MC RF WG WP structure proposal, v.2 -SRF

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Charge for the 2nd community meeting

- During the 1st community meeting, we identified a set of challenges in the delivery of the muon collider.
- The **goal** now is to confirm those challenges and to develop them into a **prioritised and resource loaded R&D list**. In particular:
  - **Identify the R&D** that has to be carried out before the next ESSU-PP to scientifically justify the investment **into a full CDR** for the muon collider and the corresponding demonstration programme. (**next 5 years**)
  - **Identify** the main components of the **demonstration programme** together with the corresponding **preparatory work**.
  - Realistic but ambitious **targets** for the performance goals of the different collider systems.
- **This includes R&D** to develop a **baseline collider concept**, well-supported performance expectations and an assessment of the associated key risks, cost and power drivers.
- Also the working groups should **consider** what could be assumed for the **demonstration programme**, i.e. in one or more **test facilities starting in 2026**, as well what one can anticipate to be **available in 2035-2040 for a first collider stage** and in 2050 for an energy upgrade.

- **Collect e**xpression **of i**nterest **(EOI)** from potential **collaborators** interested to contribute to any specific work package (task)

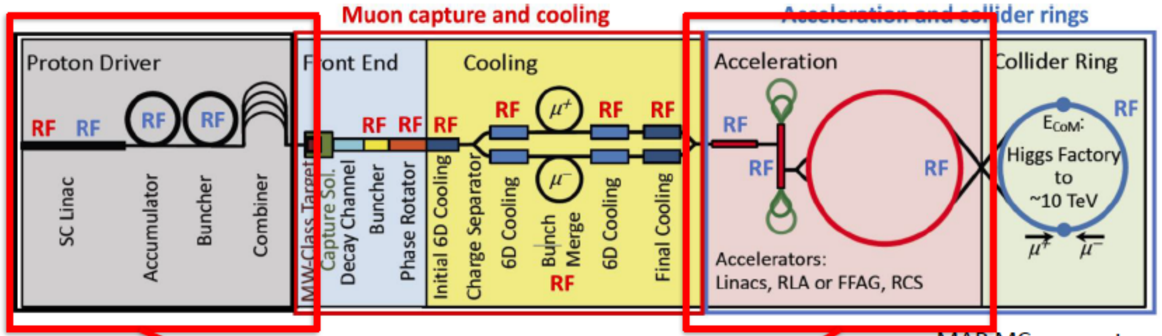
Proposed Workpackage Description

Super conducting RF (SRF) system for muon acceleration to high energy

B. Rimmer, 1st Muon Comm. Meeting

- **SRF** system for **high efficiency** and **highest acceleration rate** to minimize the muon decay losses on **the way to** very high energies: **~10TeV**
- **Key Issues:**
  - High charge, short bunches,
  - **High efficiency** at **high gradient**
  - Manufacturing quality
  - Longitudinal and transverse stability

Muon acceleration SRF challenges



MAP MC concept

- Proton driver e.g. SNS, ESS, PIP-II
- Fast acceleration - high gradient
- Large transverse beam size - low frequency
  - Depends on 6D cooling
  - 200 MHz >325 MHz, 20 MV/m> 650 MHz 25 MV/m > 975 MHz?
  - Thin film based? > bulk Nb?
- Heavy beam loading in RLA's (few% energy spreadover bunch train?)
- Proximity to high field magnets (solenoids or quads)
- Decay products (~15% muons lost in acceleration)?

Summary of IMC RF systems

https://www.dropbox.com/s/2e71dj9bzomglwm/MC_RF%20Summary%20Draft.xlsx?dl=0

System			Driver			Front-End	Cooling			Acceleration			Collider	TOTAL	CLIC
Sub-system			Driver Linac H- (SPL like)		Accum &Comp	Capture& Bunching	Initial	6D (2 lines)	Final (2 lines)	Injector Linac	RLAs (2stages)	RCS (3stages)	Ring	IMC	Acceleration
Reference expert			F.Gerigk		?	D.Neuffer	C.Rogers	D.Stratakis	C.Rogers	A.Bogacz		S.Berg	E.Gianfelice		
Beam (system exit)	Energy	GeV/c	0.16	5	5	0.255	0.255	0.255	0.255	1.25	62.5	1500	1500		1500
	# bunches (μ+ or μ-)	#	40 mA		1	12	12	1	1	1	1	1	1		312
	Charge/bunch	E12			500	3.57	2.56	7.21	4.39	3.73	3.17	2.22	2.20		3.72E-03
	Rep Freq	Hz	5	5	5	5	5	5	5	5	5	5	5		50
	Norm Transv Emitt	rad-m				1.5E-02	3.0E-03	8.3E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05		660/20E-06
	Beam dimens. (H/V) in RF	mm	?	?	?	?	?	?	?	?	?	?	?		1?
	Norm Long Emitt	rad-m				4.5E-02	2.4E-02	1.8E-03	7.0E-03	7.0E-03	7.0E-03	7.0E-03	7.0E-03		
	Pulse/Bunch length	m	2.2 ms		0.6 (2ns)	1.1E+01	1.1E+01	9.2E-02	9.2E-02	4.6E-02	2.3E-02	2.3E-02	5.0E-03		4.4E-05
	Power (μ+ and μ-)	W	6.40E+04	2.2E+06	2.0E+06	1.8E+04	1.3E+04	3.0E+03	1.8E+03	7.6E+03	3.2E+05	5.4E+06	5.3E+06		2.8E+07
RF cavities	Technology		NC Linac4	SC	SC	NC	NC	NC Vacuum	NC	SC	SC	SC	SC		NC High Grad
	Number of cavities	#	23	244	2	120	367	7182	32	52	360	2694	?	11076	149000
	RF length	m	46	237	1	30	105	1274	151	82	1364	2802	?	6092	30000
	Frf	MHz	352	704	44	326to493	325	325-650	20-325	325	650-1300	1300	800	4 to 1300	12000
	Grf	MV/m	1-3.7	19 - 25	2	20	20 to 25	19-28.5	7.2-25.5	20	25 to 38	35	?	1 to 38	100
	Aperture	mm	28	80		?	?	?	?	300	150	75	120	28 to 300	2.75
	Magnetic Field	T	0	0		2	3T	1.7-9.6	1.5-4	0	0	0	0	0 to 9.6	0
	Installed RF field	MV	169	5700	4	434	2618	30447	1836	1640	50844	98062	250	1.92E+05	3.00E+06
	Beam Energy gain	MeV	160	4840	0	0	0	0	0	1250	62500	1437000	0	1.51E+06	1.50E+06
	Recirculations	#	1	1		1	1	1	1	1	4.5 to 5	13 to 23	1000	1 to 1000	1
	RF Power/pulse (η=0.6)	MW	25	220	3.E-01	99	429	1172	43	52	360	2024	1.98E-02	4425	1.2E+07
RF power sources	Technology		klystron	klystron						Klytron-IOT					Two Beam
	Cavities/Power Source	#	23	244		4				1 to 2	1 to 2				2
	RF Pulse (fill+beam) estim.	ms	2.20	2.20	3.20	0.10	0.10	0.10	0.10	0.03	0.06	0.73	14.80		0.142
	Prf/Power Source	MW	11.7	1.93						1	1				15
	Total Power Sources	#	17	244		30				52	341			?	1638
	Installed Peak RF Power	MW	34	275		164	515	1407	52	52	341	2429	2.38E-02	5269	2.46E+04
	Average RF power (η=0.6)	MW	0.27	2.13	0.01	0.05	0.21	0.59	0.02	0.01	0.11	14.88	0.00	18.28	143
	Wall plug power (η=0.6)	MW	0.45	3.55	0.01	0.08	0.36	0.98	0.04	0.01	0.18	24.81	0.00	30.46	289

SRF system parameters and challenges

- SRF system for **high efficiency** and **highest acceleration rate** to minimize the muon decay losses on the way to very high energies: ~10TeV
  - **Large bunch charge in the linacs:** 3.6 x 10^{12} μ => **576 nC**
  - **Large bunch charge in the rings:** 2.2 x 10^{12} μ => **352 nC**
  - **Short bunch length in the collider:** **1.5 mm**
  - Highest possible gradient : ≥ 35 MV/m ?
  - **Power efficiency:** **> 70 % ?**
  - **High energy gain per turn in the rings:** **?**
  - **High level of radiation:** **?**
  - **Stray magnetic field :** **?**

Proposed Workpackage Tasks

Critical issues and R&D on SRF

- **Design of the RF system:**
  - including acceleration, longitudinal beam dynamics, wake-fields, bunch length, and energy spread control for RF cavity design.
- **High gradient:** at low frequency multi cell cavities: **>> 20 MV/m ?,** @ 325, **650 MHz**
  - with seeking for common SRF cavity frequency **beneficially applicable to various project with saving synergy.**
- **Technology choice: Bulk vs Coating**; Different materials: **Nb, (Nb3Sn, HTS**, …) in 5 yrs
- **Cavity type(shape) and Surface Treatment:** for high gradient and high Q (low loss factor)
- **Pulsed operation:** Lorenz force detuning in pulsed (strong transient) mode.
- **RF power sources:** pulsed, high peak power, high efficiency: > 70 % ?
- **Tolerance:** to external (stray) magnetic field, … Which level?
  - With common motivation with HTS beam-screen under ≥ 16 T for the FCC-hh (as long term theme)
- **Tolerance:** to the radiation and beam loss
- **Power couplers:**

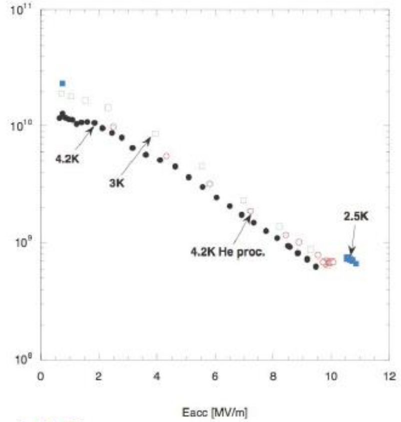
Seeking for common SRF cavity frequency beneficially applicable to various project with saving synergy.

R. Rimmer
Jlab

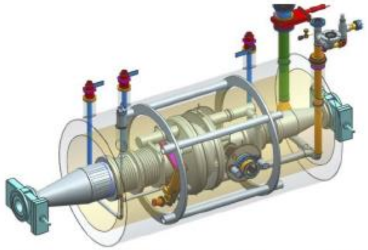
1st Muon Community Meeting
20-21 May 2021

Example cavities

Cornell 200 MHz (Nb on Cu)



400 MHz bulk Nb



EIC 591 MHz (bulk Nb)

PERLE/FCC 800 MHz (bulk Nb)

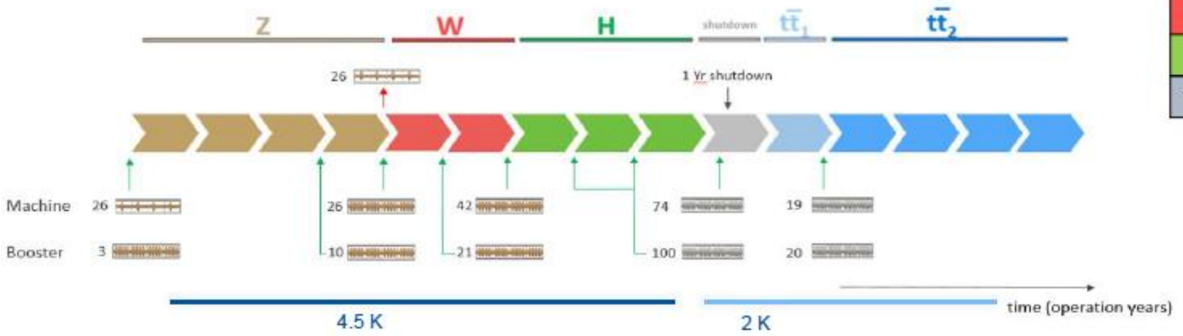
More R&D needed

- Proton drivers
- Accelerating structures
  - 325, 650, 975 MHz? 1.3 GHz?
  - LFD, microphonics
  - High stored energy?
- Efficient cryomodules
  - High packing factor (how close can the magnets be to SRF?)
  - HTS magnets?
  - Low cost construction?
- High power RF sources, modulators, components
- New materials
- Beam tests

O. Brunner, on behalf of the FCC SRF R&D team

The baseline

WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4



400 MHz 1-cell cavities

400 MHz 4-cell cavities

800 MHz 5-cell cavities

- 400 MHz ? –> “natural choice” for FCC_hh
- Very tight timeline
- Focused at optimum re-usage & installation of hardware (RF power, LLRF, controls..)

The RF system for FCC-ee

A. Butterworth, CERN

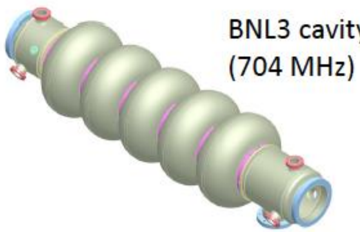
Cavity choice

Baseline: SC cavities @ 400 and 800 MHz

- Main RF system at 400 MHz for lower energy/higher beam currents
- lower loss factors → HOM power (see later), transverse stability
- possibly Nb/Cu technology @ 4.5 K cf. LEP, LHC

LHC cavities (400 MHz)

- Additional 800 MHz cavities to reach highest energy/lowest beam currents
- higher gradients (with bulk Nb @ 2K)
- higher loss factors → less interesting for high beam current operation



BNL3 cavity (704 MHz)

FCC-ee RF staging

4 values of beam energy, 3 RF configurations

Beam Energy	Parameter	Unit	Initial 400 MHz	Full 400 MHz	Baseline 400/800 MHz
Power (=# tubes)		MW	12	30	50
Max. Rf voltage		MV	1900.00	4700.00	10700.00
45 GeV (Z running)					
	beam current	mA	350.000	850.000	
	# bunches		4000	10000	
	Luminosity	**$/cm^2/s$**	**5.06E+034**	**1.53E+035**	
80 GeV (W running)					
	beam current	mA	36	90	150
	# bunches		1100	2700	4490
	Luminosity	**$/cm^2/s$**	**1.75E+034**	**5.89E+034**	**1.19E+035**
120 GeV (H running)					
	beam current	mA	7.2	18	30
	# bunches		320	800	1360
	Luminosity	**$/cm^2/s$**	**4.89E+033**	**2.34E+034**	**5.09E+034**
175 GeV (t-tbar running)					
	beam current	mA			0.0065
	# bunches				98
	Luminosity	**$/cm^2/s$**			**1.43E+034**

O. Brunner, on behalf of the FCC SRF R&D team

The prospects

- Solid baseline with well defined R&D topics
- Promising challengers
  - Single-cell and multi-cells elliptical cavities @ ~ 600 MHz
    - Beam dynamics studies must be completed
  - The new SWELL cavity has a considerable potential for ampere class accelerators
    - No showstoppers until now!
    - Long, ambitious but exciting validation process
- Rich core & specific R&D programs
  - Cavity design, beam dynamics, LLRF
  - Cavity fabrication, preparation, cryostating
    - ELL: pursue ongoing R&D
    - SWELL: 1.3 GHz simplified demonstrator -> 600 MHz full cavity
  - High efficiency klystrons & FPC (same technology at 400 & 600 MHz)
- Favors enthusiastic collaborations and synergies with other projects (EIC, PERLE,…)
  - Ease the topic selection and prioritization (limited resources)
  - Strategically & economically important

"Future comes by itself, progress does not."— Poul Henningsen

Proposed Workpackage Timeline

SRF WP1: Baseline design of the RF system for acceleration to high energy: Design study + synergy

	1	2	3	4	5	input	output
1. Baseline design of the RF systems for **RCSs** including acceleration, longitudinal beam dynamics and stability, bunch length and energy spread control. a. Provide specifications for **cavity design**: **frequency**, R/Q, HOM suppression. b. Provide specification for **RF power sources**: frequency, peak/average RF power, CW/pulse length						HEC, BD, MG	PPC
2. Calculation of **cavity parameters** for fundamental mode parameters: R/Q, Vmax; as well as for HOMs and wakes for the design work in 1.							
3. RF design of the cavities for the RCSs as input to BDR							
4. Design of the **RF cavities for LA and RLAs** based on the specifications from HEC and BD						HEC, BD	

Proposed Workpackage Timeline

SRF WP2: High gradient SRF technology for muon accelerators.

Synergy + potential proto(?)

	1	2	3	4	5	input	output
1. **High gradient** in low frequency (325 – 650 MHz) large multi-cell (1-4) SRF cavities. • Identify best technology choice: bulk vs coating, different materials: Nb, Nb3Sn, … • Provide limiting values for RF cavity design	■	■	■				RF
2. **Lorenz force detuning** in ‘pulsed’ beam loading operation			■	■			
3. **RF power sources**: • High efficiency baseline design based on the parameter specification from WP1		■	■	■			PPC
4. **Tolerance** to external magnetic fields, and to the radiation & beam loss.			■	■			
5. **Synergy**: • Look for synergy in SRF technology with already ongoing projects and R&D activities. • Direct them to the parameter space relevant for muon collider	■	■	■	■	■		
6. Provide **limiting values** for RF cavity and RF system design: gradient, etc	■	■					

Proposed Workpackage Timeline

SRF WP3: ?

	1	2	3	4	5	input	output
1.							

Normal conducting RF system for muon cooling

- To be discussed in the next session

NRF system parameters and challenges

- Complex **normal conducting RF (NRF)** system, and many of the cavities need to be independently powered and controlled at many different frequencies in the ranges from 20 to 650 MHz. Majority of the cavities operate at two main frequencies: 325 and 650 MHz at high gradients in a strong magnetic field at multi-Tesla magnitude.
- **Low frequency (large cavity): 325 - 650 MHz,**
- **High gradient: 25 - 30 MV/m,**
- **Strong magnetic field: 5 - 10 T**
- **High peak current before bunch merge:** 3.6E12 μ @325MHz => **187 A**
- **Large bunch charge after bunch merge:** 7.3E12 μ => **1168nC**
- **Large beam aperture/window:**
- **High level of beam losses and decay radiation**
- **Technology is far from being mature**. The closest example is a positron capture RF cavity: high frequency, high gradient, but not in so strong magnetic field.

Critical issues and R&D on NRF

- **Gap** between **performance** of the prototype and the test cavities achieved so far must be closed. Based on the nominal parameters from the Muon Cooling WG: frequency, gradient, B-field, aperture and on the existing (and future) test results, design, build and test prototype cavities for the muon cooling test facility.

- **Achievable high gradient** in a **strong magnetic field** requires continuous R&D on: alternative materials, gas versus vacuum, operation temperatures, pulse shapes and other new ideas. This requires a dedicated test stand on a time scale before the muon cooling test facility.

- **RF power source**: Existing commercial RF power sources are by design operate at lower peak power but higher average power than what is needed for muon collider. This is driven by current applications. A new design of the RF power source targeting muon collider parameters (higher peak power, lower duty factor) and high efficiency must be pursuit.

- **Engineering design and integration:** RF, SC magnet, cryogenics, etc.

- Safety, maintenance and etc. associated with using Beryllium materials on cavity walls and beam windows.

- **Collective effects**: beam loading, single and multi-bunch must be addressed.

NRF WP1: Baseline design of the RF system for Muon cooling complex. Design study for BDR

	1	2	3	4	5	input	output
1. Collect consistent set of specification parameters for the design of **all** RF cavities for the muon cooling complex: frequency, gradient, length, B-field, aperture, …						MC	
2. Based on available knowledge, identify best concept for achievable accelerating gradient in magnetic field: material, pulse shape, temperature, gas, …							
3. Design few reference cavities which can be used to estimate parameters of all cavities specified in 1. Make a consistent set of parameters of **all** RF cavities and associated RF system							PPC
4. Integration RF cavities into cooling cell adapting design if necessary						MC,MG ,CR, …	MC
5. Calculation of cavity parameters for simulation and mitigation of collective effects including beam loading						MC, BD	MC, BD

NRF WP2: Conceptual design of the RF system for Muon Cooling Test Facility. Design study for MCRF CDR

	1	2	3	4	5	input	output
1. Collect consistent set of specifications for the design of RF cavity(es) for the MCTF: frequency, gradient, length, B-field, aperture, …	■	■				MC	
2. Design the cavities specified in 1 using the concept identified in WP1.2	■	■					TF
3. Design of the associated RF system for the MCTF		■	■				TF
4. Integration of the RF cavity into the MCTF cooling cell(s) including SC solenoid, cryo, etc			■	■		MC,MG ,CR,…	TF
5. Engineering design of the cavity in its environment including cooling, thermal and mechanical stability, alignment, RF diagnostic and tuning, …			■	■	■		
6. Design of RF test stand for validating performance of RF cavities before installation in MCTF			■	■	■	MC,MG ,CR,TF…	TF

NRF WP3: R&D on high gradient in strong magnetic field. Potential test cavities

	1	2	3	4	5	input	output
1. Identify infrastructure available for potential use as (or setting up) a test stand for testing RF cavities in strong magnetic field: RF power source, SC solenoid,…							
2. Design and build RF test stand based on the available infrastructure and specified requirements							
3. Propose test program adapted to potential test setup, considering possible limitations in terms of available frequency, power, magnetic field strength and size of the cavity							
4. Design and build test cavities							
5. Test the test cavities							RF

NRF WP4: RF power sources for muon cooling RF system. Design study + synergy

	1	2	3	4	5	input	output
1. Based on the parameters of RF cavities set target specifications for the RF power sources for Muon cooling complex						MC	
2. Address potential issues including: - Large number of different frequency, - Higher peak power requirements than currently available - High efficiency							
3. Baseline Design of RF power source(s) to provide information on the peak power capability, efficiency and cost							RF, PPC
4.							

NRF WP5: ?

	1	2	3	4	5	input	output
1.							

Appendix:

- General Guideline given by Daniel Shulte

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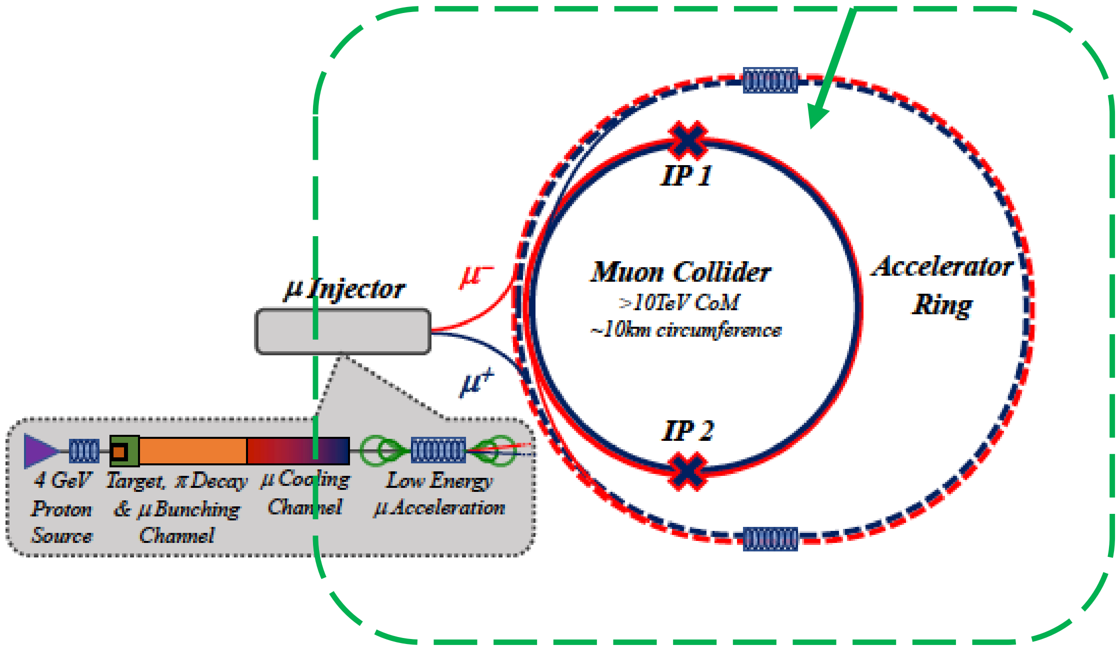
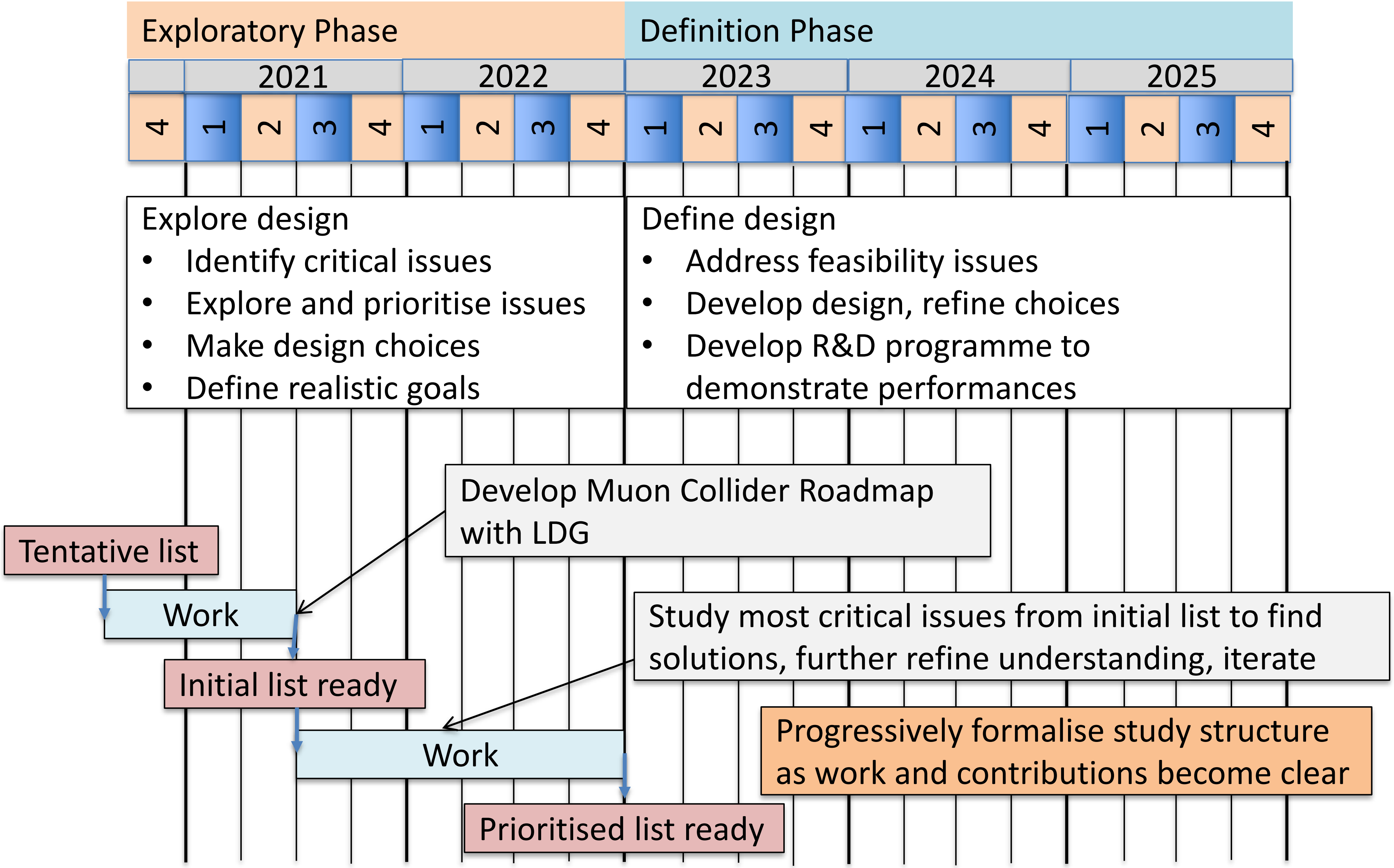


Timeline until next ESPPU



Proposed Workpackage Resources

A table of the initial estimated required resources in FTE years, specifying staff, post-doc and student. If possible, resources should be associated with the tasks.
This is only indicative to get over the shock of having to fill such tables.

Task	Staff [pm]	postdoc [pm]	student [pm]	Cash [kEUR]	Comment

Also a list of who is interested in participating to define the work and carry it out.
There is no commitment required.

Technically Limited Long-Term Timeline