BD-WG summary

Conveners: R. Ryne, T. Raubenheimer and E. Métral

International MUON Collider Collaboration

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Many thanks to all the people who participated to some BD-WG meetings:

Alexej Grudiev, Bernd Stechauner, Cary Yoshikawa, Daniel Schulte, David Kelliher, David Neuffer, Elena Fol, Heiko Damerau, Ivan Karpov, J. Scott Berg, Jean-Baptiste Lagrange, Kyriacos Skoufaris, Oscar Roberto Blanco, Shinji Machida, Xavier Buffat

Objectives							
A list of key performance specifications to ensure that the beam quality target is met and to guide the design; supported by analytical and computational calculations							
High-level Deliverables							
~~1) RF design of the RCS chain~~ (in RF-WG)							
1) Assessment of collective effects induced limitations in high-energy accelerator design (including collider)							
1) Assessment of collective effects induced limitations in muon cooling design							
2) Development of a self-consistent simulation tool for beam-matter interaction							
1) Assessment of fundamental limit of proton beam density							
Resources	**1**	**2**	**3**		**1**	**2**	**3**
Staff	~~2.8~~ 2			Student		12	
Postdoc	2 ~~(in Oct.)~~+3 (CERN fall 2021 com.)			Material			
Interested partners							
CERN, EPFL, TUD/GSI, UK (STFC), US (BNL, SLAC, LBNL), INFN, LAL Orsay, others?							

Resources are given in total number of FTE-years for the whole duration and in kEuro for material

	Task description	Resource estimate staff [FTEy]	postdoc [FTEy]	PhD [FTEy]	material [kEuro]
~~1~~	~~**RF design of the RCS chain** (new beam dynamics regime during acceleration)~~	~~0.8~~	~~2~~		
1	**Assessment of collective effects induced limitations on high-energy accelerator design** (impedance models; opposite sign bunches – beam crossing and wakes; longitudinal and transverse beam dynamics studies in the collider operating close to transition; mitigation measures; development of simulation tools)	0.5	0.75	3	
1	**Assessment of collective effects induced limitations in muon cooling design** (check of cooling studies with a second code; elaborate models that describe the electromagnetic wake fields generated by the beams passing through matter, as well as the dynamics of the charges generated by ionization including their generation, interaction with the beam and recombination; collective instabilities during ionization cooling)	0.5	0.75	3	
2	**Development of simulation tool for beam-matter interaction**	0.5	0.75	3	
1	**Assessment of fundamental limit of proton beam density** (detailed simulation studies to check that there are no major beam quality degradations and study in detail the halo formation and beam losses)	0.5	0.75	3	
		2 ~~2.8~~	3 ~~5~~	**12**	

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Workpackage Description

For the BD-WG, the idea is to have some staff (Elias Métral, Xavier Buffat, ~~Heiko Damerau and Ivan Karpov from CERN) with an RF fellow who started in October to work on the RF design of the RCS chain (with Ivan as supervisor)~~. We are currently looking for 4 university PHD supervisors (still to be determined) to coordinate the work of 4 PHD students (still to be determined) who will, each, work on one of the 4 other main topics mentioned before. To help in this work, a fellow will soon be hired and supervised by Elias (a candidate has been already identified for the CERN fall 2021 committee) who will first have a look, with the staff members, at the 4 topics to prepare the work of the PHD students:

1) Assessment of collective effects induced limitations on high-energy accelerator design: we will start by building realistic impedance models of the machines, which should be dominated by the RF cavities and the resistive-wall impedance. Longitudinal and transverse emittances need to be preserved to reach the required collider's luminosity and control the orbit. The issue is that we need to handle 2 high-charge muon bunches with opposite signs with a lot of RF (which means a strong longitudinal focusing and a high impedance) and we need to be fast. There will be 2 beam-beam collision points with wakes in the cavities, which will vary depending on where the cavities are in the ring (cavities must be distributed in several uniformly-spaced stations in the ring). This is a unique regime for collective dynamics, and the consequences for beam stability and operation need to be understood.

2) Assessment of collective effects induced limitations in muon cooling design: we will start by checking the cooling studies with a second code as cooling is the key ingredient for a muon collider, and therefore it has to be fully understood and optimized (in particular the final cooling). One should not rely on only 1 code (ICOOL, for which the most complete simulation studies were made) and use G4BL and/or G4MICE to check all the past results (e.g. ICOOL does not do hadronic interactions). Then, we will elaborate models that describe the electromagnetic wake fields generated by the beams passing through matter, as well as the dynamics of the charges generated by ionization including their generation, interaction with the beam and recombination. Finally, the possible collective instabilities which could appear during ionization cooling will be analysed in detail.

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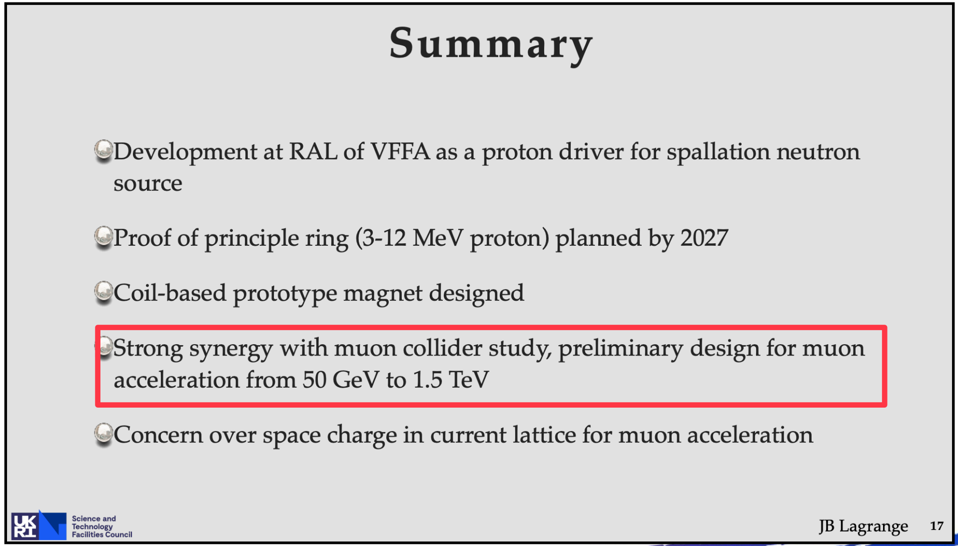
Workpackage Description
3) Development of simulation tool for beam-matter interaction: The tool is a code to estimate beam instabilities in matter, if required after first analyses (see point 2)). It has to be self-consistent in the sense that it needs to correctly take into account the intensity-dependent effects. **4) Assessment of fundamental limit of proton beam density:** It is very important to understand this limit because the more protons (and therefore the more muons we create), the easier it is afterwards. The issue is that we need a high (few MW) beam power, with a short (1-2 ns) bunch length and in particular a low (5 Hz) repetition rate. Detailed simulation studies should therefore be performed to check that there are no major beam quality degradations and study in detail the halo formation and beam losses.

On-going discussions with possible PHD supervisors

- **Assessment of collective effects induced limitations in high-energy accelerator design (including collider)**
  - Could be Mike Seidel and Tatiana Pieloni from EPFL
  - Cost: should be 50%-50%
- **Assessment of collective effects induced limitations in muon cooling design**
  - Could be Mike Seidel and Tatiana Pieloni from EPFL
  - Cost: should be 50%-50%
- **Assessment of fundamental limit of proton beam density**
  - Could be Oliver Boine-Frankenheim from TUD
  - Cost: should be 50%-50%
- ***Development of simulation tool for beam-matter interaction => We will see in a 2nd step***

Some general info/news about the BD-WG

- **11 BD meetings took place until now => See https://indico.cern.ch/category/12762/**
  - Last subject discussed: "**Current status of the vFFA studies**" by Jean-Baptiste Lagrange



Summary

- Development at RAL of VFFA as a proton driver for spallation neutron source
- Proof of principle ring (3-12 MeV proton) planned by 2027
- Coil-based prototype magnet designed
- Strong synergy with muon collider study, preliminary design for muon acceleration from 50 GeV to 1.5 TeV
- Concern over space charge in current lattice for muon acceleration

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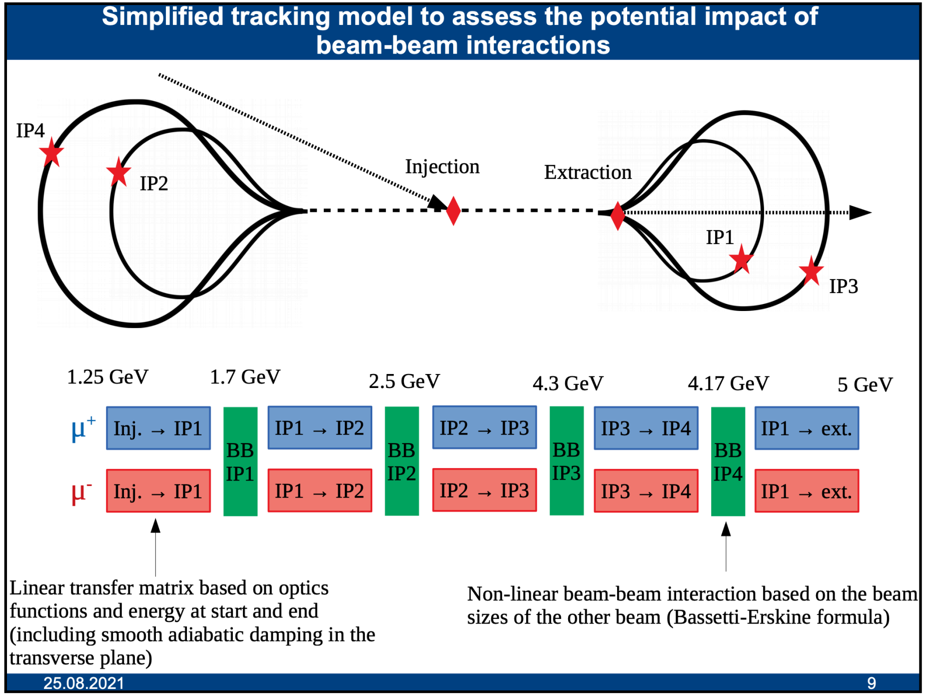
Some general info/news about the BD-WG

- Before we discussed: "**Modeling of beam-beam and wakefields in the RLAs**" by Xavier Buffat



Some general info/news about the BD-WG

- **List of the RCS chain parameters** developed by Heiko Damerau and Ivan Karpov

	Parameter	Symbol	Unit	RCS-LE (nc)	RCS-ME (hybrid)	RCS-HE (hybrid)	Remark
	Speed of light	c_0	[m/s]	299792458			
	Electron charge	e_0	$[10^{-19}C]$	1.602176634			
	Muon rest mass	m_μ	[MeV]	105.6583755			
	Muon lifetime (at rest)	τ_μ	[μs]	2.196981122			
			Unit	RCS-LE (nc)	RCS-ME (hybrid)	RCS-HE (hybrid)	Remark
	Injection energy	E_{inj}	[TeV]	**0.063**	**0.3**	**0.75**	
	Ejection energy	E_{ej}	[TeV]	**0.3**	**0.75**	**1.5**	
	Muon survival rate	N_{ej}/N_{inj}		**0.9**	**0.9**	**0.9**	
	Circumference	$2\pi R$	[km]	**5.990**	**5.990**	**10.700**	
	Pack fraction		[]	0.70	0.70	0.70	
	Bending radius	ρ	[km]	0.667	0.667	1.192	
	Total straight section length	l_{SS}	[km]	1.797	1.797	3.210	
	Injection bending field (average)	B_{inj}	[T]	0.315	1.500	2.099	
	Ejection bending field (average)	B_{ej}	[T]	1.500	3.749	4.197	
	Ejection minus injection field	$B_{ej} - B_{inj}$	[T]	1.185	2.249	2.099	
	Length of normal conducting section	l_{nc}	[km]		3.094	5.130	
	Maximum field, super conducting	$B_{sc,max}$	[T]		10.000	10.000	
	Length of super conducting section	l_{sc}	[km]		1.099	2.360	
	Injection bending field (normal cond.)	$-B_{nc,inj}$	[T]		1.520	1.536	
	Ejection bending field (normal cond.)	$B_{nc,ej}$	[T]		1.528	1.528	
	Injection relativistic mass factor	γ_{inj}	[]	596	2839	7098	
	Injection relativistic mass factor	γ_{ej}	[]	2839	7098	14197	
	Revolution frequency	f_{rev}	[kHz]	50.05	50.05	28.02	
	Gradient for survival	G	[MV/m]	2.38	1.40	1.06	Constant acceleration with linear energy increase
	Acceleration time	T_{acc}	[ms]	0.33	1.08	2.37	
Linear ramp	Number of turns	n_{turn}		17	54	66	
	Ramp rate	dB/dt	[kT/s]	3.56	2.83	1.29	
	Maximum energy gain per turn	ΔE	[GeV]	**14.23**	**8.36**	**11.29**	**No overvoltage!**
	Average gradient per straight length	$\Delta E/l$	[MV/m]	**7.921**	**4.650**	**3.518**	
	Stable phase	ϕ_S	[°]	45	45	45	
	Bucket area reduction factor	$A_B/A_{B,st}$	[]	0.16	0.16	0.16	
	RF voltage per turn	V_{RF}	[GV]	**20.13**	**11.82**	**15.97**	
	Gradient per straight length (50% RF)	$\Delta E/l$	[MV/m]	22.40	13.15	9.95	50% of straight section length available to RF
	Phase slip factor	η	[]	0.0024	0.0024	0.0024	
	Transition gamma	γ_{tr}	[]	20.41	20.41	20.41	
	RF frequency	f_{RF}	[MHz]	1300	1300	1300	
	Harmonic number	h	[]	25975.00	25975.00	46399.00	
	Injection synchrotron frequency	$f_{S,inj}$	[kHz]	74.93	26.31	14.47	
	Injection synchrotron tune	$f_{S,inj}/f_{rev}$	[]	**1.50**	**0.53**	**0.52**	
	Injection bucket area	$A_{B,inj}$	[eVs]	**0.57**	**0.96**	**1.32**	
	Ejection synchrotron frequency	$f_{S,ej}$	[kHz]	34.34	16.64	10.23	
	Ejection synchrotron tune	$f_{S,ej}/f_{rev}$	[]	**0.69**	**0.33**	**0.37**	
	Injection bucket area	$A_{B,ej}$	[eVs]	**1.25**	**1.52**	**1.86**	

Constant gradient

	Parameter	Symbol	Unit	RCS-LE (nc)	RCS-ME (hybrid)	RCS-HE (hybrid)	Remark
	Speed of light	c_0	[m/s]	299792458			
	Electron charge	e_0	$[10^{-19}C]$	1.602176634			
	Muon rest mass	m_μ	[MeV]	105.6583755			
	Muon lifetime (at rest)	τ_μ	[μs]	2.196981122			
			Unit	RCS-LE (nc)	RCS-ME (hybrid)	RCS-HE (hybrid)	Remark
	Injection energy	E_{inj}	[TeV]	**0.063**	**0.3**	**0.75**	
	Ejection energy	E_{ej}	[TeV]	**0.3**	**0.75**	**1.5**	
	Muon survival rate	N_{ej}/N_{inj}		**0.90**	**0.94**	**0.95**	
	Circumference	$2\pi R$	[km]	**5.990**	**5.990**	**10.700**	
	Pack fraction		[]	0.70	0.70	0.70	
	Bending radius	ρ	[km]	0.667	0.667	1.192	
	Total straight section length	l_{SS}	[km]	1.797	1.797	3.210	
	Injection bending field (average)	B_{inj}	[T]	0.315	1.500	2.099	
	Ejection bending field (average)	B_{ej}	[T]	1.500	3.749	4.197	
	Ejection minus injection field	$B_{ej} - B_{inj}$	[T]	1.185	2.249	2.099	
	Length of normal conducting section	l_{nc}	[km]		3.094	5.130	
	Maximum field, super conducting	$B_{sc,max}$	[T]		10.000	10.000	
	Length of super conducting section	l_{sc}	[km]		1.099	2.360	
	Injection bending field (normal cond.)	$-B_{nc,inj}$	[T]		1.520	1.536	
	Ejection bending field (normal cond.)	$B_{nc,ej}$	[T]		1.528	1.528	
	Injection relativistic mass factor	γ_{inj}	[]	596	2839	7098	
	Injection relativistic mass factor	γ_{ej}	[]	2839	7098	14197	
	Revolution frequency	f_{rev}	[kHz]	50.05	50.05	28.02	
	Gradient for survival	G	[MV/m]	2.38	2.38	2.38	Constant acceleration with linear energy increase
	Acceleration time	T_{acc}	[ms]	0.33	0.63	1.05	
Linear ramp	Number of turns	n_{turn}		17	32	29	
	Ramp rate	dB/dt	[kT/s]	3.56	4.83	2.91	
	Maximum energy gain per turn	ΔE	[GeV]	**14.23**	**14.24**	**25.44**	**No overvoltage!**
	Average gradient per straight length	$\Delta E/l$	[MV/m]	**7.921**	**7.923**	**7.924**	
	Stable phase	ϕ_S	[°]	45	45	45	
	Bucket area reduction factor	$A_B/A_{B,st}$	[]	0.16	0.16	0.16	
	RF voltage per turn	V_{RF}	[GV]	**20.13**	**20.13**	**35.97**	
	Gradient per straight length (50% RF)	$\Delta E/l$	[MV/m]	22.40	22.41	22.41	50% of straight section length available to RF
	Phase slip factor	η	[]	0.0024	0.0024	0.0024	
	Transition gamma	γ_{tr}	[]	20.41	20.41	20.41	
	RF frequency	f_{RF}	[MHz]	1300	1300	1300	
	Harmonic number	h	[]	25975.00	25975.00	46399.00	
	Injection synchrotron frequency	$f_{S,inj}$	[kHz]	74.93	34.34	21.72	
	Injection synchrotron tune	$f_{S,inj}/f_{rev}$	[]	**1.50**	**0.69**	**0.78**	
	Injection bucket area	$A_{B,inj}$	[eVs]	**0.57**	**1.25**	**1.98**	
	Ejection synchrotron frequency	$f_{S,ej}$	[kHz]	34.34	21.72	15.36	
	Ejection synchrotron tune	$f_{S,ej}/f_{rev}$	[]	**0.69**	**0.43**	**0.55**	
	Injection bucket area	$A_{B,ej}$	[eVs]	**1.25**	**1.98**	**2.80**	

Some general info/news about the BD-WG

- **Optics repository** => Talk at the Joint NDC-LNO meeting on 09/06/2021 (https://indico.cern.ch/event/1047287/contributions/4399564/attachments/2260648/3837325/OpticsRepositoryForMuonStudy_EM_09-06-21.pdf) to propose to use the CERN optics GitLab repository
    - Still under work by the optics team (contact person: Ghislain Roy)
    - For the moment, the available lattices are stored on the IMCC web page => https://muoncollider.web.cern.ch/design/lattices
        - ★ Info sent by Mark Palmer on 03/05/2021 for collider
        - ★ Info sent by Chris Rogers on 25/08/2021 for cooling

Some general info/news about the BD-WG

- **LEMMA = Low EMittance Muon Accelerator**

LEMMA Muon Accumulator

Muon Collider Design Meeting
Beam dynamics meeting #7

2021/june/16, CERN online

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INFN LNF Istituto Nazionale di Fisica Nucleare

1

Main Messages

LEMMA stands for Low EMittance Muon Accelerator

1) LEMMA targeted a normalized emittance of **~0.040 μm.rad at 22 GeV**
   In simulations we have obtained ~**5 μm.rad**
   Limited by the smallest ß* = 20 cm at the target, achieved with 500 T/m quads

2) LEMMA targeted a muon population of **10^{10} $\mu^{\pm}$** from 10^{16} e^{+}/s.
   In simulations we have obtained :
   ~ **10^{9}** $\mu^{\pm}$, (Pantaleo's et al. Accumulator)
   ~ **10^{7}** $\mu^{\pm}$, (Blanco's accumulator)
   Due to the emittance limitations we need to raise the positron rate

3) LEMMA combines three beams (e+, μ^{+}, μ^{-}) within a small 3D-space.
   The positron bunches have a population of ~ 10^{12} e^{+}.
   The effect of a growing (0 to 10^{9}) muon population in the same 3D-space of a high intensity positron beam has not been yet studied.

2

=> Difficulty to achieve competitive luminosity: novel ideas are required to overcome this limitation

Quite some challenging and interesting work ahead of us!

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Thank you for your attention!