Some Progress

Daniel Schulte and Mark Palmer for the Muon Beam Panel

LDG Plan

International MUON Collider Collaboration

Constraints on Delivery Plans

- 5 to 10 year focus within a longer overarching programme
- Specific on deliverables, demonstrators and outputs
- Reflecting three resource levels / scenarios for each area
  - 'Nominal': what we think there is a good chance we will have
  - 'Minimal': what we need to at least guarantee a viable R&D programme
  - 'Aspirational': illustrating what we could do with significantly (factor two) more resources
- Need to be broken down into manageable work packages
  - Definite scope – i.e. clear objectives, outputs and work plan
  - Time-constrained – i.e. no more than a few years
  - Resource-loaded – i.e. with an approximate estimate of human, capital and operational needs
- Should allow an assessment of the possible rate of progress for a range of funding scenarios

2 Accelerator R&D Roadmap Workshop, 30th September 2021 Dave.Newbold@stfc.ac.uk

UKRI Science and Technology Facilities Council

LDG Plan

Proposed Panel Section Structure

- Executive summary of findings to date [1p]
- Introductory material (history - explanatory material) [2p]
  - Should be written so as to be comprehensible to non-experts (i.e. particle physicists); rest of the section can be more technical
  - Should explain the *relevance* of the R&D area to future facilities, and a brief account of the key challenges and the history
  - May talk about existing collaborations and structures
- Motivation [2p]
  - Should explain the *requirements* on the system, and the need for R&D to address them
  - Should explain the required long-term timeline for R&D , which contains the immediate 5-10 year plan
- Panel activities [1p]
- State of the art [8p]
  - More or less as the interim report, but less dense and more 'narrative' than 'a list' (laser/plasma and ERL are good examples]
- R&D objectives [8p]
  - Lists *what needs to be achieved*, and why
- Delivery plan [10p]
  - Indicates the breakdown of the work into tasks to meet the R&D objectives; tasks in each objective should be in rough time order
  - Explains the nature of each tasks, and the resources required to achieve it
- Facilities, demonstrators and infrastructure [5p]
  - States the existing major facilities being used in the field; Explains the necessary investment into facilities and infrastructure
  - Talks about any potential science delivery from future facilities (this can include facilities outside the 5-10 year immediate timeline)
- Collaboration and organisation [3p]
  - What relevant work is being done outside the field (assume work in non-European countries is covered in 'state of the art')
  - Explains how the R&D will be coordinated
- References [2p]

LDG Plan

Timeline

Week beginning	Council / SPC	LDG activities	Panel activities	Editing activities
30-Aug-2021				1-Sep-2021: IR draft 2 frozen
6-Sep-2021		8-Sep-2021: LDG review of interim report and next steps		
13-Sep-2021			Preparation of slides for SPC	15-Sep-2021: IR final draft
20-Sep-2021	SPC 21-Sep-2021	28-Sep-2021: IR to RECFA reps, two-week deadline for feedback		
27-Sep-2021		30-Sep-2021: Workshop for LDG and panel chairs on delivery plans and costings		
4-Oct-2021			Workshops on delivery plans	
11-Oct-2021		12-Oct-2021: Cross-panel workshop on initial delivery plans; deadline for RECFA feedback		15-Oct-2021: Deadline to panels for non-DP parts of text
18-Oct-2021			Presentation of delivery plans to LDG	Editing of non-DP parts of text, figures Incorporation of delivery plans
25-Oct-2021		27-Oct-2021 (?): LDG review of draft delivery plans	Finalisation of report text (inlcuding intro / conclusion)	29-Oct-2021: FR draft to LDG.
1-Nov-2021		5-Nov-2021: Deadline for substantive LDG comments.		5-Nov-2021: FR frozen for final editing
8-Nov-2021		12-Nov-2021: Deadline for detailed LDG comments	Respond to substantive LDG comments with deadline of 12-	Final editing
15-Nov-2021				Final editing / Council documents preparation
22-Nov-2021	Council papers deadline			
29-Nov-2021				
6-Dec-2021	SPC 6-Dec-2021; Council 10-Dec-2021			

- Time is now very short: many things need to go in parallel

The Process

Muon Beam Panel
Daniel Schulte (CERN, chair)
Mark Palmer (BNL, co-chair)
Tabea Arndt (KIT)
Antoine Chance (CEA/IRFU)
Jean-Pierre Delahaye (retired)
Angeles Faus-Golfe (IN2P3/IJClab)
Simone Gilardoni (CERN)
Philippe Lebrun (European Scientific Institute)
Ken Long (Imperial College London)
Elias Metral (CERN)
Nadia Pastrone (INFN-Torino)
Lionel Quettier (CEA/IRFU), Magnet Panel link
Tor Raubenheimer (SLAC)
Chris Rogers (STFC-RAL)
Mike Seidel (EPFL and PSI)
Diktys Stratakis (FNAL)
Akira Yamamoto (KEK and CERN)

Contributors:
Alexej Grudiev (CERN), RF panel link
Roberto Losito (CERN), Test Facility link
Donatella Lucchesi (INFN) MDI link

Working groups identified the challenges, the required scope work and estimated the resources needed

Community meetings served to disseminate, discuss and refine the findings of the working groups as well as to propose urgency levels

The results were integrated into

In closed session, the panel reviewed scope and urgency levels as well as resource needs
It started to define the urgency level of the different workpackages

- Will iterate based on feedback today

Many thanks to our MAP and MICE colleagues who paved they way and whose design and progress is instrumental for our effort

Community Working Group Convener

Conveners list

Radio-Frequency (RF): Alexej Grudiev (CERN), Jean-Pierre Delahaye (CERN retiree), Derun Li (LBNL), Akira Yamamoto (KEK).

Magnets: Lionel Quettier (CEA), Toru Ogitsu (KEK), Soren Prestemon (LBNL), Sasha Zlobin (FNAL), Emanuela Barzi (FNAL).

High-Energy Complex (HEC): Antoine Chance (CEA), J. Scott Berg (BNL), Alex Bogacz (JLAB), Christian Carli (CERN), Angeles Faus-Golfe (IJCLab), Eliana Gianfelice-Wendt (FNAL), Shinji Machida (RAL).

Muon Production and Cooling (MPC): Chris Rogers (RAL), Marco Calviani (CERN), Chris Densham (RAL), Diktys Stratakis (FNAL), Akira Sato (Osaka University), Katsuya Yonehara (FNAL).

Proton Complex (PC): Simone Gilardoni (CERN), Hannes Bartosik (CERN), Frank Gerigk (CERN), Natalia Milas (ESS).

Beam Dynamics (BD): Elias Metral (CERN), Tor Raubenheimer (SLAC and Stanford University), Rob Ryne (LBNL).

Radiation Protection (RP): Claudia Ahdida (CERN).

Parameters, Power and Cost (PPC): Daniel Schulte (CERN), Mark Palmer (BNL), Jean-Pierre Delahaye (CERN retiree), Philippe Lebrun (CERN retiree and ESI), Mike Seidel (PSI), Vladimir Shiltsev (FNAL), Jingyu Tang (IHEP), Akira Yamamoto (KEK).

Machine Detector Interface (MDI): Donatella Lucchesi (University of Padova), Christian Carli (CERN), Anton Lechner (CERN), Nicolai Mokhov (FNAL), Nadia Pastrone (INFN), Sergo R Jindariani (FNAL).

Synergy: Kenneth Long (Imperial College), Roger Ruber (Uppsala University), Koichiro Shimomura (KEK).

Test Facility (TF): Roberto Losito (CERN), Alan Bross (FNAL), Tord Ekelof (ESS,Uppsala University).

Muon Collider Collaboration

Goal

In time for the next European Strategy for Particle Physics Update, aim to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**

Scope

- Focus on two energy ranges:
  - **3 TeV**, with technology ready for **construction in 15-20 years, can use MAP results**
  - **10+ TeV**, with more advanced technology, **the unique potential of the muon collider**
- Explore synergies (neutrino facility/higgs factory)
- Define **R&D path**

The panel endorsed this ambition

It concludes that

- The muon collider presents enormous potential for fundamental physics research at the energy frontier
- At this stage the panel did not identify any showstopper in the concept and sees strong support of the feasibility from previous studies
- It identified important R&D challenges

Deliverables

- We collected the input in less formal fashion (talks) and via a formal template
- We have much detail that is important to assess resource estimates and to guide the work later
- But deliverables seem too detailed for this report

Our main deliverables are

- An assessment whether the muon collider is a promising option and addressing the following questions:
  - What is a realistic luminosity target?
  - What are the background conditions in the detector?
  - Can one consider implementing such a collider at CERN or other sites?
  - What are the cost drivers and what is the cost scale of such a collider?
  - What are the power drivers and what is the power consumption scale of the collider?
  - What are the key technical risks?
- A report describing an R&D path toward the collider
  - A conceptual design for the muon colling test facility
  - A description of other R&D efforts required

Template Example

HE-Acceleration

Objectives							
Develop a credible design concept of the high-energy muon acceleration complex with cost scale, upgrade path, and demonstration facility requirements based on reasonable assumptions on technology development.							
Complete beamline description with lattices and ideally have start-2-end tracking of full system to demonstrate luminosity performance and bunch compression during the process.							
Identify outstanding challenges with possible mitigation approaches.							
High-level Deliverables							
Immediate) Overall design parameters							
Immediate) Rapid Cycling System (RCS) design							
Urgent) Linac and Recirculating Linac (RLA) design							
Urgent) Alternative to RCS: FFA							
Resources	1	2	3		1	2	3
Staff	0.5	1	0.3	PhD	3	3	
Postdoc	4	3		Material			
Interested partners							
BNL (FFA + RCS), CEA (RCS), IJCLab-In2p3 (RLA), JLAB (Linac), UKRI-STFC (FFA)							

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

Template Example

HE-Acceleration

Objectives
Develop a cre path, and dem development.
Complete bea demonstrate
Identify outst
High-level De
Immediate) O
Immediate) R
Urgent) Linac
Urgent) Alter

Resources	
Staff	
Postdoc	

Interested pa
BNL (FFA + RC

Resources are

HE-Acceleration

1	Task description	Resource estimate staff [FTEy]	postdoc [FTEy]	PhD [FTEy]	material [kEuro]
	Get a baseline layout and gather all parameters in a table including cost estimation and powering budget.	0.1	1.5		
	Start to end simulations of HEC complex	0.1	0.5	0.5	
	Lattice optics design and single particle dynamics in the RCS	0.2		2.5	
	Tolerance studies (alignment and field quality)	0.1	2		
	Evaluate the collective effects in the RCS	In Beam Dynamics package			
	Radiation mitigation in the arcs	In Radiation Protection package			

2	Task description	staff	postdoc	PhD	material
	Assess the key issues of the linac +RLA system (muon decay effects on SRF cavities, injection, alignment, …)	0.1	1		
	Lattice optics and single particle dynamics of the linac and RLA	0.2	2		
	Assess the potential benefits of FFA as an alternative	0.3			
	Lattice optics design and single particle dynamics, in FFA	0.4		3	
	Evaluate the collective effects in the linac system	In Beam Dynamics package			
	Evaluate the collective effects in FFA	In Beam Dynamics package			

3	Task description	staff	postdoc	PhD	material
	Build a synergy around FFAs (spallation sources for instance)	0.3			

Template Example

HE-Acceleration

Objectives
Develop a cre… path, and dem… development.
Complete bea… demonstrate …
Identify outst…
High-level De…
Immediate) O…
Immediate) R…
Urgent) Linac…
Urgent) Altern…
Resources
Staff
Postdoc
Interested pa…
BNL (FFA + RC…

Resources are…

HE-Acceleration

1	Task description	Resource estimate staff [FTEy]	postdoc [FTEy]	PhD [FTEy]	material [kEuro]
	Get a… inclu…				
	Start…				
	Lattic…				
	Toler…				
	Evalu…				
	Radia…				
2	Task…				
	Asses… effec…				
	Lattic…				
	Asses…				
	Lattic…				
	Evalu…				
	Evalu…				
3	Task…				
	Build…				

HE-Acceleration

Workpackage Description
This work-package is focused on the feasibility and optimization of the muon acceleration complex from the cooling channel to the collider. The main goal is to develop a credible design concept of the high-energy muon acceleration complex with cost estimate, upgrade path, and demonstration facility requirements based on reasonable assumptions on technology development. In this aim, this work package will completely describe the beamline by gathering all relevant information in a parameter table. This work package will provide a full set of lattices with critical technologies identified and will have start-2-end tracking of full system to demonstrate luminosity performance and to validate the bunch compression and emittance preservation during the acceleration process. This work package will identify outstanding challenges with possible mitigation approaches. This work package will have an iterative and collaborative process in the collective effects part with the Beam Dynamics and with the technology work packages like SRF and magnet WPs to validate the feasibility of the machine parameters.

Muon Collider Collaboration

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Timeline Discussions

Muon collider is a long-term direction toward high-energy, high-luminosity lepton collider

Collaboration prudently also explores if muon collider can be option as next project (i.e. operation mid2040s) in case Europe does not build higgs factory

Exploring shortest possible aggressive timeline with initial 3 TeV stage on the way to 10+ TeV

- Important ramp-up 2026

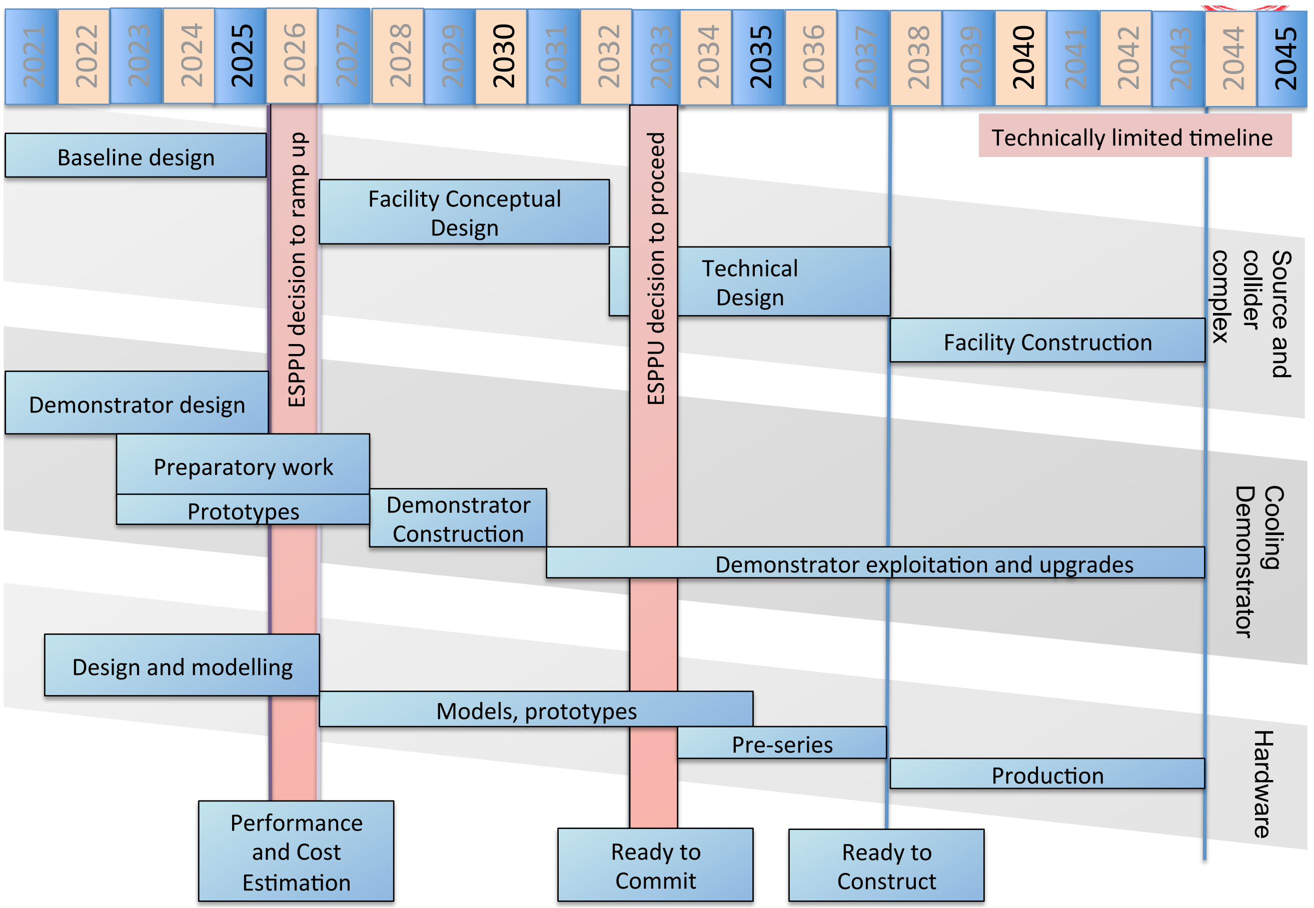
High-field magnet and RF programmes will allow to judge maturity what can be reached in a collider with this timeline

Preparation of R&D programme needs to be advanced enough for implementation after next ESPPU

Based on strategy decisions a significant ramp-up of resources could be made to accomplish construction by 2045 and exploit the enormous potential of the muon collider.

Tentative Target for Aggressive Timeline

to assess when 3 TeV could be realised, assuming massive ramp-up in 2026



Key Challenge Areas

10+ TeV is uncharted territory

- **Physics potential** evaluation, including d**etector concept and technologies**

- Impact on the environment
  - The **neutrino flux mitigation** and its impact on the site (first concept exists)

- The impact of **machine induced background** on the detector, as it might limit the physics reach.

- **High-energy systems** after the cooling (acceleration, collision, …)
  - Fast-ramping magnet systems
  - High-field magnets (in particular for 10+ TeV)

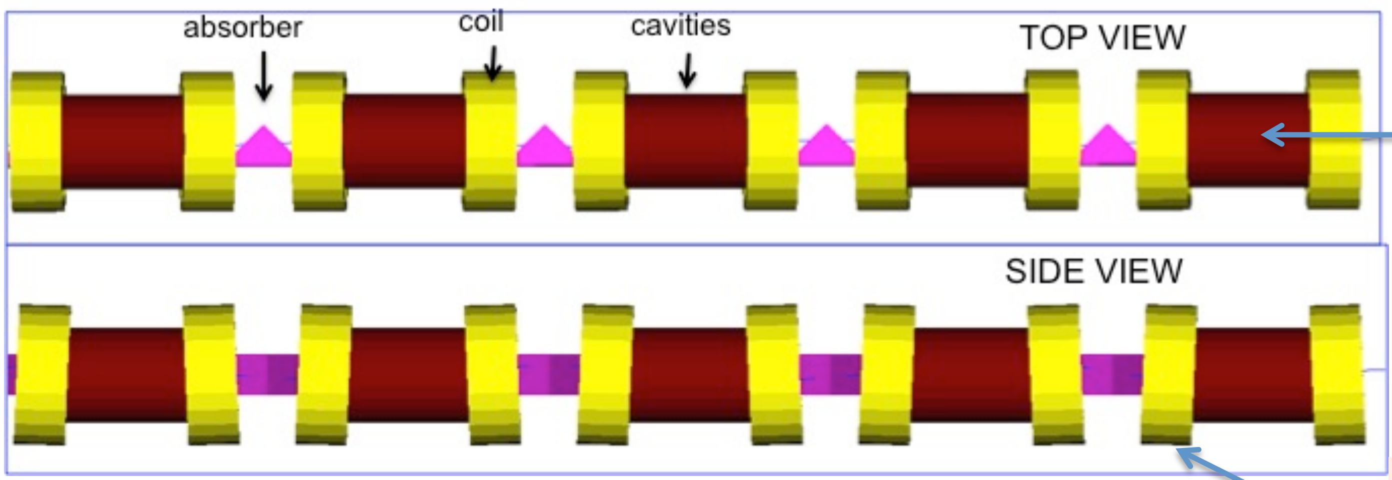
- **High-quality muon beam production**
  - Special RF and high powering systems
  - Superconducting solenoids
  - Cooling string demonstration (cooling cell engineering design, demonstrator design)
  - Full power target demonstration

- **Proton complex**
  - H- source, compressor ring

Only one Example Package

Cooling Challenges

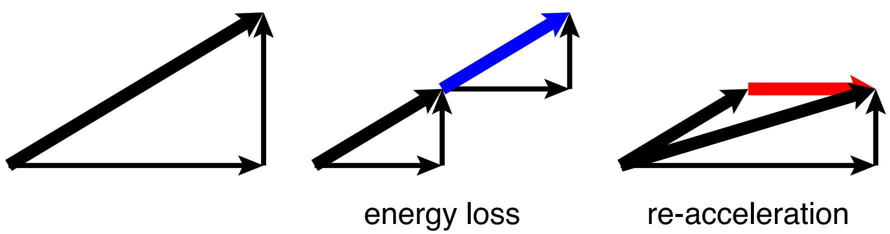
MAP collaboration

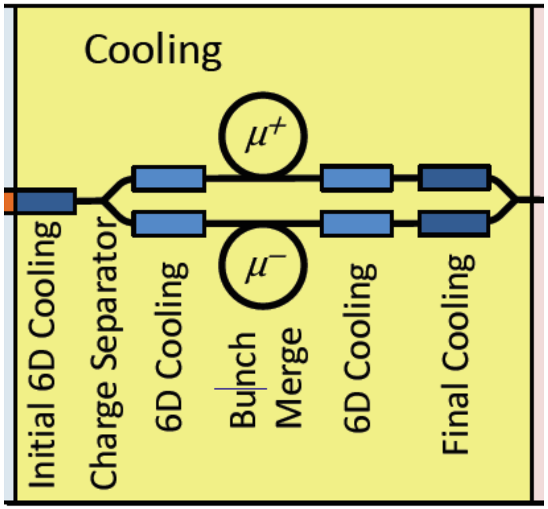


Limit muon decay, cavities with **high gradient in a magnetic field** tests much better than design values but need to develop

Compact integration to minimise muon loss

Minimise betafunction with **many strong solenoids** (up 14 T in MAP design, 20-25 T for us)





A few final cooling solenoids pushing to the absolute limit (30 - 50 T)
Luminosity is proportional to field

Need to **optimise lattice design** to gain factor 2 in emittance, integrating demonstrated better hardware performances

This is the **unique** and **novel** system of the muon collider
Will need a **test facility**

Muon Cooling Complex

1) Establishing basic concept

- Baseline 6D cooling based on MAP
- Optimised final cooling scheme
- Assessment of bottlenecks due to collective effects
- Assessment if beam-matter interaction could lead to instability

2) Improved design, profiting from technologies and ideas

- Optimise 6D cooling system taking into account available RF gradients and solenoid fields
- Develop other elements of the muon capture and cooling system
- Performance estimates of alternative final cooling schemes

3) Engineering considerations for muon cooling module and definition of future R&D

- Understand potential material physics issues, collective effects in ionisation cooling. Look at engineering integration issues. Look at absorber design including heat load and its removal. Assess possibility for experimental verification of any simulation issues.
- Assessment of final cooling engineering integration issues – in particular the absorber engineering where there is large instantaneous heat load and challenges in integrating Hydrogen cryogenics with magnet systems.

	Staff/FTEy	Postd/FTEy	Stud/FTEy	Mat/kEuro	Sum/MEur
6D and final cooling	3	8.5	9	0	2.07
Other cooling/alternative	2	8	9	0	1.81
Engineering	5	16.5	18	0	3.88

Interest: RAL (some resources), CERN (some resources), FNAL, BNL, JLAB

Demonstrators

- Demonstration of muon cooling module solenoid
- Demonstration of muon cooling module cavity
- Demonstration of powered muon cooling module
- Facility to demonstrate muon production and cooling technology with beam
  - Conceptual design for next ESPPU
- Demonstration of 20-25 T solenoid for the 6D cooling
- Demonstration of highest-field final cooling solenoid
- Facility to demonstrate performance of cavities for muon cooling module in high magnetic field
- Demonstration of fast-ramping magnet and power converter system
- Demonstration of target materials in HiRadMat

Interaction with other Programmes

High-field magnet programme

- Cable development is vital, in particular HTS
- Development of solenoids for muon collider would be very good for the programme as they are easier to fabricate and could excellent tool to help testing cables and technologies, solenoids would help to reach out to other fields
- Fast-ramping magnets using superconductors would be additional application of cables and could address specific aspect
- The muon collider might profit from higher temperature operation to minimise cooling power requirements

RF

- Superconducting RF is important key in the muon collider
- High gradients at low frequencies are important
- Could profit from existing programme if tests for high gradients can be performed

High-efficiency klystron development is essential for the muon collider

- Could reduce 4000 klystrons for cooling by an order of magnitude

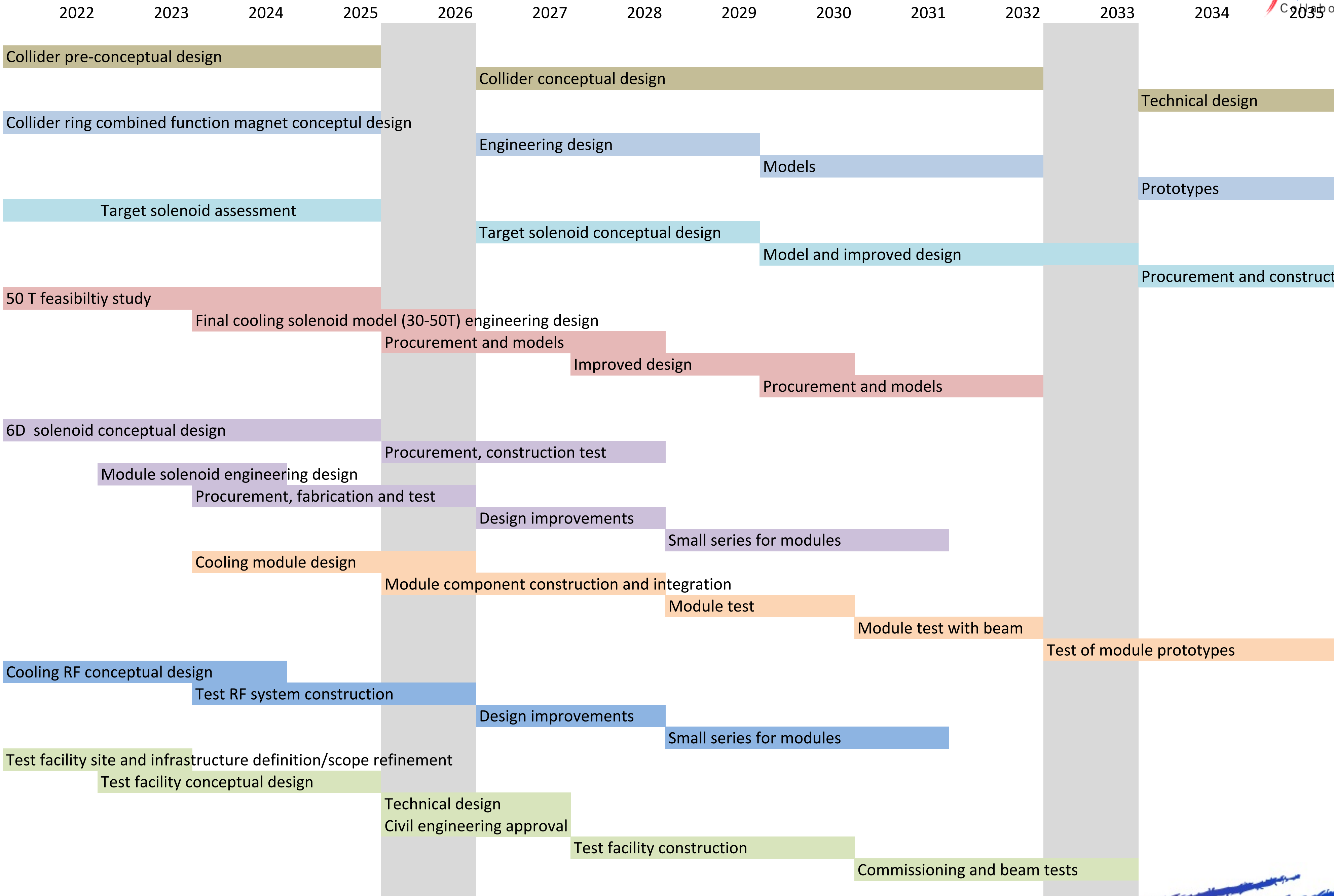
Resources Full Progress

	Staff FTEy	Postdoc FTEy	Student FTEy	Material kEuro	Sum MEuro
Neutrino flux mitigation	8	11.5	12	150	3.73
Machine-detector interface	5	10	0	0	2.2
HE-complex	5.8	13.5	18	0	3.68
Muon cooling	7	16.5	18	0	4.28
Target system	27	33	3	495	9.975
Proton complex	5.7	13	15	0	3.45
High-field magnets	45	27.5	13	2450	15.4
Fast-ramping magnets	6.8	7	4	770	3.17
RF	2.8	9	3	0	1.79
RF test stand	10	0	0	2900	4.9
Muon cooling test module and test facility	24.7	42	10	1700	12.18
Coordination and general	7.2	9	2	500	3.12
Sum	155	192	98	8935	67.875

Available 10 MCHF from CERN, some FTEy at INFN, some FTEy at RAL, some effort at Darmstadt

Quite some interest but attitude is to wait for Roadmap

Schedule Discussion



Conclusion

- Need to spend O(60 MEuro) to achieve goal
  - pre-conceptual design report with cost and power scale
  - test facility conceptual design
  - prepared R&D programme
- With funding could achieve goal by 2026
  - solenoids would still be under construction

- Are converging on stretched programmes
  - Minimum could be O(25 MEuro) before 2025
    - will not be good enough to judge the muon collider, except by its progress
    - and delay test facility
  - Iterating on intermediate speed programme
- Your guidance is welcome

- Integration of solenoid development with high-field magnet programme should be envisaged
- Use of superconducting cavities from RF programme for high-gradient tests would be useful

Comments from LDG

- LDG not shocked by resource scale
- Need only minimal and aspirational programme, not nominal
- Agreed on idea to change timescale rather than scope
  - however in some case had plan up to technical design (target) in others not
- Solenoids were considered of interest for HFM programme

- Need to make minimum programme
- Need to be careful in what we have to deliver by next strategy
  - do not promise too much
    - should be careful to expect more resources at CERN
    - can expect resources from partners
  - separate what is needed to see if the muon collider is realistic and what is needed to advance the maturity more rapidly
- Find a way to present the need for more resources but

- Need to define timelines
  - even without explicit years
  - the proposals from the detector seem not useful
  - the one from magnet panel is also quite simplistic

Discussion

Neutrino flux and MDI are the most critical challenges

- With no solution we can stop the effort

⇒ We need an intermediate milestone with a preliminary report on the two subjects before we launch into larger spending

⇒ Can also include progress on other important challenges

Need to define how far we would need to be at next ESPPU to have meaningful assessment

- Expectation management
- Should we be ambitious with the minimum programme because we believe only this is funded?
  - but high risk if it is not
- Should we have a small programme so we are quite sure to have it funded?
  - may help to support that additional activities should be funded
  - but risk that they are not
  - extreme case: only consider funded activities
- Logical progression of stage for R&D programme for different challenges is required

Timeline Discussion

Example for test module

- Goals: Identify the challenges and solutions, accelerate the programme after the next ESPPU
- Steps
  - parameter choice
  - conceptual module design
  - engineering module design
  - construction of key components (solenoids and cavities)
  - construction of module
  - test of module with power
  - test of module with (proton?) beam
  - implementation in test facility
- Probably can aim for twice the current resource level with minimum programme
- Approach could be to have
  - concept assessment, which requires minimum effort to be able to judge muon collider credibility
  - R&D programme preparation/maturity improvement, which advances the technology
  - But hard to draw a clear line

Conclusion

- Challenging days are ahead for community meeting and Muon Beam Panel
- Key is to discuss the priorities and timelines more this meeting
  - today
  - on Friday across all the working groups
- Critical to identify potential contributions
  - Need this to be able to put something into the minimum programme
- Very hard indeed to stay in minimum envelope
  - will have to make hard decisions
  - will have to show that we do hard decisions
- Which holes hurt less?
  - will fill them if possible as we go along