International
MUON Collider
Collaboration

Muon Roadmap

Daniel Schulte and Mark Palmer for the Muon Beam Panel

Muon Collider Collaboration Goals

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

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

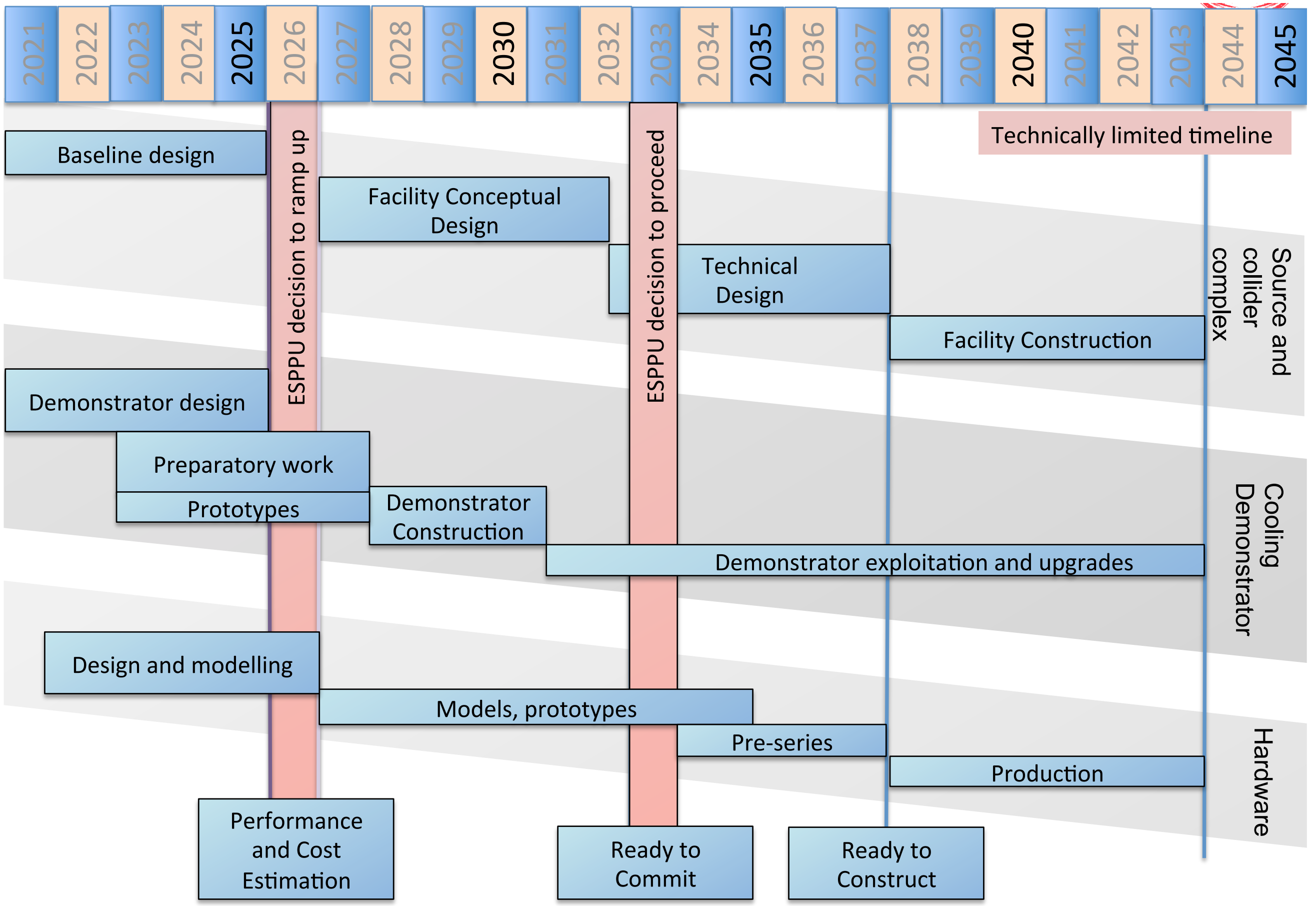
High-field magnet and RF programmes will allow to judge maturity what can be reached in a collider with this timeline

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



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

ESPPU decision to ramp up

ESPPU decision to proceed

Source and collider complex

Baseline design

Facility Conceptual Design

Technical Design

Facility Construction

Cooling Demonstrator

Demonstrator design

Preparatory work

Prototypes

Demonstrator Construction

Demonstrator exploitation and upgrades

Hardware

Design and modelling

Models, prototypes

Pre-series

Production

Performance and Cost Estimation

Ready to Commit

Ready to Construct

Full-scope Deliverables

- 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 cooling test facility
  - A description of other R&D efforts required

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

Expectations

Hard to think that we get all we need in time

LDG wants three scenarios

- Minimal meaningful progress
- Nominal (which we do not need to provide)
- Aspirational

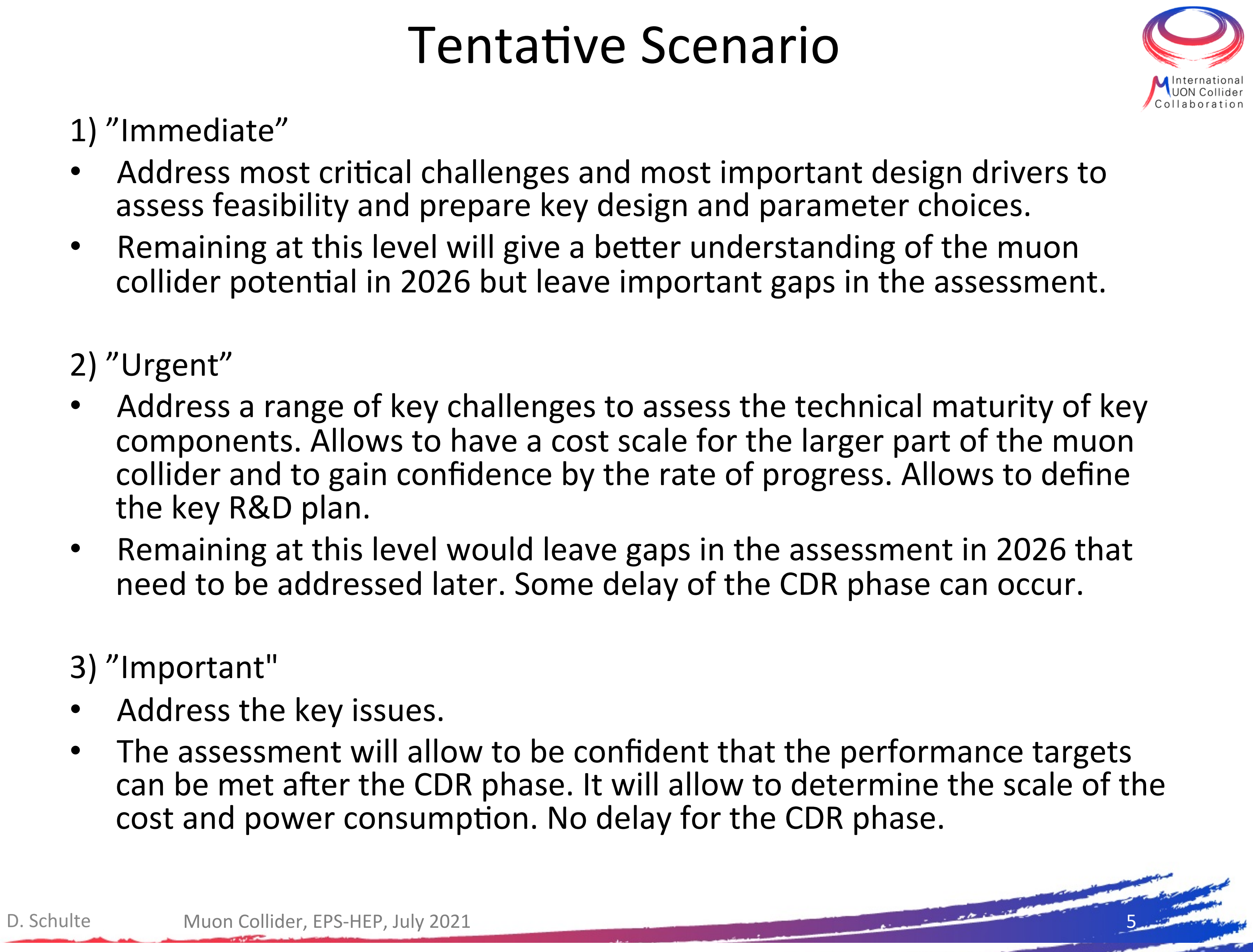
We have the aspirational programme

Need to make minimum programme

- ambitious goal is 2 x current investment (O(10 MCHF))

Ansatz

Only include the “immediate” resources in minimal programme



Tentative Scenario

1) ”Immediate”

- Address most critical challenges and most important design drivers to assess feasibility and prepare key design and parameter choices.
- Remaining at this level will give a better understanding of the muon collider potential in 2026 but leave important gaps in the assessment.

2) ”Urgent”

- Address a range of key challenges to assess the technical maturity of key components. Allows to have a cost scale for the larger part of the muon collider and to gain confidence by the rate of progress. Allows to define the key R&D plan.
- Remaining at this level would leave gaps in the assessment in 2026 that need to be addressed later. Some delay of the CDR phase can occur.

3) ”Important"

- Address the key issues.
- The assessment will allow to be confident that the performance targets can be met after the CDR phase. It will allow to determine the scale of the cost and power consumption. No delay for the CDR phase.

Consequences

Obviously it makes sense to start with the things that need to be started early

- important, otherwise they would not be on the list
- they drive other R&D efforts

However, only including the “immediate” resources in minimal programme has some consequences

- No full feasibility assessment
- No full cost scale, only cost driver considerations
- No costing on the test facility
- Delay of the CDR programme by several years

We hope to fill the gaps as we gain momentum and more partners join

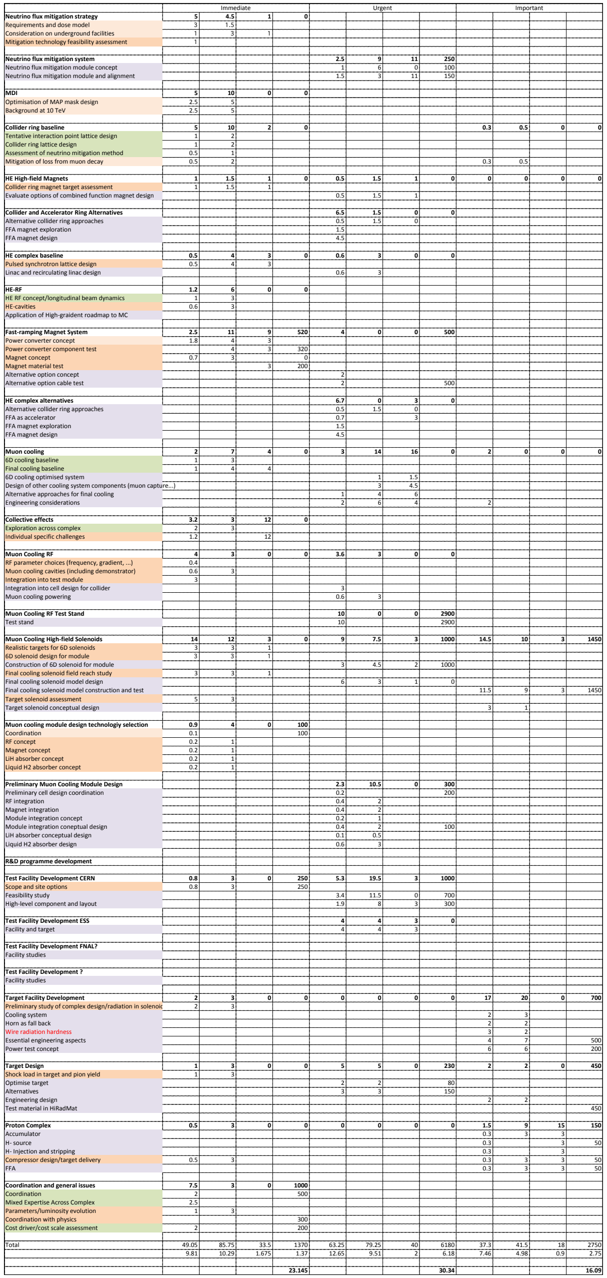
- In particular the US

Quick run through the resources

Cost Envelope

Total is
About 50 staff-years
about 86 postdoc-years
about 33 student-years
about 1.4 MCHF

Equivalent to CERN value of 23 MCHF



	Immediate				Urgent				Important			
Neutrino flux mitigation strategy	**5**	**4.5**	**1**	**0**								
Requirements and dose model	3	1.5										
Consideration on underground facilities	1	3	1									
Mitigation technology feasibility assessment	1											
Neutrino flux mitigation system					**2.5**	**9**	**11**	**250**				
Neutrino flux mitigation module concept					1	6	0	100				
Neutrino flux mitigation module and alignment					1.5	3	11	150				
MDI	**5**	**10**	**0**	**0**								
Optimisation of MAP mask design	2.5	5										
Background at 10 TeV	2.5	5										
Collider ring baseline	**5**	**10**	**2**	**0**					**0.3**	**0.5**	**0**	**0**
Tentative interaction point lattice design	1	2										
Collider ring lattice design	1	2										
Assessment of neutrino mitigation method	0.5	1										
Mitigation of loss from muon decay	0.5	2							0.3	0.5		
HE High-field Magnets	**1**	**1.5**	**1**	**0**	**0.5**	**1.5**	**1**	**0**	**0**	**0**	**0**	**0**
Collider ring magnet target assessment	1	1.5	1									
Evaluate options of combined function magnet design					0.5	1.5	1					
Collider and Accelerator Ring Alternatives					**6.5**	**1.5**	**0**	**0**				
Alternative collider ring approaches					0.5	1.5	0					
FFA magnet exploration					1.5							
FFA magnet design					4.5							
HE complex baseline	**0.5**	**4**	**3**	**0**	**0.6**	**3**	**0**	**0**				
Pulsed synchrotron lattice design	0.5	4	3									
Linac and recirculating linac design					0.6	3						
HE-RF	**1.2**	**6**	**0**	**0**								
HE RF concept/longitudinal beam dynamics	1	3										
HE-cavities	0.6	3										
Application of High-graident roadmap to MC												
Fast-ramping Magnet System	**2.5**	**11**	**9**	**520**	**4**	**0**	**0**	**500**				
Power converter concept	1.8	4	3									
Power converter component test		4	3	320								
Magnet concept	0.7	3		0								
Magnet material test			3	200								
Alternative option concept					2							
Alternative option cable test					2			500				
HE complex alternatives					**6.7**	**0**	**3**	**0**				
Alternative collider ring approaches					0.5	1.5	0					
FFA as accelerator					0.7		3					
FFA magnet exploration					1.5							
FFA magnet design					4.5							
Muon cooling	**2**	**7**	**4**	**0**	**3**	**14**	**16**	**0**	**2**	**0**	**0**	**0**
6D cooling baseline	1	3										
Final cooling baseline	1	4	4									
6D cooling optimised system						1	1.5					
Design of other cooling system components (muon capture...)						3	4.5					
Alternative approaches for final cooling					1	4	6					
Engineering considerations					2	6	4		2			
Collective effects	**3.2**	**3**	**12**	**0**								
Exploration across complex	2	3										
Individual specific challenges	1.2		12									
Muon Cooling RF	**4**	**3**	**0**	**0**	**3.6**	**3**	**0**	**0**				
RF parameter choices (frequency, gradient, ...)	0.4											
Muon cooling cavities (including demonstrator)	0.6	3										
Integration into test module	3											
Integration into cell design for collider					3							
Muon cooling powering					0.6	3						
Muon Cooling RF Test Stand					**10**	**0**	**0**	**2900**				
Test stand					10			2900				
Muon Cooling High-field Solenoids	**14**	**12**	**3**	**0**	**9**	**7.5**	**3**	**1000**	**14.5**	**10**	**3**	**1450**
Realistic targets for 6D solenoids	3	3	1									
6D solenoid design for module	3	3	1									
Construction of 6D solenoid for module					3	4.5	2	1000				
Final cooling solenoid field reach study	3	3	1									
Final cooling solenoid model design					6	3	1	0				
Final cooling solenoid model construction and test									11.5	9	3	1450
Target solenoid assessment	5	3										
Target solenoid conceptual design									3	1		
Muon cooling module design technologiy selection	**0.9**	**4**	**0**	**100**								
Coordination	0.1			100								
RF concept	0.2	1										
Magnet concept	0.2	1										
LiH absorber concept	0.2	1										
Liquid H2 absorber concept	0.2	1										
Preliminary Muon Cooling Module Design					**2.3**	**10.5**	**0**	**300**				
Preliminary cell design coordination					0.2			200				
RF integration					0.4	2						
Magnet integration					0.4	2						
Module integration concept					0.2	1						
Module integration coneptual design					0.4	2		100				
LiH absorber conceptual design					0.1	0.5						
Liquid H2 absorber design					0.6	3						
R&D programme development												
Test Facility Development CERN	**0.8**	**3**	**0**	**250**	**5.3**	**19.5**	**3**	**1000**				
Scope and site options	0.8	3		250								
Feasibility study					3.4	11.5	0	700				
High-level component and layout					1.9	8	3	300				
Test Facility Development ESS					**4**	**4**	**3**	**0**				
Facility and target					4	4	3					
Test Facility Development FNAL?												
Facility studies												
Test Facility Development ?												
Facility studies												
Target Facility Development	**2**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**17**	**20**	**0**	**700**
Preliminary study of complex design/radiation in solenoic	2	3										
Cooling system									2	3		
Horn as fall back									2	2		
Wire radiation hardness									3	2		
Essential engineering aspects									4	7		500
Power test concept									6	6		200
Target Design	**1**	**3**	**0**	**0**	**5**	**5**	**0**	**230**	**2**	**2**	**0**	**450**
Shock load in target and pion yield	1	3										
Optimise target					2	2		80				
Alternatives					3	3		150				
Engineering design									2	2		
Test material in HiRadMat												450
Proton Complex	**0.5**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**1.5**	**9**	**15**	**150**
Accumulator									0.3	3	3	
H- source									0.3		3	50
H- Injection and stripping									0.3		3	
Compressor design/target delivery	0.5	3							0.3	3	3	50
FFA									0.3	3	3	50
Coordination and general issues	**7.5**	**3**	**0**	**1000**								
Coordination	2			500								
Mixed Expertise Across Complex	2.5											
Parameters/luminosity evolution	1	3										
Coordination with physics				300								
Cost driver/cost scale assessment	2			200								
Total	49.05	85.75	33.5	1370	63.25	79.25	40	6180	37.3	41.5	18	2750
	9.81	10.29	1.675	1.37	12.65	9.51	2	6.18	7.46	4.98	0.9	2.75
				23.145				**30.34**				**16.09**

Scope Discussion

Neutrino Radiation

Objectives
Basic: Assess whether the neutrino flux can in principle be mitigated sufficiently to allow implementation of the collider in the Geneva area or elsewhere.
Develop a concept of the neutrino flux mitigation technology and assess its maturity.

High-level Deliverables
1) Assessment of the dose and a plan to demonstrate compliance
1) Verification that the proposed mitigation method does not compromise beam operation
2) A basic concept for the mechanical system including the cryogenics.
2) A basic concept of accurate large-stroke, high-resolution mover and alignment system

Resources	1	2	3		1	2	3
Staff	1.45, 2.05	2.5		Student	1	11	
Postdoc	0.25, 2.25	9		Material		150	

Interested partners
CERN, resources partly in place, FNAL with support by DOE and Snowmass/P5

Neutrino Flux Mitigation Strategy

Objectives

Assess whether the neutrino flux can in principle be mitigated sufficiently to allow implementation of the collider in the Geneva area or elsewhere.

Develop a concept of the neutrino flux mitigation technology and assess its maturity.

High-level Deliverables

1) Assessment of the dose and a plan to demonstrate compliance

1) Verification that the proposed mitigation method does not compromise beam operation (in collider ring)

1) Assessment of the challenges of the mechanical system and strategy to address them (new)

Resources	1	2	3		1	2	3
Staff	1.45, 2.05+1			Student	1		
Postdoc	0.25, 2.25			Material			

Interested partners

CERN, resources partly in place, FNAL with support by DOE and Snowmass/P5

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

Neutrino Flux Mitigation Technology

Objectives							
Assess whether the neutrino flux can in principle be mitigated sufficiently to allow implementation of the collider in the Geneva area or elsewhere.							
Develop a concept of the neutrino flux mitigation technology and assess its maturity.							
High-level Deliverables							
2) A basic concept for the mechanical system including the cryogenics.							
2) A basic concept of accurate large-stroke, high-resolution mover and alignment system							
Resources	1	2	3		1	2	3
Staff		2.5		Student		11	
Postdoc		9		Material		150	
Interested partners							
CERN, resources partly in place, FNAL with support by DOE and Snowmass/P5							

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

MDI

Objectives

Develop a concept of the neutrino flux mitigation technology and assess its maturity.

High-level Deliverables

1) Optimised shielding concept at 3 TeV.

1) Evaluation of radiation damage in detector

1) Concept of 10 TeV interaction region with shielding

Evaluation of radiation damage in detector

Resources	1	2	3		1	2	3
Staff	5			Student			
Postdoc	3.5+6.5			Material			

Interested partners

INFN, resources partly in place, CERN, resources partly in place

Collider Ring

Objectives
Basic: Development of a credible design concept for a Muon Collider ring with cost estimate and investigation of feasibility of a high energy muon collider. Identification of the main difficulties and measures for their mitigation and potential showstoppers
Complete beamline description with lattices
Identification of outstanding challenges with possible mitigation approaches.

High-level Deliverables
Priority 1: Immediate) Parameter table of muon collider
Priority 1: Immediate) Design of a muon collider lattice comprising interaction regions, straight sections for all necessary equipment and arcs. Critical aspects are the neutrino radiation issue and chromatic effects.
Priority 1: Immediate) Operational concept of muon collider including squeezing methodology
Priority 2: Urgent) Alternative optics of muon collider (UKRI-STFC)

Resources	1	2	3		1	2	3
Staff	2.5	0.5		PhD	0		
Postdoc	5.0	1.5		Material			

Interested partners
CERN, resources partly in place, UKRI-STFC for alternative optics, BNL for collider ring

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

Collider Ring

Objectives

Basic: Development of a credible design concept for a Muon Collider ring with cost estimate and investigation of feasibility of a high energy muon collider. Identification of the main difficulties and measures for their mitigation and potential showstoppers

Complete beamline description with lattices

Identification of outstanding challenges with possible mitigation approaches.

High-level Deliverables

1) Design of relevant muon collider lattice including interaction regions and arcs. Critical aspects are the neutrino radiation issue and chromatic effects.

1) Assessment of impact of neutrino flux mitigation method on beam operation

2) Alternative optics of muon collider (UKRI-STFC)

Resources	1	2	3		1	2	3
Staff	2.5	0.5		PhD	0		
Postdoc	5.0	1.5		Material			

Interested partners

CERN, resources partly in place, UKRI-STFC for alternative optics, BNL for collider ring

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

Radiation in Collider Ring

Objectives

Basic: Study the radiation load to magnets and other accelerator systems in the collider ring arising from muon decay and possible other kinds of beam losses

Develop a conceptual shielding design which allows for a safe operation with acceptable heat deposition and radiation damage in magnets and assess the need for protection systems, including beam extraction

High-level Deliverables

1) Quantify the radiation load to collider ring magnets and develop a shielding design for different collider options (√s=3 TeV and √s=10 TeV)

3) Shower studies to assess the need of protection system for accidental beam losses, including extraction system for different collider options

Resources	1	2	3		1	2	3
Staff	0.7		0.3	Student			
Postdoc	2		0.5				

Interested partners

CERN STI

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

HE-Acceleration

Objectives
Basic: Develop a credible design concept High-energy muon acceleration complex with cost estimate, 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
Priority 1) Overall design parameters
Priority 1) Rapid Cycling System (RCS) design
Priority 2) Linac and Recirculating Linac (RLA) design
Priority 2) 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

HE-Acceleration

Objectives
Basic: Develop a credible design concept High-energy muon acceleration complex with cost estimate, 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
1) Rapid Cycling System (RCS) concept
2) Linac and Recirculating Linac (RLA) concept
2) 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

6D cooling

Objectives

Basic: Develop a realistic 6D cooling scheme.

Develop the existing component designs to make an integrated 6D cooling scheme. This is essential to deliver a realistic performance estimate.

High-level Deliverables

1) Develop a baseline 6D cooling system, taking as input MAP and euronu concepts and assuming reasonable parameters for other parts of the muon production system (e.g. capture, charge separation, bunch merge, etc).

2) Optimise the 6D cooling system, taking into account likely available RF gradients and magnetic fields.

2) Develop other elements of the capture and cooling system. In particular, re-optimise the capture chicane and muon front end; design a charge separation system; optimise the bunch merge system

3) 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.

Resources	1	2	3		1	2	3
Staff	0.5	0	2	Student		6	4
Postdoc	3	4	6	Material	(compute)	0	0

Interested partners

RAL, resources partly in place, FNAL, BNL

Final cooling

Objectives

Basic: Develop an optimised final cooling scheme.

The final cooling scheme is a performance driver for the entire facility, so it has been picked out as especially deserving effort.

High-level Deliverables

1) Optimised final cooling scheme, taking into account current and future availability of high-field solenoids.

2) Performance estimates for alternate final cooling schemes to reach extremely low emittances that can yield vastly improved facility performance. Schemes such as PIC, frictional cooling and emittance exchange should be considered.

3) Assessment of engineering integration issues – in particular the absorber engineering where there is large instantaneous heat load and challenges in integrating Hydrogen cryogenics with magnet systems.

Resources	1	2	3		1	2	3
Staff	0.5	0	2	Student		6	
Postdoc	4	4	0	Material	(compute)	0	

Interested partners

RAL, CERN, FNAL, BNL, Jlab, maybe PSI?

Target facility

Objectives

Basic: Assess the target facility and perform targeted engineering studies to deal with significant risks.

The existing magnet pion capture scheme has a number of outstanding issues which will be assessed, in particular radiation and heat load on the capture solenoid. The target complex itself has not been developed; for example, a viable solution for cooling of the target shielding and design of an appropriate proton beam dump is required.

High-level Deliverables

1) Estimation of the heat load on the target and superconducting coils. A shielding scheme to ensure that the SC magnet has a reasonable cryogenic system and radiation damage is not prohibitive.

1) Preliminary concept of target complex

2) Study the cooling system for the target shielding and ensure that heat can be removed.

2) Study the potential performance of a target horn as a fall back if any risks on the solenoid capture scheme are realised.

2) Perform experiments to validate the effects of radiation on a SC wire. (Link to HFM programme)

3) Development of essential engineering aspects of the target facility, including remote handling, target complex design and preliminary prototyping

3) Development of a concept for a full power test of such a target on the CERN site.

Resources	1	2	3		1	2	3
Staff	2	7	10	Student		0	
Postdoc	3	7	13	Material	15	0	700

Interested partners

Target

Objectives

Basic: Develop the target itself.

MAP considered Hg as a target material which is not viable in Europe. A more conventional graphite target will be adopted as a baseline, with appropriate estimates for heat load and pion yield; alternate solutions should also be studied.

High-level Deliverables

1) Estimate shock load and pion yield of a graphite target. Assess potential mitigation schemes.

2) Optimise the graphite target for improved pion yield and shock load. Perform preliminary engineering assessments.

2) Consider appropriate non-solid target designs e.g. powder jet, eutectic, packed bed.

3) Study experimentally the impact of high shocks on target designs at HiRadMAt or equivalent facility

3) Further develop the engineering design for the graphite target.

Resources	1	2	3		1	2	3
Staff	1	5	2	Student		0	
Postdoc	3	5	2	Material	0	230	450

Interested partners

RAL, CERN, Warwick

Proton Complex

<table>
<tr><th colspan="8">Objectives</th></tr>
<tr><td colspan="8"></td></tr>
<tr><td colspan="8"></td></tr>
<tr><th colspan="8">High-level Deliverables</th></tr>
<tr><td colspan="8">1) Compressor and buncher concept to assess proton beam limit and provide beam for target</td></tr>
<tr><td colspan="8">2) Linac and accumulator concept</td></tr>
<tr><td colspan="8">2) FFA alternative</td></tr>
<tr><th>Resources</th><th>1</th><th>2</th><th>3</th><th></th><th>1</th><th>2</th><th>3</th></tr>
<tr><td>Staff</td><td>0.3</td><td>1.2</td><td>10</td><td>Student</td><td>3</td><td>12</td><td></td></tr>
<tr><td>Postdoc</td><td>3</td><td>6</td><td>13</td><td>Material</td><td>50</td><td>100</td><td></td></tr>
<tr><th colspan="8">Interested partners</th></tr>
<tr><td colspan="8">RAL, CERN, Warwick, Fermilab</td></tr>
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Test Facility at CERN

Objectives
Basic: Choose the best siting for a muon cooling test facility at CERN, and provide a conceptual design.
Optimise some of the designs developed in other WPs for the test facility implementation

High-level Deliverables
1) Selection of the site
2) Provide civil engineering feasibility study of the site
3) High level selection of the muon production and cooling components and layout

Resources	1	2	3		1	2	3
Staff	0.8	3.4	1.9	Student			3
Postdoc	3	11.5	8	Material	250	700	300

Interested partners
CERN, STFC, CEA. (US?)

Radiation Protection (Test Facility)

Objectives
Basic: Optimize the design of the test facility as well as key areas of the complex for the exposure of persons to radiation and the radiological impact on the environment

High-level Deliverables
1) RP assessment of the test facility (2022-2025)
3) First RP assessment of the key areas of the complex*

Resources	1	2	3		1	2	3
Staff	1		(0.4)*	Student			
Postdoc	4			Material			

Interested partners
CERN

ESS-based Muon Collider Proton Complex Test Facility

Objectives

Basic: Demonstrate the feasibility of a Muon Collider Proton Complex Test Facility that is based on the use of the power-upgraded ESS linac, of an adapted ESSnuSB accumulator ring and of a new compressor/buncher ring for achieving 2 ns pulses of 10^{14}-10^{15} protons at 14 Hz as well as the feasibility of a granular Titanium target with forced He gas cooling for use with such a beam.

High-level Deliverables

Assessment of the possibility to use of the ESS linac as proton driver for a Muon Collider Proton Complex Test Facility

Design of the Proton Complex Test Facility and evaluation of its operation using simulations

Evaluation of the effect of the heat shocks from 2 ns 10^{14}-10^{15} protons bunches at 14 Hz on the granular Titanium target

Resources	1	2	3		1	2	3
Staff		4		Student		3	
Postdoc		4		Material			

Interested partners

The European ESSnuSB Collaboration and the ESS Laboratory

Muon Cooling Module Concept

Objectives
Basic: Choose the technology to be used for the different components of a cooling cell (RF, Magnet, Absorber).
Optimise some of the designs developed in other WPs for the test facility implementation
Provide a conceptual engineering design of the cell
High-level Deliverables
1) Selection of the technologies to be used
2) Provide a preliminary design of the cooling cell
3) Provide an engineering design of the module

Resources	1	2	3		1	2	3
Staff	0.9	2.7		Student			
Postdoc	4	12.5		Material	100	300	

Interested partners
CERN, STFC, CEA. (US?)

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

High-field Magnets

Objectives

Basic: Promote R&D tasks required to developed magnet designs to allow implementation of the collider in the Geneva area or elsewhere.

Propose a magnet design for each area and assess its maturity

High-level Deliverables

1) Define a high field/large bore solenoid for the target area
2) Develop high field HTS magnets for cooling stage; develop and test a complete cooling module, with a superconducting solenoid and a NC RF
3) Define a conceptual magnet design for the accelerator ring
4) Define a conceptual magnet design for the collider ring

Resources	1	2	3		1	2	3
Staff				Student			
Postdoc				Material			

Interested partners

CEA, RAL, ???

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

Collider Ring Magnets

Objectives

Basic: Promote R&D tasks required to developed magnet designs to allow implementation of the collider in the Geneva area or elsewhere.

Propose a magnet design for each area and assess its maturity

High-level Deliverables

1) Develop realistic performance specifications for the collider ring magnets
2) Chose the technology for the combined function magnet

Resources	1	2	3		1	2	3
Staff	1	0.5		Student	1	1	
Postdoc	1.5	1.5		Material			

Interested partners

CERN-KEK collaboration

FFA Alternative Magnets

International
MUON Collider
Collaboration

Objectives

Basic: Promote R&D tasks required to developed magnet designs to allow implementation of the collider in the Geneva area or elsewhere.

Propose a magnet design for each area and assess its maturity

High-level Deliverables

2) Magnet system concept for the pulsed synchrotron
3) Magnets for FFA

Resources	1	2	3		1	2	3
Staff		1.5	4.5	Student			
Postdoc				Material			

Interested partners

RAL

High-field Solenoids

Objectives

Basic: Promote R&D tasks required to developed magnet designs to allow implementation of the collider in the Geneva area or elsewhere.

Propose a magnet design for each area and assess its maturity

High-level Deliverables

1) Based on HFM programme, develop realistic target performance specifications for the high field/large bore solenoid for the target area
2) Conceptual design

1) Based on HFM, realistic target performance specification for final cooling solenoid
2) Design of model
3) Construction of model

1) Based on HFM, performance specifications for &D solenoids
1) Design of solenoid for test module
2) Construction of 6D cooling solenoid model

Resources	1	2	3		1	2	3
Staff	14	9	14.5	Student	3	3	3
Postdoc	12	7.5	10	Material			2450

Interested partners

CEA, Karlsruhe

RF

Objectives

High-level Deliverables

1) Baseline design of the RF system for acceleration to high energy (SRF)
2) Application of high gradient SRF technology for muon accelerators (SRF)
3) Baseline design of the RF system for Muon cooling complex (NRF).
4) Conceptual design of the RF system for Muon Cooling Demonstrator (NRF).
5) RF test stand and test cavities for R&D on high gradient NRF in strong magnetic field (NRF).
6) Baseline design of RF power sources for muon collider RF systems

Resources	1	2	3		1	2	3
Staff	0.6	18.2		Student			
Postdoc	3	9		Material	2900(9500)		

Interested partners

1) CERN(resources in place), Uni of Rostock
2) CERN(?)
3) CEA, LBNL
4) CEA, LBNL
5) CEA, Uni of Strathclyde
6) Uni of Lancaster

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

High-energy RF

<table>
<tr><th colspan="8">Objectives</th></tr>
<tr><th colspan="8">High-level Deliverables</th></tr>
<tr><td colspan="8">1) Baseline design of the RF system for acceleration to high energy taking into account RF Accelerator R&D Roadmap (SRF) (includes the minimum exploration of RF roadmap)</td></tr>
<tr><td colspan="8">2) Application of high-gradient SRF technology for muon accelerators (SRF)</td></tr>
<tr><th>Resources</th><th>1</th><th>2</th><th>3</th><th></th><th>1</th><th>2</th><th>3</th></tr>
<tr><td>Staff</td><td>0.6 + 0.8</td><td>17.4</td><td></td><td>Student</td><td></td><td></td><td></td></tr>
<tr><td>Postdoc</td><td>3 + 3</td><td>6</td><td></td><td>Material</td><td>2900(9500)</td><td></td><td></td></tr>
<tr><th colspan="8">Interested partners</th></tr>
<tr><td colspan="8">CERN(resources in place), Uni of Rostock, CERN?</td></tr>
</table>

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

Muon Cooling RF

Objectives

High-level Deliverables

1) Baseline design of the RF system for Muon cooling complex with one example (NRF).

1-2) Conceptual design of the RF system for Muon Cooling Demonstrator (NRF).

2) Baseline design of RF power sources for muon collider RF systems

Resources	1	2	3		1	2	3
Staff	1-4	3.6		Student			
Postdoc	3	3		Material	2900(9500)		

Interested partners

1) CEA, LBNL
2) CEA, LBNL
3) Uni of Lancaster

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

Muon Cooling RF Test Stand

Objectives

High-level Deliverables

1) Baseline design of the RF system for Muon cooling complex with one example (NRF).

4) Conceptual design of the RF system for Muon Cooling Demonstrator (NRF).

2) RF test stand and test cavities for R&D on high gradient NRF in strong magnetic field (NRF).

2) Baseline design of RF power sources for muon collider RF systems

Resources	1	2	3		1	2	3
Staff		10		Student			
Postdoc				Material		2900(9500)	

Interested partners

1) CEA, Uni of Strathclyde

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

Fast-ramping Magnet System

Objectives

1) Develop a concept of the power converter

1) Test capacitors for switched polarity power converters

1) Develop magnet concept

1) Test and characterise magnet material

2) Concept of superconducting fast-ramping magnet

2) Cable tests for fast-ramping superconducting magnets

High-level Deliverables

1) A concept of the power converter with supporting measurements

Resources	1	2	3		1	2	3
Staff	2.5	4		PhD	9		
Postdoc	11			Material	520	500	

Interested partners

CERN

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

Collective Effects

Objectives							
High-level Deliverables							
1) Assess collective effects across the facility (HE-complex, muon cooling complex, proton complex and beam-matter interaction in muon cooling complex) and address the most critical ones							
Resources	1	2	3		1	2	3
Staff	2+1.2			PhD	12		
Postdoc	3			Material			
Interested partners							
CERN, EPFL, TUD, STFC, BNL, SLAC, LBNL, INFN, LAL							

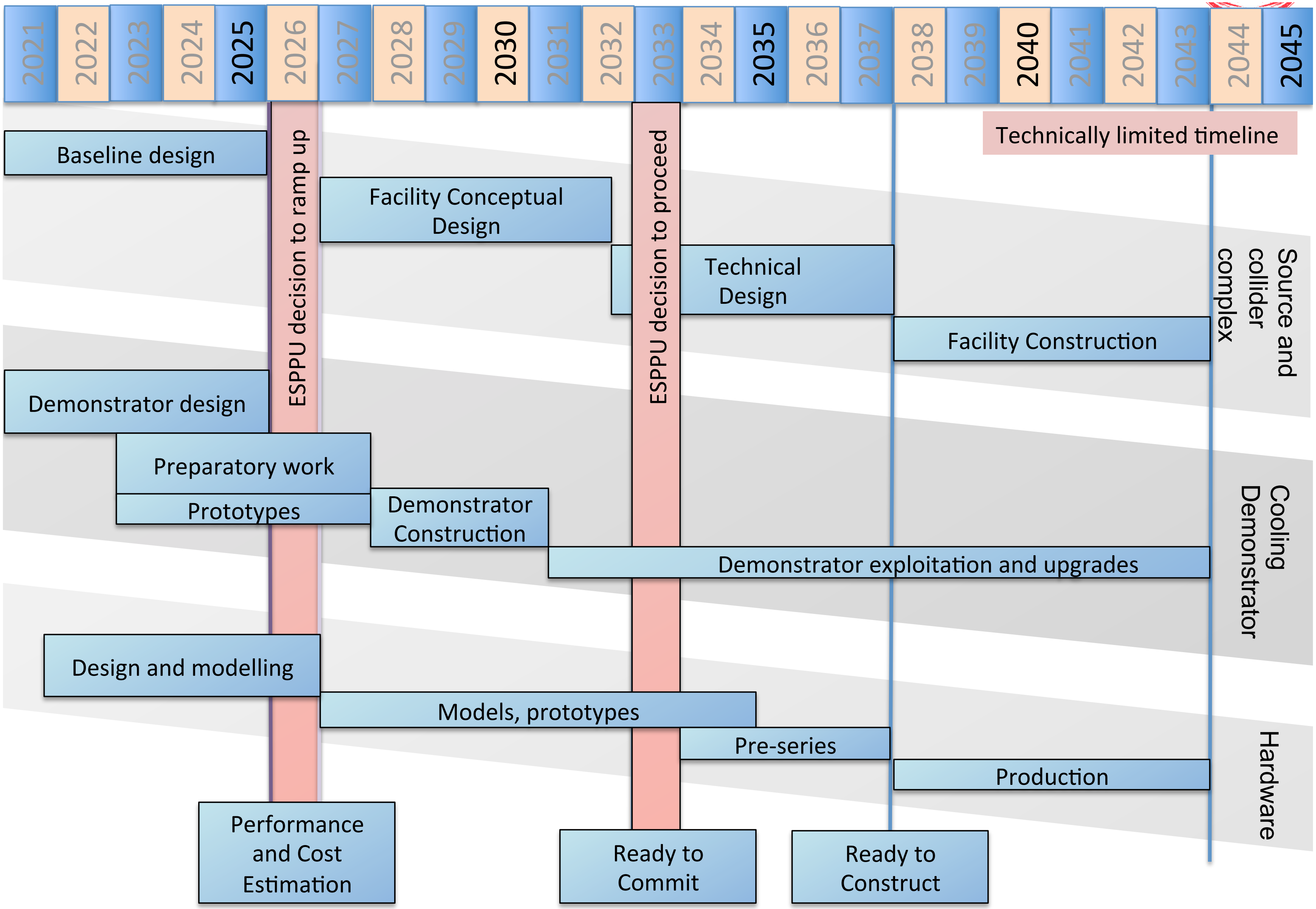
Resources are given in total number of FTE-years for the whole duration and in kEuro for material

Timeline Discussion

Timeline Discussions

Tentative Target for Aggressive Timeline

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



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

ESPPU decision to ramp up

ESPPU decision to proceed

Source and collider complex

- Baseline design
- Facility Conceptual Design
- Technical Design
- Facility Construction

Cooling Demonstrator

- Demonstrator design
- Preparatory work
- Prototypes
- Demonstrator Construction
- Demonstrator exploitation and upgrades

Hardware

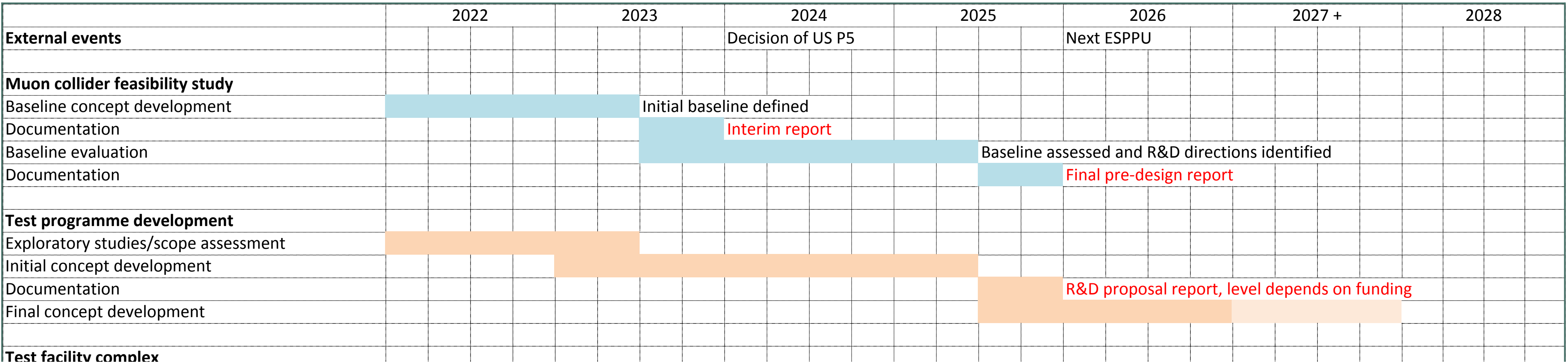
- Design and modelling
- Models, prototypes
- Pre-series
- Production

Performance and Cost Estimation

Ready to Commit

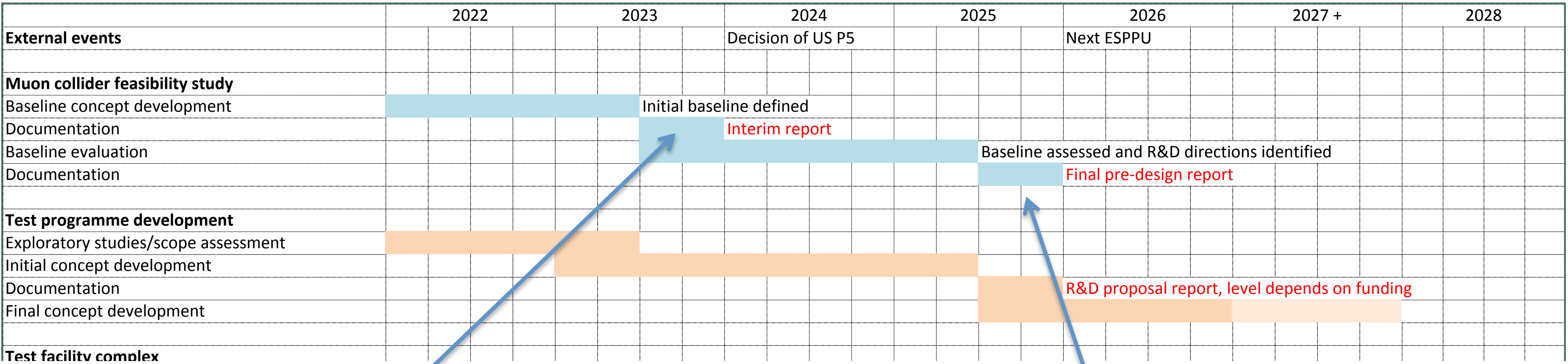
Ready to Construct

Fundamental Timeline



	2022				2023				2024				2025				2026				2027 +				2028			
External events									Decision of US P5								Next ESPPU											
Muon collider feasibility study																												
Baseline concept development	🟦	🟦	🟦	🟦	🟦	🟦	Initial baseline defined																					
Documentation							🟦	🟦	Interim report																			
Baseline evaluation							🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	Baseline assessed and R&D directions identified													
Documentation															🟦	🟦	Final pre-design report											
Test programme development																												
Exploratory studies/scope assessment	🟧	🟧	🟧	🟧	🟧	🟧																						
Initial concept development					🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧														
Documentation															🟧	🟧	R&D proposal report, level depends on funding											
Final concept development															🟧	🟧	🟧	🟧	🟧	🟧	▨	▨	▨	▨				
Test facility complex																												

Fundamental Timeline



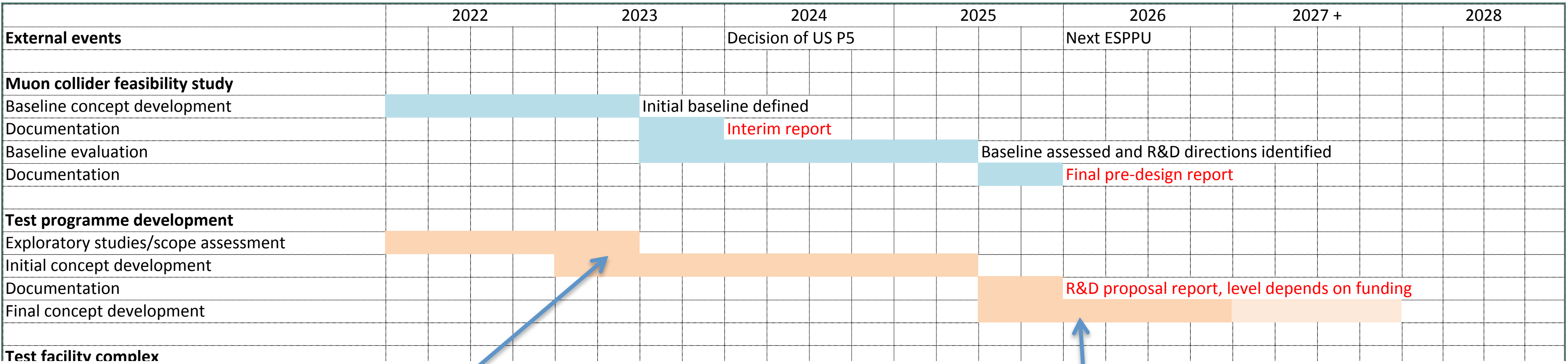
	2022	2023	2024	2025	2026	2027 +	2028
External events			Decision of US P5		Next ESPPU		
Muon collider feasibility study							
Baseline concept development	▨	▨ Initial baseline defined					
Documentation		▨	Interim report				
Baseline evaluation		▨	▨	▨ Baseline assessed and R&D directions identified			
Documentation				▨	Final pre-design report		
Test programme development							
Exploratory studies/scope assessment	▨	▨					
Initial concept development		▨	▨	▨			
Documentation				▨	R&D proposal report, level depends on funding		
Final concept development				▨	▨	▨	
Test facility complex							

Intermediate report to show that we are on a good track

Final feasibility report to show that muon collider is credible

The minimum scenario should cover most of this, but it is only partially funded

Fundamental Timeline



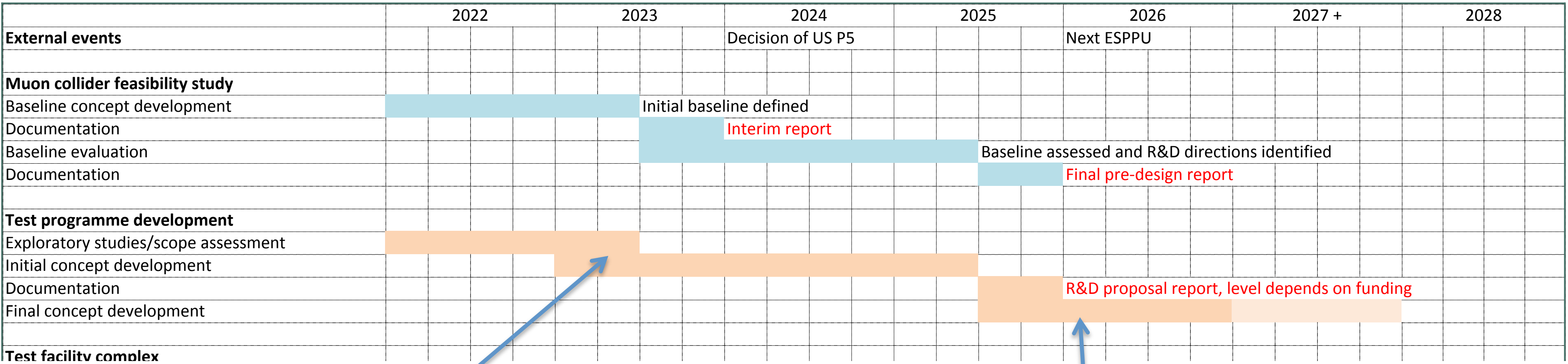
	2022	2023	2024	2025	2026	2027 +	2028
External events			Decision of US P5		Next ESPPU		
Muon collider feasibility study							
Baseline concept development		Initial baseline defined					
Documentation			Interim report				
Baseline evaluation				Baseline assessed and R&D directions identified			
Documentation					Final pre-design report		
Test programme development							
Exploratory studies/scope assessment							
Initial concept development							
Documentation					R&D proposal report, level depends on funding		
Final concept development							
Test facility complex							

Test programme development can only seriously start after some time

Need to deliver description of R&D programme but can expect to continue with more detailed work

Our main margin is the scope of this document

Fundamental Timeline



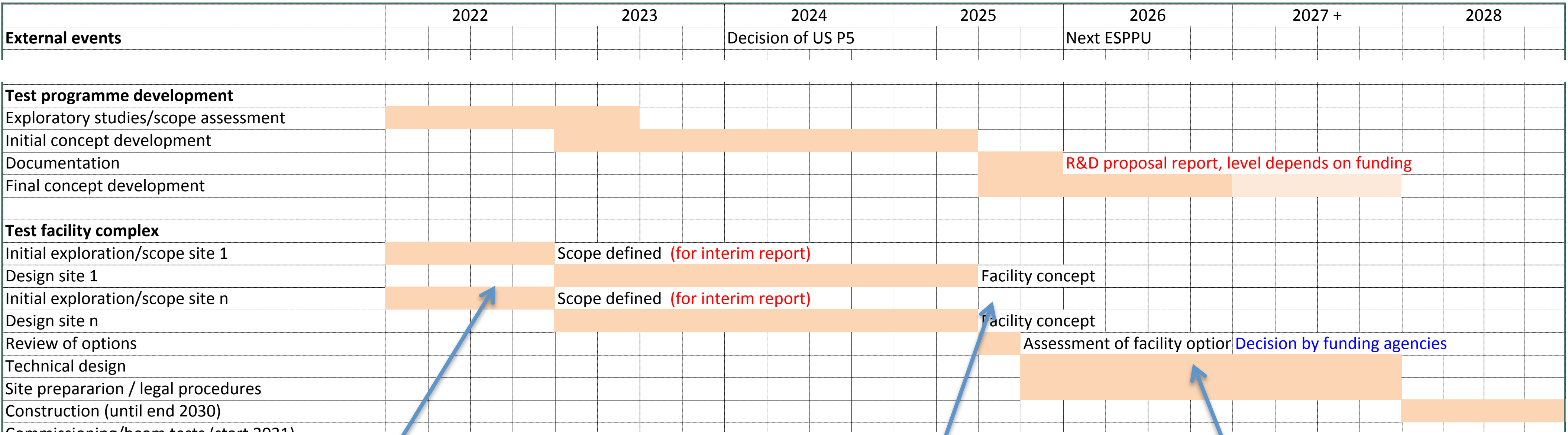
	2022	2023	2024	2025	2026	2027 +	2028
External events			Decision of US P5		Next ESPPU		
Muon collider feasibility study							
Baseline concept development	🟦	🟦 Initial baseline defined					
Documentation		🟦	Interim report				
Baseline evaluation		🟦	🟦	🟦 Baseline assessed and R&D directions identified			
Documentation				🟦	Final pre-design report		
Test programme development							
Exploratory studies/scope assessment	🟧	🟧					
Initial concept development		🟧	🟧	🟧			
Documentation				🟧	R&D proposal report, level depends on funding		
Final concept development				🟧	🟧	░	
Test facility complex							

Test programme development can only seriously start after some time

Need to deliver description of R&D programme but can expect to continue with more detailed work

Our main margin is the scope of this document

Test Facility Timeline



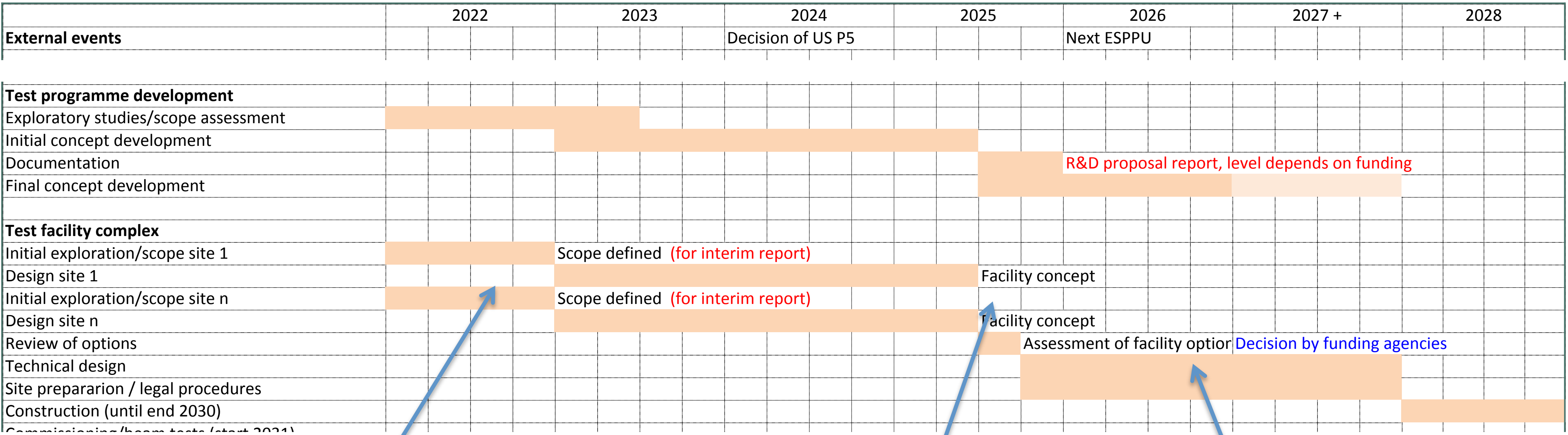
	2022				2023				2024				2025				2026				2027 +				2028			
External events									Decision of US P5								Next ESPPU											
Test programme development																												
Exploratory studies/scope assessment	▨	▨	▨	▨	▨	▨																						
Initial concept development					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨														
Documentation															▨	▨	R&D proposal report, level depends on funding											
Final concept development															▨	▨	▨	▨	▨	▨	░	░	░	░				
Test facility complex																												
Initial exploration/scope site 1	▨	▨	▨	▨	Scope defined (for interim report)																							
Design site 1					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Facility concept													
Initial exploration/scope site n	▨	▨	▨	▨	Scope defined (for interim report)																							
Design site n					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Facility concept													
Review of options															▨	Assessment of facility optior					Decision by funding agencies							
Technical design																▨	▨	▨	▨	▨	▨	▨	▨	▨				
Site prepararion / legal procedures																▨	▨	▨	▨	▨	▨	▨	▨	▨				
Construction (until end 2030)																									▨	▨	▨	▨
Commissioning/beam tests (start 2031)																												

Develop one or more test facilities

Proposal of which one(s) to select

Continue during decision process to avoid stall

Test Facility Timeline



	2022				2023				2024				2025				2026				2027 +				2028			
External events									Decision of US P5								Next ESPPU											
Test programme development																												
Exploratory studies/scope assessment	▨	▨	▨	▨	▨	▨																						
Initial concept development					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨														
Documentation															▨	▨	R&D proposal report, level depends on funding											
Final concept development															▨	▨	▨	▨	▨	▨	░	░	░	░				
Test facility complex																												
Initial exploration/scope site 1	▨	▨	▨	▨	Scope defined (for interim report)																							
Design site 1					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Facility concept													
Initial exploration/scope site n	▨	▨	▨	▨	Scope defined (for interim report)																							
Design site n					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Facility concept													
Review of options															▨	Assessment of facility optior					Decision by funding agencies							
Technical design																▨	▨	▨	▨	▨	▨	▨	▨	▨				
Site prepararion / legal procedures																▨	▨	▨	▨	▨	▨	▨	▨	▨				
Construction (until end 2030)																									▨	▨	▨	▨
Commissioning/beam tests (start 2031)																												

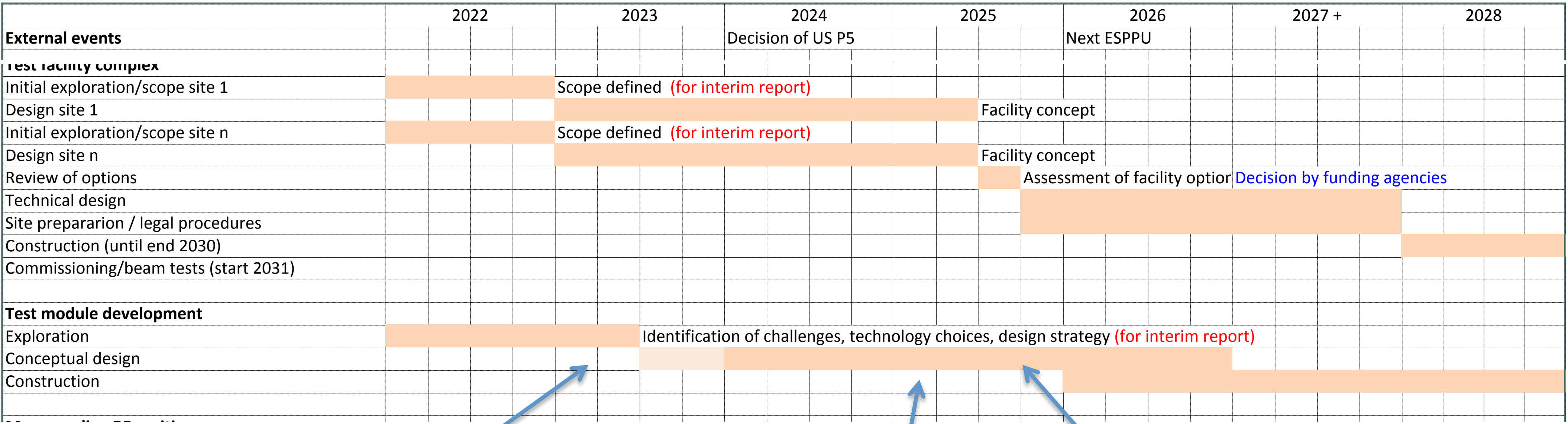
Develop one or more test facilities

Proposal of which one(s) to select

This is put in danger by limited funding
because TF design is not part of the minimal programme

Continue during decision process to avoid stall

Test Facility Timeline



	2022				2023				2024				2025				2026				2027 +				2028			
External events									Decision of US P5								Next ESPPU											
Test facility complex																												
Initial exploration/scope site 1	▨	▨	▨	▨	Scope defined (for interim report)																							
Design site 1					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Facility concept													
Initial exploration/scope site n	▨	▨	▨	▨	Scope defined (for interim report)																							
Design site n					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Facility concept													
Review of options															▨	Assessment of facility optior					Decision by funding agencies							
Technical design																▨	▨	▨	▨	▨	▨	▨	▨	▨				
Site prepararion / legal procedures																▨	▨	▨	▨	▨	▨	▨	▨	▨				
Construction (until end 2030)																									▨	▨	▨	▨
Commissioning/beam tests (start 2031)																												
Test module development																												
Exploration	▨	▨	▨	▨	▨	▨	Identification of challenges, technology choices, design strategy (for interim report)																					
Conceptual design							░	░	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨								
Construction																	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

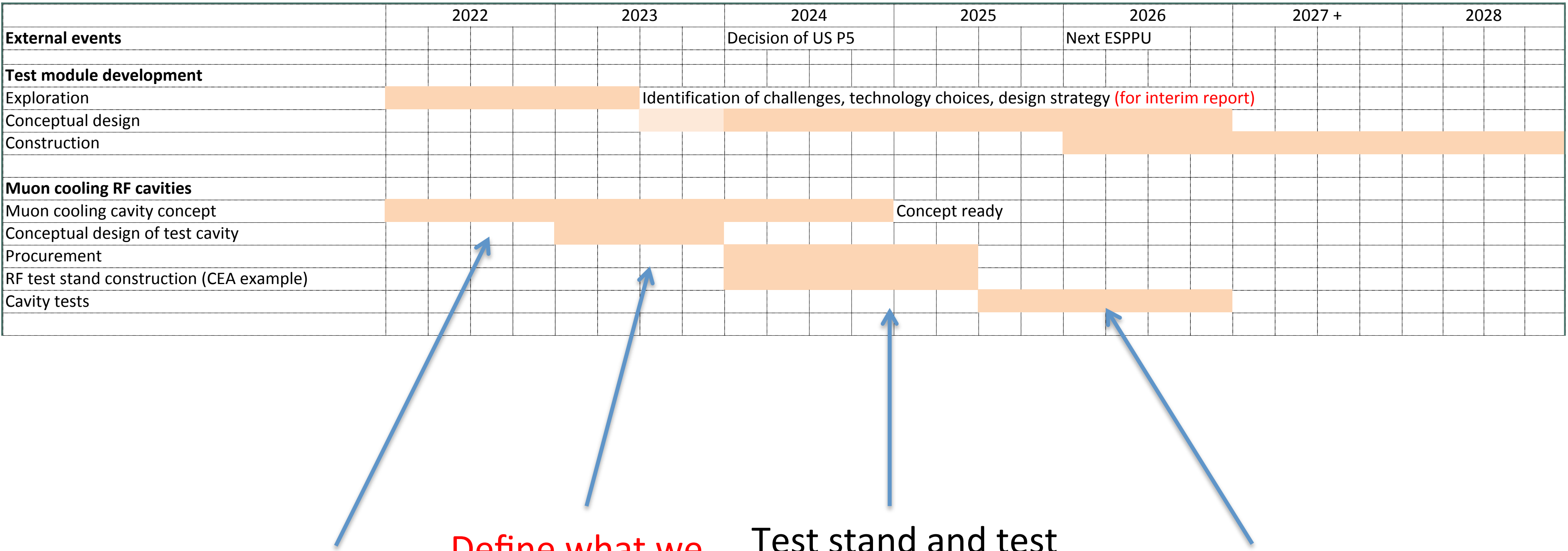
Cannot do that much initially

Design phase will extend over ESPPU

Need to provide input for R&D proposal during work

If we have the funding

Timeline Discussions: NC RF Cavity



	2022		2023		2024		2025		2026		2027 +		2028	
External events					Decision of US P5				Next ESPPU					
Test module development														
Exploration	■	■	■	Identification of challenges, technology choices, design strategy (for interim report)										
Conceptual design				░	■	■	■	■	■	■				
Construction									■	■	■	■	■	■
Muon cooling RF cavities														
Muon cooling cavity concept	■	■	■	■	■	■	Concept ready							
Conceptual design of test cavity			■	■										
Procurement					■	■	■							
RF test stand construction (CEA example)					■	■	■							
Cavity tests								■	■	■				

Realistically later start

Define what we want to test

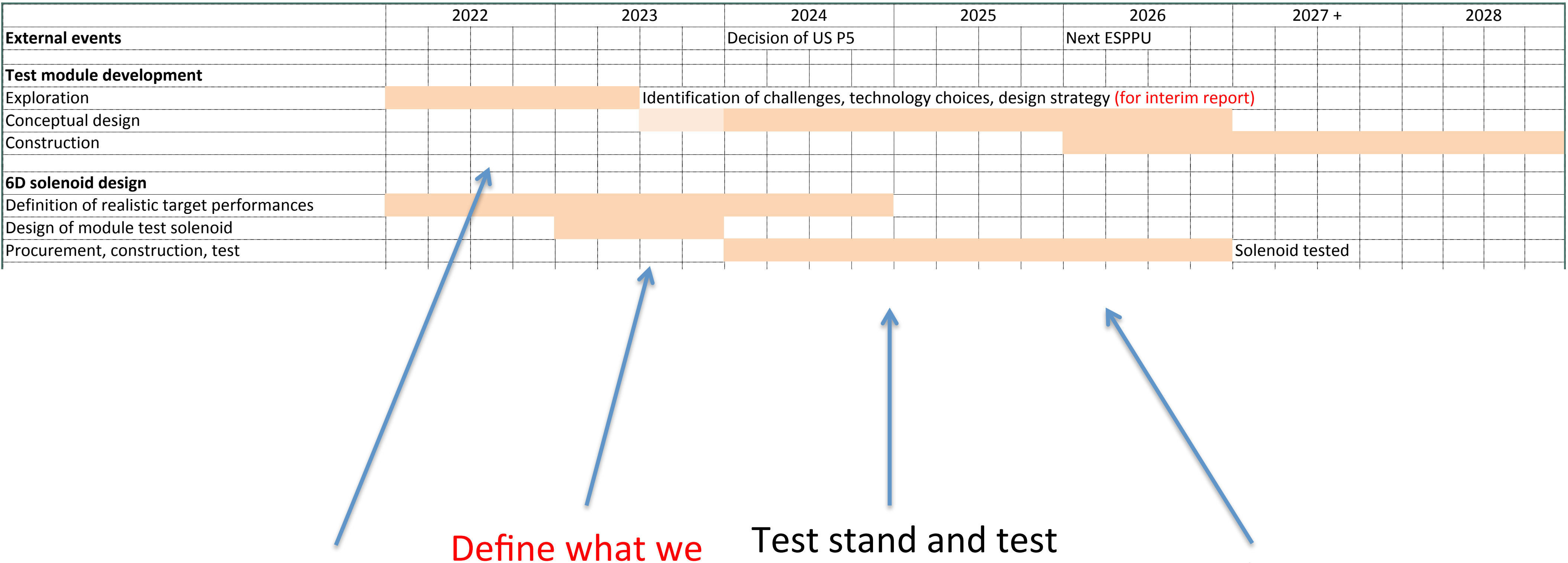
Test stand and test cavity in parallel

Results during ESPPU

Hard to see a cavity exactly for the module at this timescale, but could have one for fundamental tests

Need funding

Timeline Discussions: 6D Solenoid



	2022	2023	2024	2025	2026	2027 +	2028
External events			Decision of US P5		Next ESPPU		
Test module development							
Exploration	▨	▨ Identification of challenges, technology choices, design strategy (for interim report)					
Conceptual design		▨	▨	▨	▨		
Construction					▨	▨	▨
6D solenoid design							
Definition of realistic target performances	▨	▨	▨				
Design of module test solenoid		▨					
Procurement, construction, test			▨	▨	▨	Solenoid tested	

Realistically later start

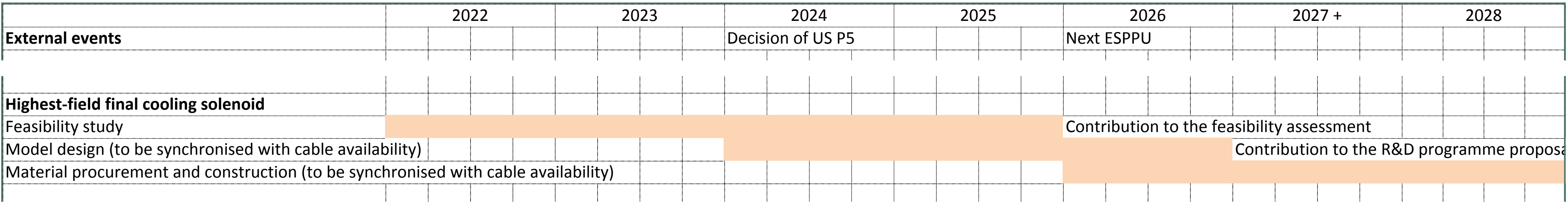
Define what we want to test

Test stand and test cavity in parallel

Results during ESPPU

I do not see that we can have a solenoid that is exactly suited for the module at this time scale but could have a model
Need funding

Timeline Discussions: Solenoid



	2022	2023	2024	2025	2026	2027 +	2028
External events			Decision of US P5		Next ESPPU		
Highest-field final cooling solenoid							
Feasibility study	▨	▨	▨	▨	Contribution to the feasibility assessment		
Model design (to be synchronised with cable availability)			▨	▨	▨	Contribution to the R&D programme proposa	
Material procurement and construction (to be synchronised with cable availability)					▨	▨	▨

Spending
during ESPPU

Reasonable schedule

Conclusion

Use “immediate” as minimum funding scenario can be reasonable

- still requires increase in resources

Need to define a flexible schedule for the test facility and prototypes that gives the logic for the progress but no fixed year

Most important is to get going

- resources are more likely to come if we show that some challenges are successfully addressed
- in particular, neutrino flux and MDI

Reserve

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)

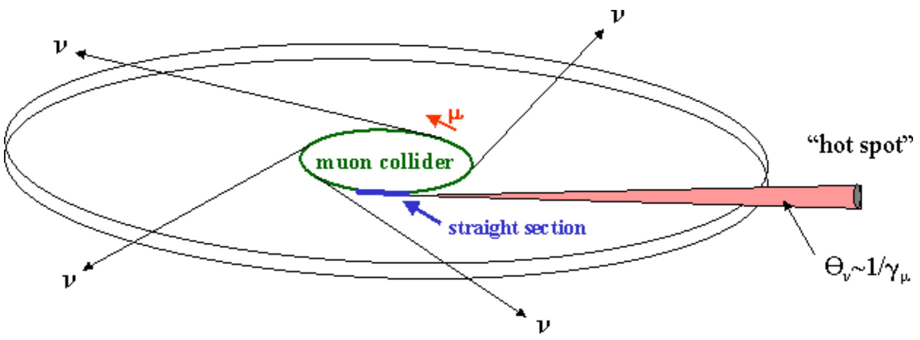
- The impact of **machine induced background** on the detector, as it might limit the physics reach.

- **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

Neutrino Flux Mitigation



Narrow cone of dense neutrino flux may prevent installation in populated area

- In particular at 10+ TeV arcs can exceed legal limit, but have proposed solution
- Arcs of 3 TeV in 200 m depth is OK
- But apply ALARA

Goal is to reach levels similar to LHC

Insertions lead to higher values and have to be consider in detail

1) Basic concept

- Assessment of requirements and strategy to show conformity
- Verification of radiation model
- Assessment of impact on beam operation
- Assessment of impact of insertions on site choice
  - Tool to link beam in tunnel to surface
  - Exploration of surface
  - Lattice design

2) Assessment of feasibility/concept of mechanical system

	Staff/FTEy	Postd/FTEy	Stud/FTEy	Mat/kEuro	Sum/MEur
Basic concept	5.5	2.5	1	0	1.45
Technical/alignment concept	2.5	9	11	150	2.28

Interest: CERN, some resources in place, FNAL with support by DOE and Snowmass/P5 demonstration of technical systems not covered

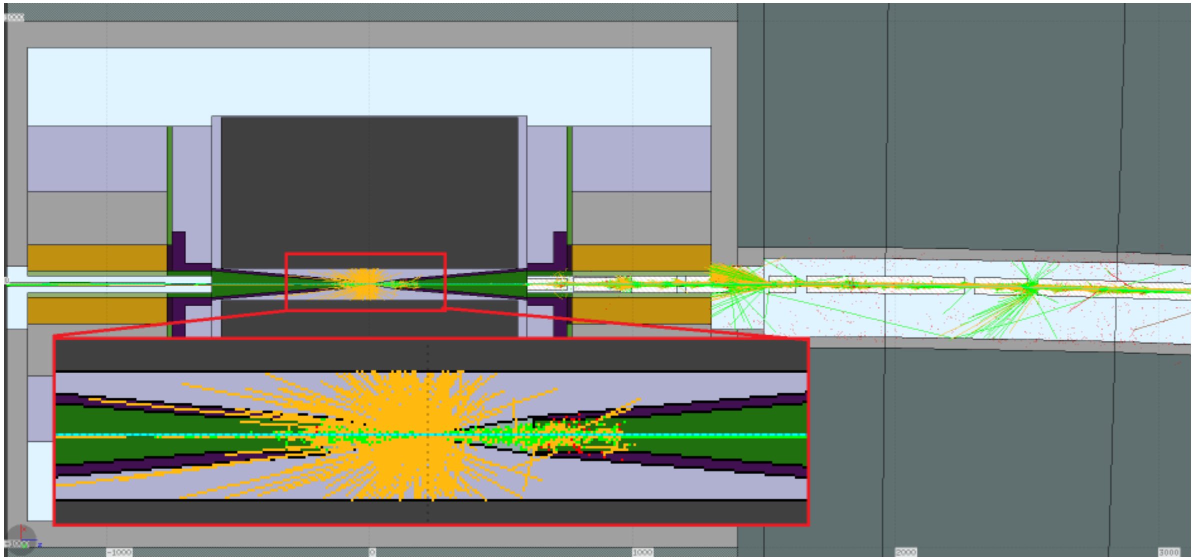
Machine Detector Interface

Main background sources

- Muon decay products (40,000 muons/m/crossing at 14 TeV)
- Beam-beam background
- Note: background reduces while beam burns off

Mitigation methods

- masks
- detector granularity
- detector timing
- solenoid field
- event reconstruction strategies
- …



Simulation tools for loss along beam line exist

First studies at lower energies (125 GeV, 1.5 TeV, 3 TeV) are encouraging (D. Lucchesi et al.)

Will develop systems for higher energies

1) Basic concept

- Simulation of background in the detector for different mask configurations
- Beam-beam background simulation tool

	Staff/FTEy	Postd/FTEy	Stud/FTEy	Mat/kEuro	Sum/MEur
Basic concept	5	10			2.2

Interest: INFN and CERN cover part of this

High-energy Complex

Collider ring

- Increasingly challenging with energy, feeds to neutrino flux and MDI

Pulsed synchrotron

- Increasingly challenging with energy, contains longest systems, also neutrino flux

Linac and recirculating linac

- MAP design seems good but need evaluation, also relevant to link to muon cooling section

FFA could be an alternative

- In particular for initial energies

Collective effects need to be assessed across the complex

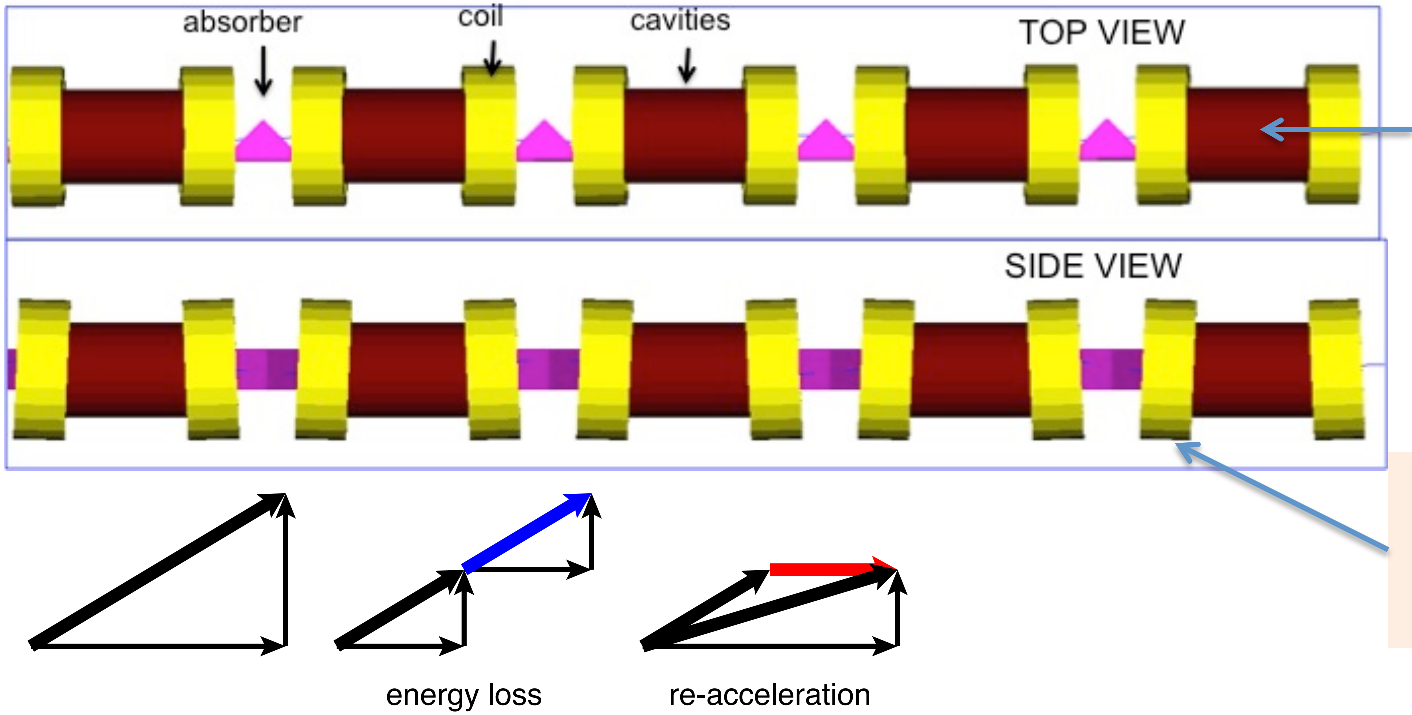
1) Collider ring and pulsed synchrotron
2) Linac and alternatives (FFA)

	Staff/FTEy	Postd/FTEy	Stud/FTEy	Mat/kEuro	Sum/MEur
Collider and synchrotron	4	10.5	9	0	2.51
Linac and FFA	1.8	3	9	0	1.17

Interest: CERN covers most of collider ring, UKRI-STFC for alternative optics, BNL for collider ring
Accelerators: BNL (FFA + RCS), CEA (RCS), IJCLab-In2p3 (RLA), JLAB (Linac), UKRI-STFC (FFA)

Cooling Challenges

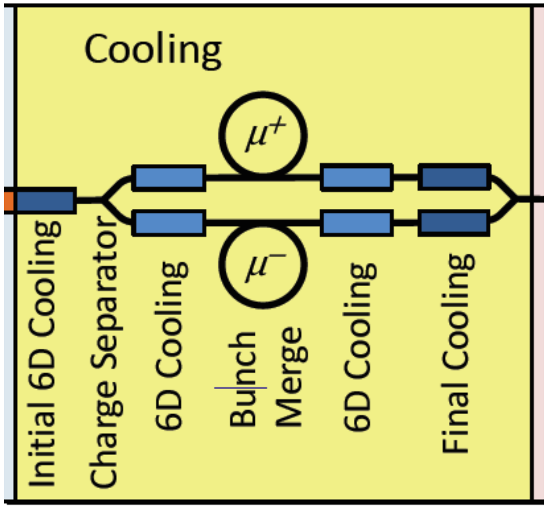
MAP collaboration



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

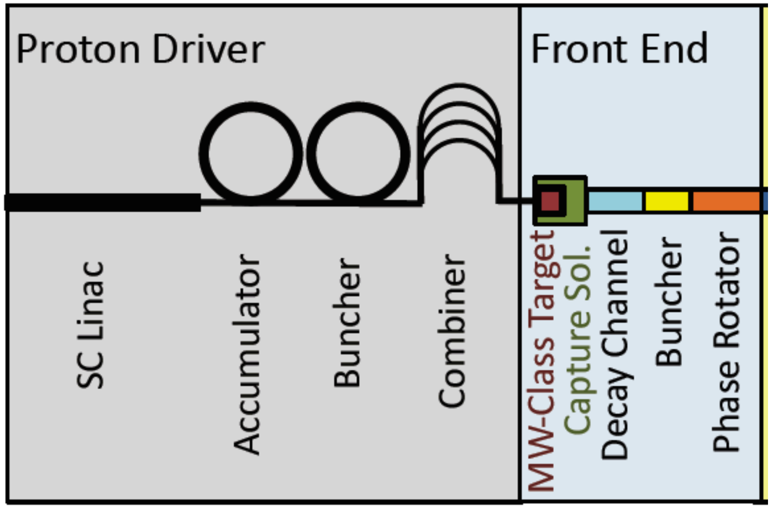
3) Engineering considerations for muon cooling module and definition of future R&D

- 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

Proton Complex and Target Facility

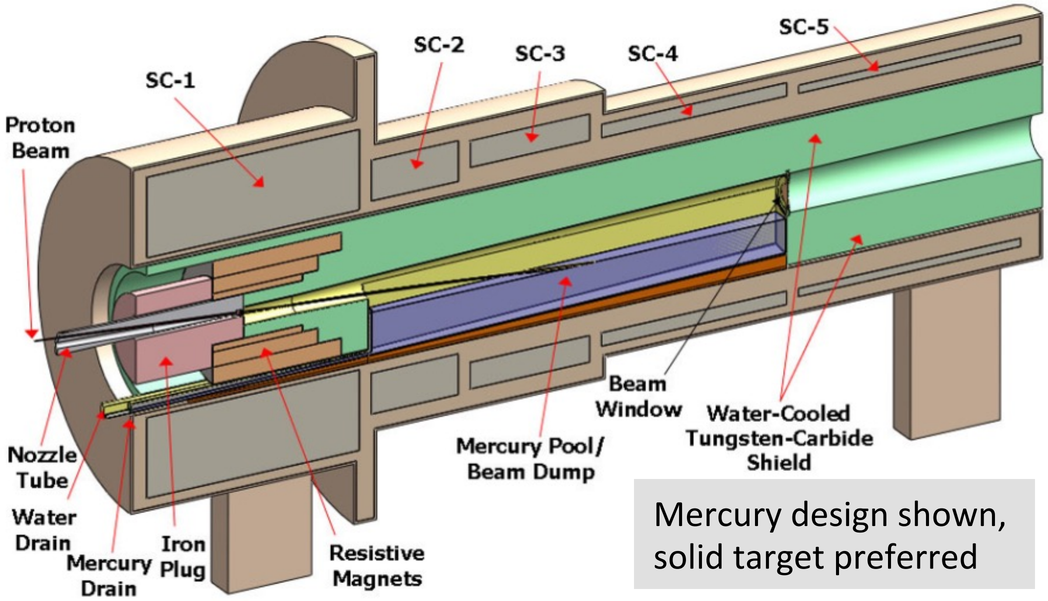


H- source and **accumulator and combiner complex**
10^{14}-10^{15} protons in ns-long bunch

Liquid mercury target demonstrated (MERIT) but safety calls for **graphite target, granular Ti** or **fluidized W**

5 Hz, 2 MW proton beam
requires radiation protection
leads to heat load and stress

Note: some margin would be useful to compensate potential higher rate of muon decay in cooling channel or smaller capture efficiency



Mercury design shown, solid target preferred

Large aperture O(1.2m) allows shielding

High field to efficiently collect pions/muons: 20 T
Using copper solenoid in 15 T superconducting solenoid

Target Area and Target

1) Feasibility of 2 MW target

- Estimate heat load on target and radiation in magnets; design shielding
- Preliminary study of target area design
- Shock load and pion yield estimates

2) Target concept

- Optimise graphite target for yield
- Consider non-solid target designs (powder jet, …)
- Cooling system for target shielding
- Explore target horn as fallback solution
- Verify impact of radiation on superconducting wire experimentally (could be in HFM Roadmap)

3) Target conceptual design

- Develop essential engineering aspects of target area, including remote handling
- Develop concept for full power test of target
- Study impact of shocks on material (HiRadMat)
- Engineering design of graphite target

	Staff/FTEy	Postd/FTEy	Stud/FTEy	Mat/kEuro	Sum/MEur
Feasibility	3	6	3	15	1.485
Target Concept	12	12	0		3.84
Target Conceptual Design	12	15	0	450	4.65

Interest: RAL, CERN, Warwick; European ESSnuSB, ESS Laboratory via EU design study proposal

Proton Complex

European Design Study proposal by European ESSnuSB Collaboration and ESS Laboratory

Design proton complex based on ESS and granular target

1) Basic parameters

2) Proof of concept

- Preliminary lattice design for accumulator (and linac)
- H- source exploration
- Preliminary design of compressor (and target delivery system)
- Addressing fundamental charge density limit
- FFA option as alternative

	Staff/FTEy	Postd/FTEy	Stud/FTEy	Mat/kEuro	Sum/MEur
Basic parameters	0.5	0	0	0	0.1
Proof of Concept	1.2	9	12		1.92
ESS proposal	4	4	3		1.43

Interest: CERN (but no resources), European ESSnuSB, ESS Laboratory via EU design study proposal

Magnet Development: Dipoles, …

High-field Magnet programme (Roadmap) is key ingredient, in particular for HTS

- cables, stress and radiation, topologies, …

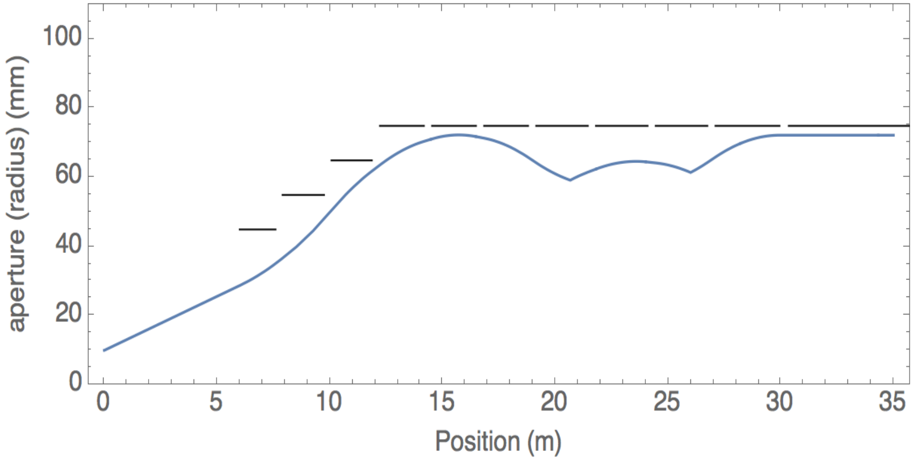
For 3 TeV:

- Dipoles and quadrupoles with 11-12 T
- Combined function magnets mitigate neutrino flux
- Larger aperture in arc, but single aperture

For 10 TeV:

- Would like to go to technology limit
- including HTS for final focus, if possible
- But wait for high-field magnet programme

3 TeV FFS Design (MAP)



Parameter	Q1	Q1	Q3	Q4
Aperture (mm)	90	110	130	150
Gradients (T/m)	267	218	-154	-133.5
Peak field (T)	12	12	10+	10+
Dipole field (T)	0	0	2.00	2.00

Interest: CERN-KEK collaboration

Magnet Development: Solenoids

Solenoids are key to the muon production and cooling high performance essential at 3 TeV

Many solenoids in 6D cooling complex
- High field, cost effectiveness, large aperture
- Proposed 20-25 T HTS solenoids (experts from CEA and KIT) would be important improvement (previously up to 13.8 T)
  - Makes system significantly shorter: cost and muon survival
  - Will improve final cooling

One 15 T, 1.2m aperture solenoid around 2 MW proton target
- Determines capture rate for muons and luminosity
- Radiation because of target
- Stress due to size

A few highest field solenoids in final cooling
- Determines final emittance
- Luminosity is proportional to field
- Small aperture (O(50 mm))
- Aim for 30 - 50 T

Solenoids are ideal to test new cables

Magnet Development

1) Baseline concept
- Exploratory study of combined function magnet
- Design of 20-25 T solenoid for 6D muon cooling
- Study of reach of final cooling solenoid
- Feasibility study for target solenoid

2) Preparation of experimental programme and test facility CDR
- Design of solenoid for 6D cooling test module
- Design of models for final cooling solenoid

3) Model/prototype
- Construction of solenoid for 6D cooling module
- Construction of models for solenoid for final cooling

3) FFA magnets

3) Combined function magnet conceptual design

	Staff/FTEy	Postd/FTEy	Stud/FTEy	Mat/kEuro	Sum/MEur
Baseline concept	7.5	6	4	0	2.42
Preparation of experiments	5	4	2	0	1.88
Model/prototype	6.5	7.5	5	2450	4.9
FFA	6				1.2
Combined function magnet	12	6	2		3.22

Interest: IRFU-CEA, KIT, CERN and KEK collaboration for combined function magnet

RF Systems

Cavity gradient is reduced in magnetic field

Can overcome this by use of Be or filling the cavity with high-pressure hydrogen

Gradient demonstrated in single pieces, but
- do need to address breakdown rate
- reproducibility of results
- check different options for performance
- e.g. can cooled copper be better?

Fundamental design choices so needed early

Test stand for cavities in high magnetic field would be unique facility to address fundamental questions
- cool copper
- breakdown rate
- potential synergy with electron and positron sources
- Note: the one in the US is dismantled
- Cost estimate for IRFU in Saclay using existing equipment (also from MICE) 10 FTE, 2.9-7 MEuro

Currently need many klystrons for muon cooling, also an issue for the test facility
High power klystrons (based on CLIC) could solve this
Other options are also being considered

Concept to deal with challenging beam dynamics in high-energy system:
bunch charge is 10 x HL-LHC bunch charge
but only 1 mm bunch length
⇒ wakefield effects are very large

RF Systems

1) Baseline concept
- Cavity design choices for muon cooling: operating temperature, gas-filled/Be, frequencies, …
- RF power system design for muon cooling
- RF concept for high-energy acceleration

2) Preparation experimental programme and CDR
- RF design for muon cooling module (accounted for in module and test facility)
- High-energy RF cavity design

3) Infrastructure for cavity development
- Test stand for muon cooling module RF to test cavities for choices

	Staff/FTEy	Postd/FTEy	Stud/FTEy	Mat/kEuro	Sum/MEur
Baseline Concept	2.2	9	0	0	1.52
RF test stand	10	0	0	2900	4.9
HE cavity design	0.6	0	3	0	0.27

Interest: CEA, Strathclyde, Rostock, CERN (some resources), LBNL, Lancaster

Fast-ramping Magnet Systems

Fast-ramping magnets dominate the pulsed synchrotrons

- This is the longest system of the collider O(25 km) for 10 TeV collider

O(n x 100 MJ) stored in the magnets

Synchrotron ring magnets need to ramp from O(-2 T) to O(2 T) in 0.4 - 11.7 ms

- Unprecedented O(n x 10 GW) peak power flowing to magnets
- Unprecedented O(n x 1 GW) average power flow

Normal-conducting magnets work in principle but influence the shape of the field tramp, losses in steel has to be assessed

Superconducting magnets are alternative

- Superferric option for efficiency
- Air coils with higher field reach, shortening the system

Some work in the US, but a key system

First studies show that **power converters** are expected to drive the cost (O(GCHF)), more than the ramping magnets

Need cost-effective, highly-efficient system
Significant uncertainty on capacitor energy density with voltage sign change

No previous study

Fast-ramping Magnet Systems

1) Basic concept

- Power converter conceptual design
- Normal-conducting magnet pre-design to assess power loss and field ramp
- Power converter material tests (capacitors)
- Test of materials for fast-ramping magnets

2) Alternatives

- Concept of superconducting fast-ramping magnet
- Test of cable for fast-ramping superconducting cable

Synergy with cable development for HFM programme

	Staff/FTEy	Postd/FTEy	Stud/FTEy	Mat/kEuro	Sum/MEur
Basic concept	2.8	7	4	520	2.12
Alternative	4	0	0	250	1.05

Interest: CERN, INFN, Darmstadt, EPFL

Test Facility and Muon Cooling Cell Module

Module integration is critical

- compactness for muon survival
- integration of RF and magnets is challenging
- many “details” need to be addressed
- cryogenics, vacuum, instrumentation, power couplers, …

Important to have module ready before test facility

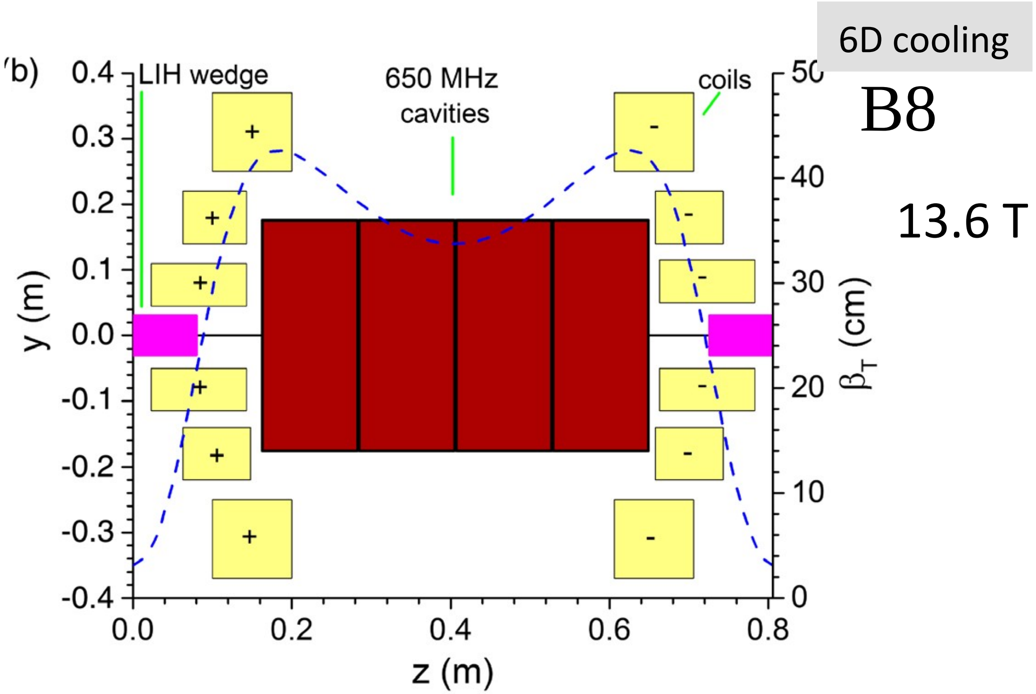
Will learn a lot already

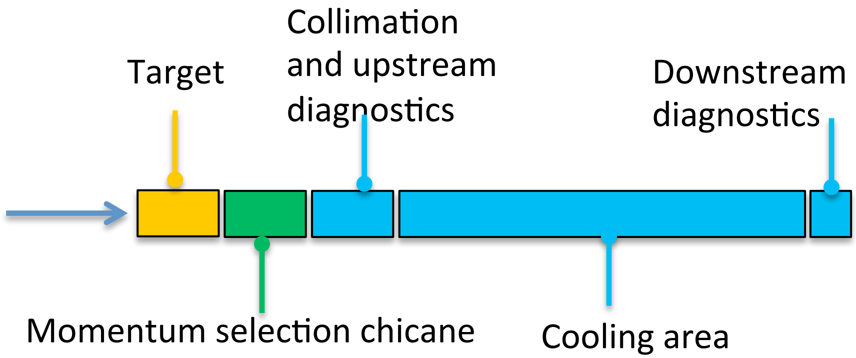
Test facility to test cooling modules with beam

Exploring some sites at CERN

- tradeoff cost and scope

Two candidate sites identified





Target

Collimation and upstream diagnostics

Downstream diagnostics

Momentum selection chicane

Cooling area

Interest: STFC, CEA, CERN, US?

Test Facility and Module

Deliverables for full programme

- Selection of the site
- Cooling module design
- Provide civil engineering feasibility study of the site and costing of the infrastructure
- Selection of the muon production and cooling components and layout, optimization of expected performance wrt cost.

Tasks

1) Module and site
2) Key component concepts 1
- Layout drivers
3) Key component concepts 2
- Remote handling, target vessel, instrumentation, …

	Staff/FTEy	Postd/FTEy	Stud/FTEy	Mat/kEuro	Sum/MEur
Site choice, module	12.2	18	0	1000	5.6
Module in RF and design	8	6	4	0	2.52
Key component concept 1	2.6	10	3	400	2.27
Key component concept 2	1.9	8	3	300	1.79

Interest: STFC, CEA, CERN, US?

Demonstrators (before 2032)

- Demonstration of muon cooling module solenoid
- Demonstration of muon cooling module cavity
- Demonstration of powered muon cooling module

- Facility to test muon cooling module with proton beam

- 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

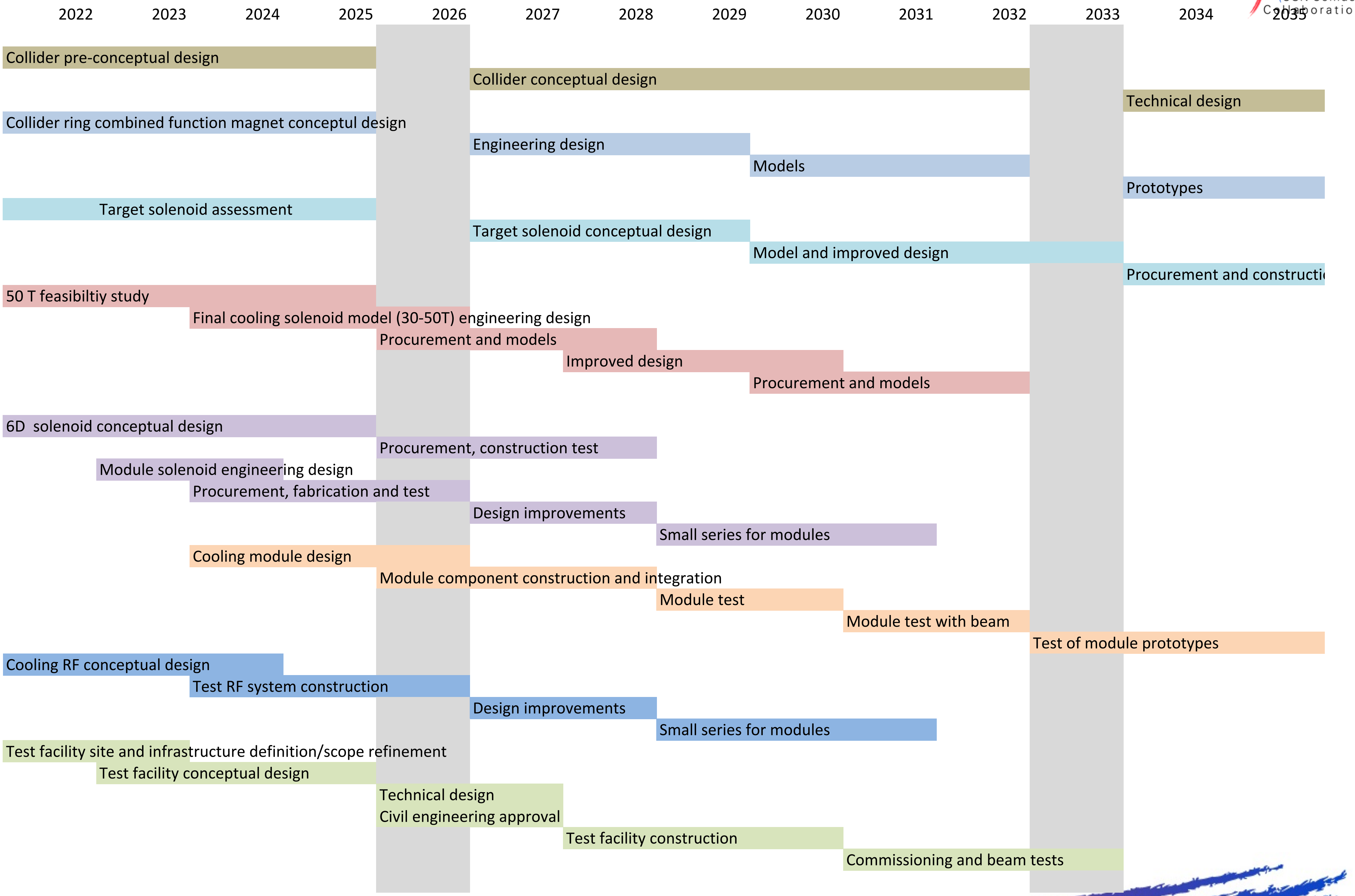
RF

- 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

Schedule Discussion



Collider pre-conceptual design

Collider conceptual design

Technical design

Collider ring combined function magnet conceptul design

Engineering design

Models

Prototypes

Target solenoid assessment

Target solenoid conceptual design

Model and improved design

Procurement and constructi

50 T feasibiltiy study

Final cooling solenoid model (30-50T) engineering design

Procurement and models

Improved design

Procurement and models

6D solenoid conceptual design

Procurement, construction test

Module solenoid engineering design

Procurement, fabrication and test

Design improvements

Small series for modules

Cooling module design

Module component construction and integration

Module test

Module test with beam

Test of module prototypes

Cooling RF conceptual design

Test RF system construction

Design improvements

Small series for modules

Test facility site and infrastructure definition/scope refinement

Test facility conceptual design

Technical design

Civil engineering approval

Test facility construction

Commissioning and beam tests

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

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

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

- Expectation management
- Should we be ambitious 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