per turn	V_{RF}	[GV]	**20.1**	**11.8**	**16.0**
Gradient in straight section	$\Delta E/l$	[MV/m]	11.2	6.6	5.0
Phase slip factor	η		0.0024	0.0024	0.0024
RF frequency	f_{RF}	[GHz]	**1.3**	**1.3**	**1.3**

F. Batsch, MC RF WG meeting #7, Jan 1, 2022

- **Task objectives**:
  - by iterating with WP5, determine a full set of parameters for all cavities addressing longitudinal beam dynamics and stability…
    (f, R/Q, Vmax, Q_L,…)
  - provide a conceptual design of cavities
    (eg: RCS-HE)
- **Challenges**:
  - Short muon lifetime
    -> huge RF voltages = need for high gradients (SRF cavities, eg XFEL like)
  - Optimize distribution of RF cavities along the cyclotron circumference
  - High intensity of muon bunches
    -> strong beam loading & wake field effects
    -> high induced voltage and high HOM power loss

Task 6.1: Concept of RF systems for acceleration to HEC (RCS's)

Progress on the design and simulation of RF systems for RCS

Fabian Batsch et al.

(Accelerator design meeting, 27/02/2023: https://indico.cern.ch/event/1254683/)

- **Reminder of previous studies:**
  - In total, short-range wakefields and beam loading cause induced voltage of ~2.2 MV/m per cavity, or 10% of V_{acc}, but do not harm beam transport
  - On the order n_{RF} = 32 RF stations needed to ensure a sufficiently low synchrotron tune between stations, less but n_{RF} > 16 for RCS3
- **Beam induced power estimates for muon RCS RF systems**:
  - The induced power is very large, up to 13 kW for RCS1&2 per bunch and cavity
  - → Bunch crossings inside the cavity increases power up to 4 times, to be avoided
  - HOM power capability limit is 1 kW, 3-4 kW under development → up to 20 kW per cavity estimate
  - Design of high-capacity power absorbers or lower RF frequency with larger iris needed (wakefields scale with $1/a^2$, a the iris radius)
  - The present parameter tables are based on the ILC cavity (1.3 GHz), but a lower frequency, e.g. 800 MHz, might be required if the HOM power cannot be handled
- **Studies on synchronous phase and consequences on the acceleration**:
  - The synchronous phase could be a mean to reduce P_{HOM} due to increasing bunch lengths
  - Larger ϕ_s , can reduce required V_{RF} by >20%, even more for a 800 MHz system

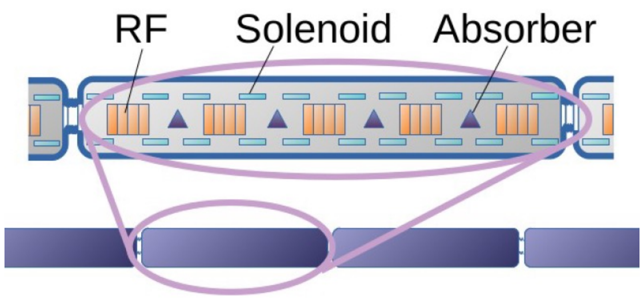
Task 6.2: Concept of RF systems for the muon cooling complex (INFN Milano, CEA, INFN LNL, CERN)

- Normal conducting cavities
- $f \sim 325\ MHz, 650\ MHz$ (MAP)
- Short RF pulses (~μs)
- High gradients (>30 MV/m)
- High magnetic field (up to 13 T)

Region	Length [m]	N of cavities	Frequencies [MHz]	Peak Gradient [MV/m]	Peak RF power [MW/cav.]
Buncher	21	54	490 - 366	**0 - 15**	1.3
Rotator	24	64	366 – 326	**20**	2.4
Initial Cooler	126	360	325	**25**	**3.7**
Cooler 1	400	1605	325, 650	**22, 30**	
Bunch merge	130	26	108 - 1950	**~ 10**	
Cooler 2	420	1746	325, 650	**22, 30**	
Final Cooling	140	96	325 - 20		
Total	**~1300**	**3951**			**~12GW**

It is a very large and complex RF system with high peak power

- **Task objectives**:
  - by iterating with BD (WP4), determine a full set of parameters for all cavities
  - provide a conceptual design of cavities (6D cooling)
- **Challenges**:
  - High beam loading -> mitigate energy spread
  - Breakdown needs to be mitigated (task 6.3)



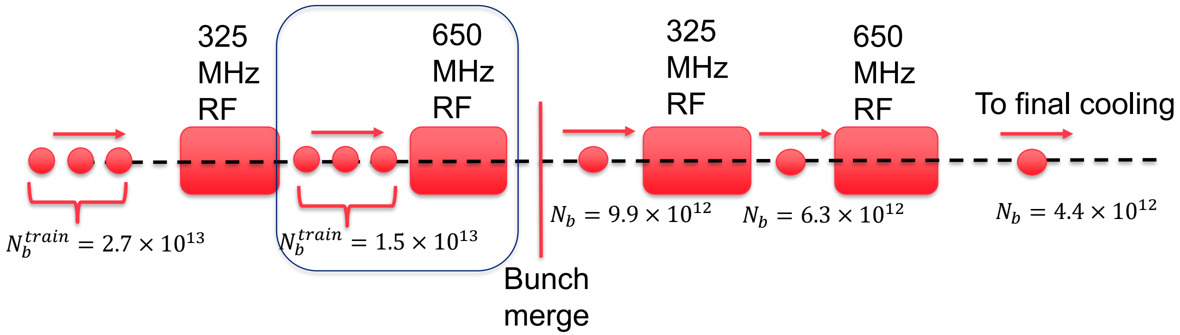
Task 6.2: Concept of RF systems for the muon cooling complex

International MUON Collider Collaboration

Beam loading mitigation idea by detuning (S. Arsenyev, A. Grudiev):

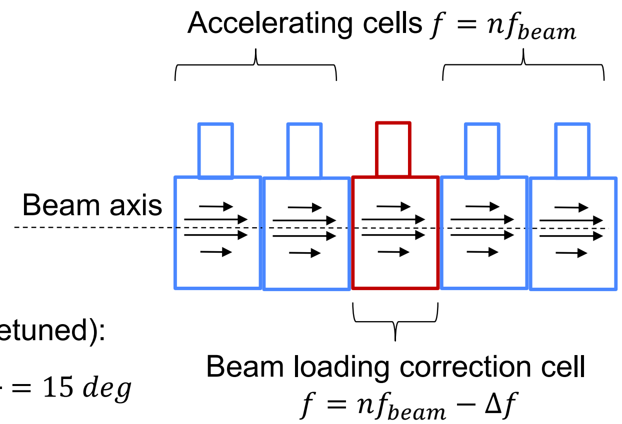
Mismatch cavity frequency and bunch frequency

->each bunch 'sees' different RF phase, so that if V0 is reduced, Vacc is maintained constant at first order



Detune RF frequency from the beam frequency for

- all RF cells
- a few "correction cells"

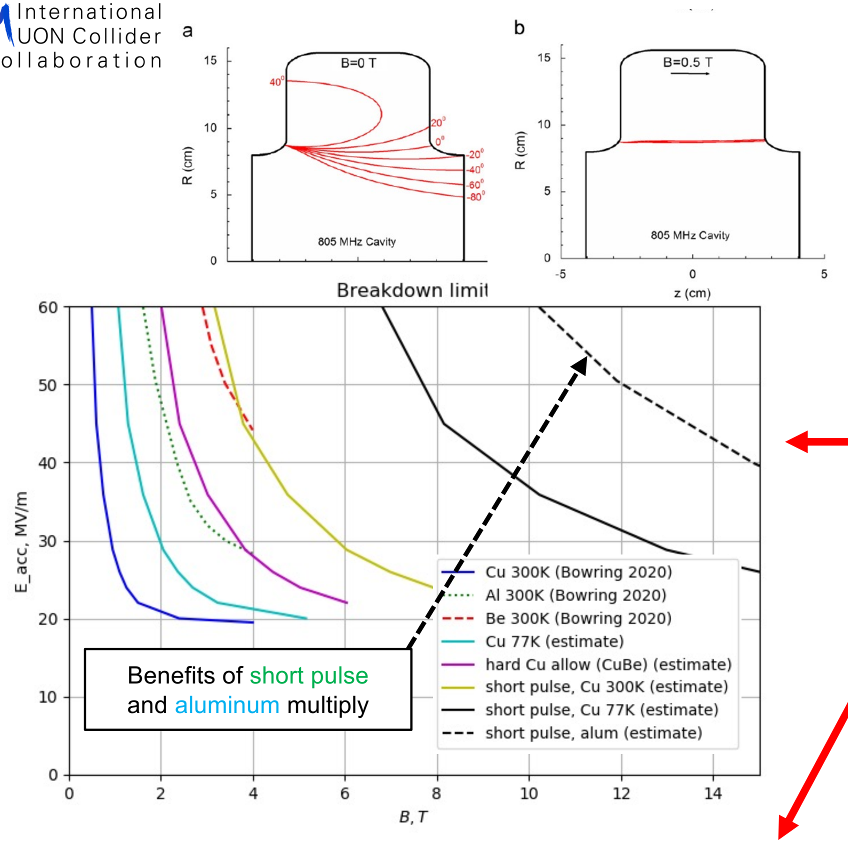


Needed detuning (if all RF cells detuned):

$$2\pi\Delta f\ t_{train} = \Delta\varphi_{beam} \approx \frac{|V_{beam}|}{|V_{head}|} = 15\ deg$$

$$\Delta f = 700\ kHz$$

Task 6.3: Break-down mitigation studies for muon cooling cell cavities (CEA, INFN, Strathclyde)



Model developed by US labs, checked against measurements in high B. Papers: Palmer et.al PRAB 2009, Stratakis et.al NIMPR 2010, Bowring et.al PRAB 2020

- **Task objectives**:
  - find best cavities & RF properties to minimize breakdown due to HG in high magnetic field (material type, gas filled, temperature, pulse length, …)

- **Methodology:**
  - 1/scaling using no-diffusion beamlet model (done)
  - 2/develop semi-analytical model based on simulations of the electron beam in the cavity (like done in US beamlet approach)
  - 3/adjust coefficients of semi-analytical model on existing and maybe new experimental data (UK) (MICE 200 MHz Be, MUCOOL 800 MHz Be, …)
  - 4/test new ideas (cavity length, shape, couplers,..)

Task 6.3: Break-down mitigation studies for muon cooling cell cavities

- **Simulations need to be validated by experimental tests**
- **Need high gradient RF test facilities with B field up to ~10T**

  Test cavities for technology development

  - Frequency: 300 to 700 MHz range, some useful tests even in S-band
  - RF power to get gradients from 25 to 50 MV/m
  - Short RF pulses (~ms)
  - Magnetic field: 0 – *O*(10T), different field configurations
  - Different materials: Cu, Be, **Al**, …
  - Different conditioning algorithms
  - Different surface preparations
  - Different temperatures: 300K -> **70K** ->…

- Include in MUCOL presentation of few possible test stands (CEA, INFN, UK), including cost estimate. Will need to be funded by EU TECH call and/or lab funds

Task 6.4: Concept of high efficiency and high power RF sources
(Uni. Lancaster, CERN)

High power L-band Multi Beam Klystrons (MBK). Commercial tubes.

Frequency: 1.0 GHz
Peak RF power: 20 MW
Efficiency: 70%

Frequency: 1.3 GHz
Peak RF power: 10 MW
Efficiency: 65%

Scaling the Canon tube to 0.7GHz, 24MW and 30 μsec.

Canon E37503
6 beams MBK

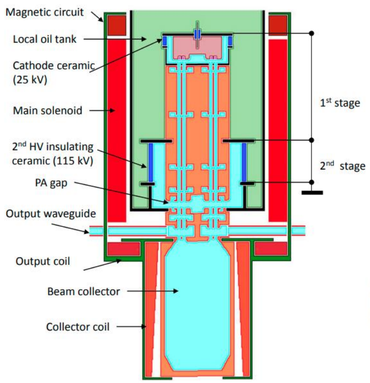
F=	999,5 MHz
P max=	20.2 MW
T =	150 μsec
V=	159.4 kV
I total =	180 A
Eff.=	70.5 %
uP=	0.47 μAxV$^{-3/2}$/beam
Gain =	53.9 dB
$P_{average}$ (50Hz)=	150kW

Mu-tube, 0.7 GHz
6 beams MBK

F=	700 MHz
P max=	24 MW
T =	30 μsec
V=	171 kV
I total =	200 A
Eff.=	70.0 %
uP=	0.47 μAxV$^{-3/2}$/beam
Gain =	53.9 dB
$P_{average}$ (5Hz) =	3.6kW


Scaling Procedures and Post-Optimization for the Design of High-Efficiency Klystrons

Jinchi Cai, Igor Syratchev, and Zening Liu



- **Task objectives**:
  - collect requirements for all RF power sources of the muon collider (f, peak power, efficiency) and identify the most challenging ones (wrt to commercially available RF sources)
  - provide a conceptual design for those, in particular for the muon cooling section that may be used for the muon cooling demonstrator, with emphasis on high efficiency to ensure sustainability

Methodology:
- build upon experience acquired in the HEIKA collaboration on CLIC, combining novel designs
- possibly scale over the range of frequencies

Table 3.1b: EU funded manpower

Work package number	6		**Lead beneficiary**			CEA	
Work package title	RadioFrequency Systems						
Participant number							
Short name of participant	CEA	*ULA*	UROS	INFN	*Strathclyde*	*CERN*	
Person months per participant (EU funded):	22	36	12	36		0	
Start month	1			**End month**	48		

Table 3.1c : List of Deliverables

Deliverable (number)	Deliverable name	Work package number	Short name of lead participant	Type	Dissemination level	Delivery date (in months)
6.1	Consolidated report on baseline concept of high efficiency and high-power RF sources (task 6.4)	6	Uni. Lancaster	R	Public	42
6.2	Consolidated report on baseline concepts of the RF systems for the MCC and HEC complexes, including breakdown mitigation studies for MCC cavities (tasks 6.1,6.2,6.3)	6	CEA, INFN, UROS	R	Public	45

Table 3.1d: List of Milestones

Milestone number	Milestone name	Related work package(s)	Due date (in month)	Means of verification
6.1	Preliminary report on breakdown mitigation for cavities for muon cooling cells	6.3	24	Report approved by StCom
6.2	Preliminary assessment of specifications for RF power sources for muon collider	6.4	24	Report approved by StCom
6.3	Preliminary report on RF acceleration for rapid cycling cyclotrons of HEC	6 .1	32	Report approved by StCom
6.4	Preliminary set of parameters for cavities for muon cooling complex	6 .2	33	Report approved by StCom

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Thank you
for your attention