International MUON Collider Collaboration

MuCol

Parameters

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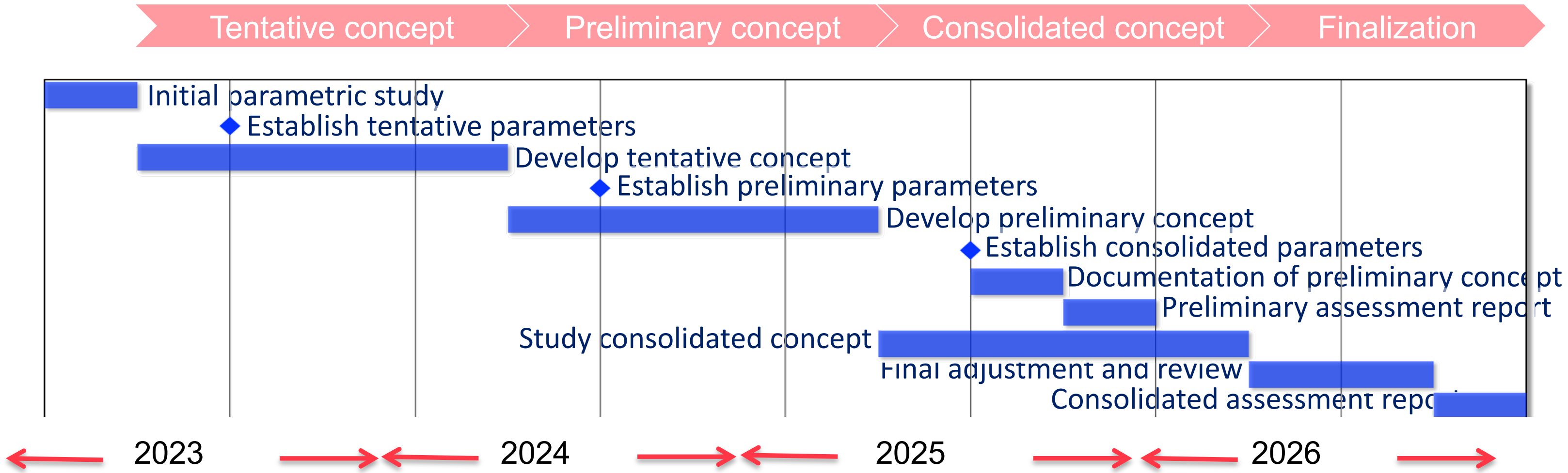
Roadmap/MuCol Goals

In **aspirational scenario** can make **informed decisions**:

Three main deliverables are foreseen:

- a **Project Evaluation Report** for the next ESPPU will contain an assessment of whether the 10 TeV muon collider is a promising option and identify the required compromises to realise a 3 TeV option by 2045. In particular the questions below would be addressed.
  - 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, and can it have one or two detectors?
  - What are the key performance specifications of the components and what is the maturity of the technologies?
  - 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 risks of the project?
- an **R&D Plan** that describes an R&D path towards the collider;
- an **Interim Report** by the end of 2023 that documents progress and allows the wider community to update their view of the concept and to give feedback to the collaboration.

MuCol Timeline



Will improve parameters in between milestones

But aim for consistency at each milestone

Key Tentative Parameters

- **Overall target performance for physics**
  - E.g. energy and luminosity

- **Beam parameters at the interfaces along the machine**
  - Energy, charge, emittance, …
  - Targets for the accelerator designers

- **Key performance specifications for the components**
  - Realistic targets for the component designers and basis for the accelerator designers
    - e.g. cross section of the collider ring magnet, shielding and cooling

- **Machine and component parameters and designs**
  - To document key known parameters and highlight what has to be defined by R&D
  - Expect these to change during the study

Highlight knowledge, but more importantly what will need to provide at the end of the study

First iteration due August 2023

Target Performance for Physics

- **Collision energy**
  - **10 TeV is baseline**
    - This is the reason to consider a muon collider
    - Focus to show that this is realistic
  - **3 TeV potential initial stage**
    - Only consider important simplifications compared to 10 TeV to have more aggressive schedule
    - If something can be solved for 10 TeV
  - Other energies as emerging and important (e.g. site specific)

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

- **Luminosity**
  - Integrated luminosity scales with energy squared

Up to the physics potential experts to confirm choices

Impact of Staging

Aim is 10 TeV machine, but

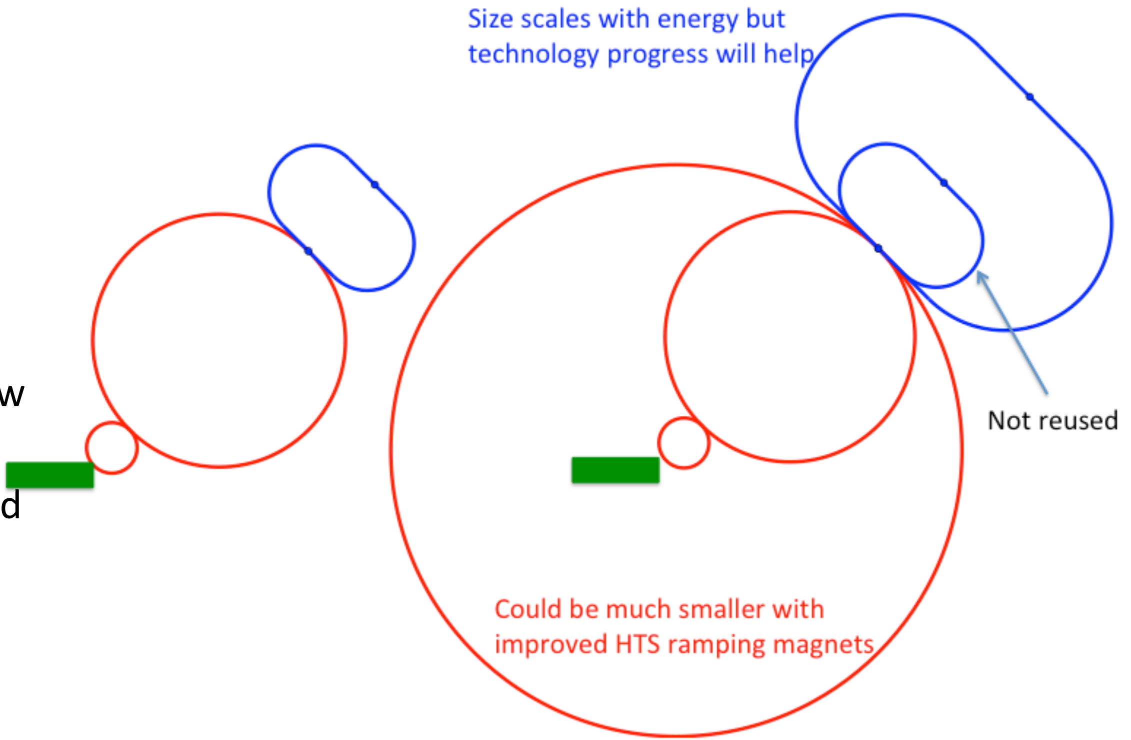
- Already a good physics case for 3 TeV
- Substantially less cost for a first stage
- Can make technical compromises

Potential initial stage of 3 TeV planned

Upgrade adds one more accelerator and new collider ring

- only first collider ring is not being reused

However, this fixes several parameters of last RCS

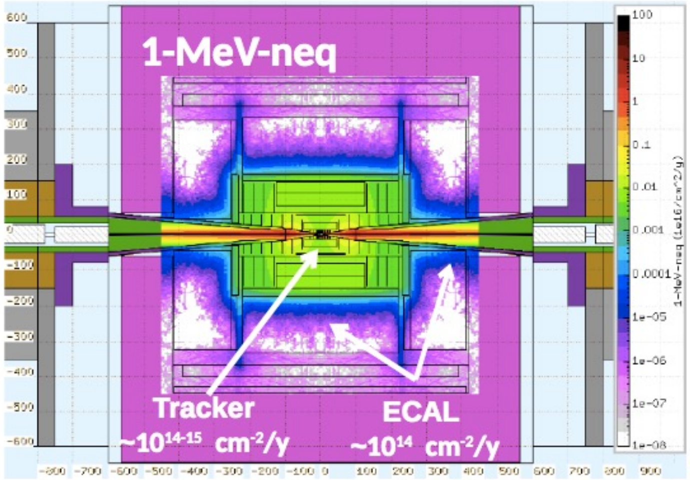


Detector Parameters

- **Detector target performances, interface between physics potential and detector**
  - Angular coverage
  - Key resolutions
  - Key particle/jet identification performances
  - …
  - Have used DELPHES card

- **Beam-induced background and MDI**
  - L*
  - Fundamental solenoid parameters
  - Mask parameters, beam pipe radius etc.
  - Identify parameters to simplify description of background and its impact
    - E.g. hit density in vertex detector layers

- **Main detector parameters**
  - Once we have a 10 TeV design



Luminosity (Collider Ring)

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$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

Collider ring circumference
- Collider ring dipole fields
- Filling factor

Energy acceptance
- beta-function = bunch length

Bunch charge
- target and muon survival

Emittances
- cooling and blow-up

Beam power
- neutrino flux
- target and muon survival
- power consumption

High-level Tentative Collider Parameters

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Parameters achieve integrated luminosities in 5 years at full performance

- 6×10^7 s per 5 year cycle

Parameters are hard to achieve but seem possible with enough R&D

Do not change if magnets are OK

Parameter	Unit	3 TeV	10 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**20**
N	10^{12}	2.2	1.8
f_r	Hz	5	5
P_{beam} (injected)	**MW**	**5.3**	**14.4**
C	km	4.5	10
<B> (average)	T	7	10.5
ε_L (norm, 1σ)	MeV m	7.5	7.5
σ_E / E	%	0.1	0.1
σ_z	mm	5	1.5
β	mm	5	1.5
ε (norm, 1σ)	µm	25	25
$\sigma_{x,y}$	µm	3.0	0.9

Are the Targets Good?

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Final cooling studies come close to emittance goals

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D. Schulte: Tentative Parameters, June 2023

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Bunch charge seems possible (e.g. muon survival, collective effects)

Collider ring lattice design comes close to achieving goals

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Are the Targets Good?

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Average magnetic field to be reviewed

Based on dipole field and filling factor of the lattice

Need values for NbTi, Nb_3Sn and HTS

Optics design looks promising

Parameter	Unit	3 TeV	10 TeV
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N	10^{12}	2.2	1.8
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Should not change them until we have clear studies showing that we need to do so

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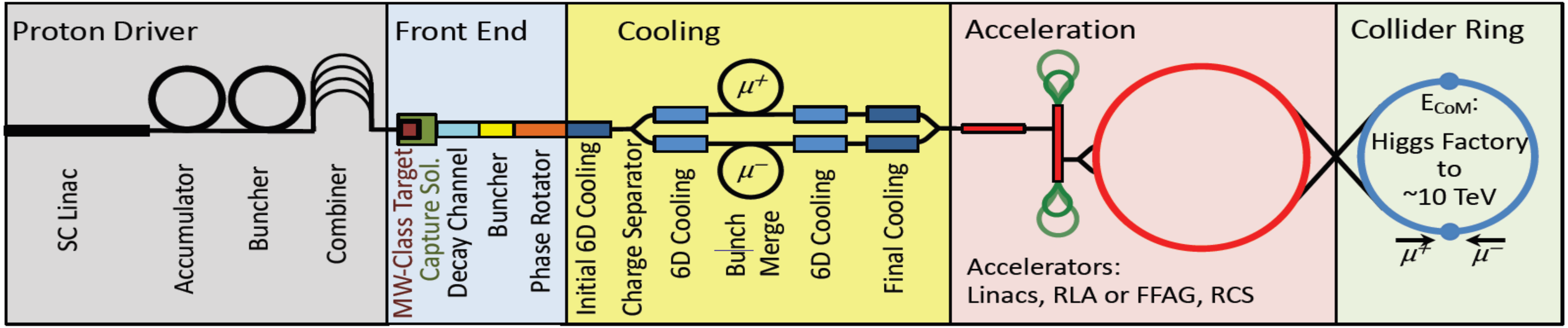
Beam Parameters along Facility

- **Define parameters at the interfaces of different areas**
  - allows to locally optimise, e.g. acceleration chain
- **Ideally transmit full beam phase space to evaluate performance**
  - However, for target parameters use simplified approach for now
- **At production and cooling muons behave in a very special fashion, after cooling like protons**
  - Fix parameters at pivotal point at the end of final cooling



Muon Bunch Charge

With input from MAP studies

Location	N [10^{12}]
5 GeV protons at target (400 kJ)	500
muons after front end	48
…	…
muons after final cooling (5-20 MeV)	6?
muons after reacceleration 0.2 GeV	4
…	…
muons at 60 GeV	2.7
…	…
muons in collider (3 TeV)	2.2
muons in collider (10 TeV)	1.8

Acceptance in RCS/collider ring in range of +/- 2σ

- charge should refer to muons in this range

Charge along the complex appears reasonable

Survival assumes average gradients

- 2.4 MV/m from 0.2 to 1500 GeV
- 1 MV/m from 1500 to 5000 GeV

This can be optimised internally

Muon cooling based on MAP, verification required

Optimise proton energy

Alternative design with twice the proton charge

Bunch Parameters

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Parameter			
Energy	0.2 GeV	1500	5000
Muons per bunch	4 x 10^{12}	2.2 x 10^{12}	1.8 x 10^{12}
Transverse emittance	25 um	27.5 um	27.5 um
Longitudinal emittance	7.5 MeVm	8.25 MeVm	8.25 MeVm
RMS Bunch length	0.375 m	5.5 mm	1.65 mm
RMS Energy spread	10%	0.1%	0.1%

Targets for final cooling are tough but maybe in reach

Verify 0.2 GeV with Chris and Antoine that is best interface point
Energy spread vs bunchlength my guess

Allow 10% emittance degradation

Collider ring requirement

Stages of acceleration up to relevant team
But will link to global optimization for risk, cost and power consumption

Note: Muon Bunch Emittance Budgets

- **Emittance target at final cooling end should remain as a target for now**
  - Do not know better for the moment
- **Emittance blow-up from final cooling to IP should remain limited**
  - The specifications for equipment imperfections should be made accordingly
  - Would assume **a total budget of 10%** (most relaxed acceptable tolerance) or **1%** (no issue for the moment)
  - Need to distribute fractions to the different systems and imperfections (for the area team)

rel. emittance blow-up	relative tolerance	relative luminosity
0.1%	0.03	0.999
1%	0.1	0.99
10%	0.3	0.9
100%	1	0.5
1000%	3	0.1

Area Parameter Example: RCS Design

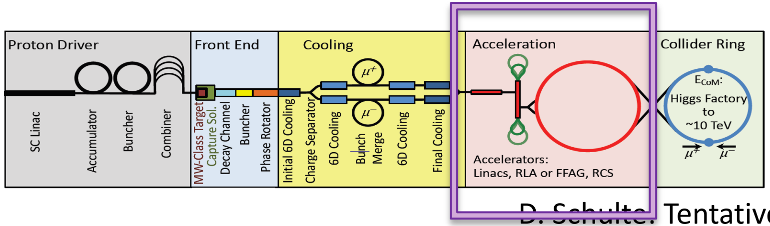
A. Chance, F. Batsch et al.

Need to perform an optimisation of the whole chain for cost and power, so all numbers will potential change

The table very important defining starting point

Things that we should add some parameters that where also results from the studies

- RF frequencies and gradients
  - Important result of studies
- Beam parameters between RCS
- Ramp rates
- Summaries of total system lengths
  - E.g. fast-ramping magnets
- How to best include impedance study results?



Example parameters for the muon RCSs

	RCS1	RCS2	RCS3	RCS4
Hybrid RCS	No	Yes	Yes	Yes
Circumference [m]	5990	5990	10700	26659
Injection/extr. energy [TeV]	0.06/0.30	0.30/0.75	0.75/1.5	1.5/4.2
Survival rate [%]	90	90	90	90
Acceleration time [ms]	0.34	1.10	2.37	5.75
Number of turns	17	55	66	65
Energy gain/turn [GeV]	14.8	7.9	11.4	41.5
NC dipole field [T]	0.36/1.8	-1.8/1.8	-1.8/1.8	-1.8/1.8
SC dipole field [T]	-	10	10	16
NC/SC dipole length [m]	2.6/-	4.9/1.1	4.9/1.3	8.0/1.3
Number of arcs	34	26	26	26
Number of cells/arc	7	10	17	19
Cell length [m]	21.4	19.6	20.6	45.9
Path length diff. [mm]	0	9.1	2.7	9.4
Orbit difference [mm]	0	12.2	5.9	13.2
Min. dipole width [mm]	17.4	19.6	10.7	18.8
Min. dipole height [mm]	14.8	6.4	4.2	4.4

Area Parameter Example: RCS Design

A. Chance, F. Batsch et al.

We will iterate on the design
- Also to optimise cost and power consumption

For this we need specific R&D:
- The maximum energy swing of an RCS
    - The fewer we need the better
- The synchronisation of RF and magnets
    - They like different ramp profiles
- Some simplified cost model for the components
- …

Example parameters for the muon RCSs

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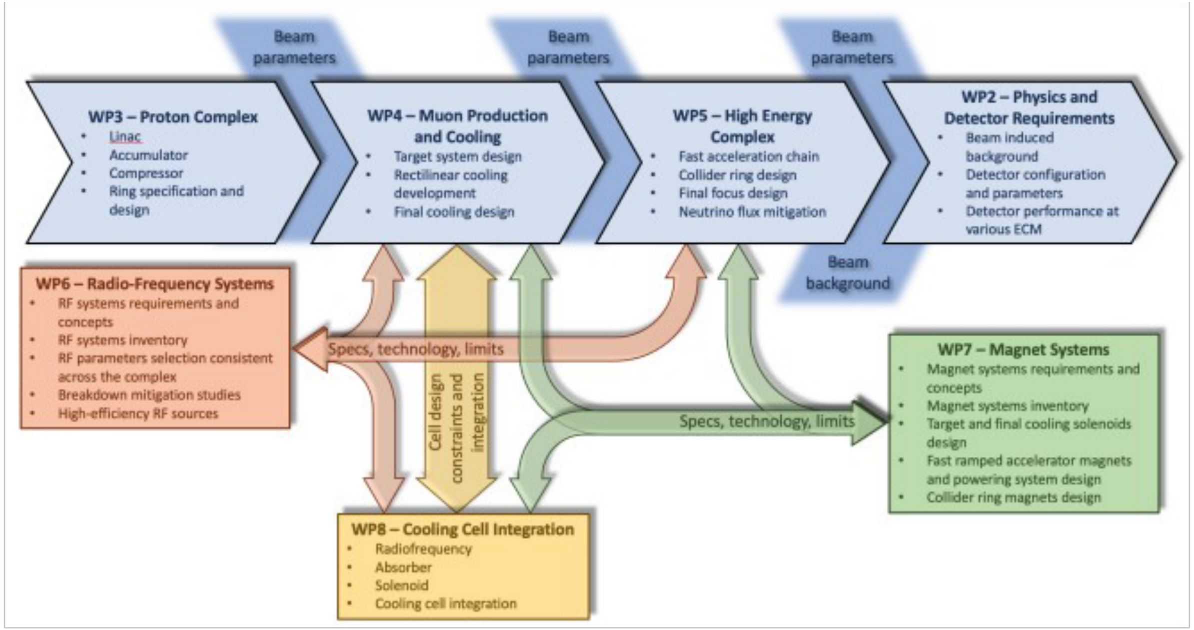
Tentative Technology Limits



Simplified view for MuCol

- More relevant technologies
- Shows strong dependence of design on technologies

Tentative Technology Limits

- **Educated guesses of performance limits by the experts**
  - Required for the accelerator design
  - E.g. magnet review at this meeting
- **Magnets**
  - Potential technologies
  - Performance parameters with dependencies
    - field level, field quality, aperture, radiation resistance, heat load resistance
- **Target**
  - Limits for shock and radiation
  - …
- **RF**
- **Cryogenics**
  - Example of important conclusions for magnet temperature range
- **…**

Need rough cost and power consumption models soon to optimize the overall design

Conclusion

- The workshop showed rapid growth in understanding of the collider design
  - Great progress in many areas
    - E.g. collider ring lattice, cryogenics cooling design, …
  - Great discussions on integrated subjects
    - Seed for R&D task forces

- Need to put this down in our data base
  - Goal for the different teams and area leaders
  - Follow the example of the RCS
  - Reminder to myself: follow the example of the RCS

- Plan is overall optimization for performance, cost and power at the best level that we can achieve
  - Be prepared to make simple models
  - Be prepared for changes

Reserve

Parameter Rational

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

- Bending field in collider ring as high as possible
  - Best guess from magnet team needed

- Transverse emittance is given by physics in final cooling O(25 um)

- Beam-beam effects limit N_0 as function of transverse emittance

Key Considerations

- **Public acceptance is the key for a new collider**

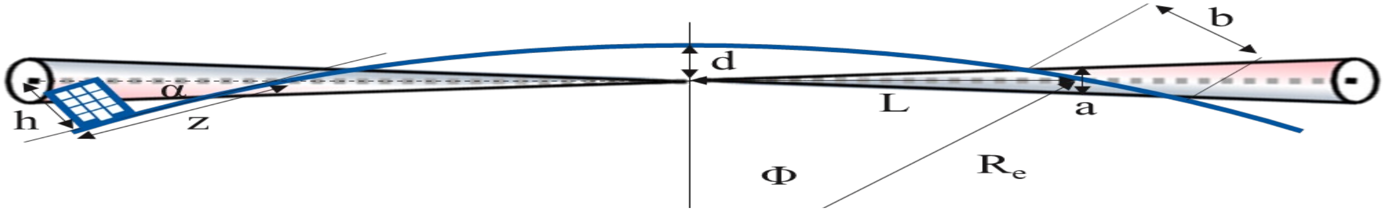
- **Energy and luminosity**
  - to have an attractive physics case to convince that it is worth doing it

- **Detector performance and background**
  - to be able to realise the physics programme

- **Cost, power consumption and environmental impact**
  - to ensure that people are willing to pay the price

- **Technical risk and schedule**
  - to ensure that the project is realistic

Neutrino Flux



Parameter choices have been done with the goal to have **not more impact than the LHC**

- This should not be changed, can express in **neutrino flux**

Collider arcs:

- Calculated that mover range should yield +/- 1 mradian
- Assuming short straights are compensated with horizontal wiggling (14 TeV)
- Detailed study of interaction between mover and beam

- Need to identify the range of angles that can be achieved
  - this might be a limit for even higher energies

Detector straights are treated independently

Acceleration Stages

- Fast-ramping magnets
  - Total amount depends on the field (neglecting injection energies)
    - 11.6 m per GeV of beam energy for 1.8 T magnets
  - Half as much in hybrid designs (injection energy is not relevant)
    - 5.8 m per GeV of beam energy for 1.8 T magnets

Acceleration Stages

- Survival of muons depends on the gradient

- Assume acceleration from 0.2 GeV to 1.5 TeV with average of 2.4 MV/m
  - Best to have higher gradient at the beginning and lower at the end
    - But fewer passages through linacs than through RCS
    - Also lower frequency at the beginning so higher cost per MV
    - Need to optimize as design progresses
  - leads to 55% survival

- Assume acceleration from 1.5 to 5 TeV with 1.0 MV/m
  - Assume lower gradient to save cost, to be reviewed
  - Leads to 82% survival, i.e. 2.2 to 1.8 x 10^{12}

- Power for the RF depends on the gradient
  - A ring with gradient of 2.4 MV/m needs 230 - 460 MW
- Need to understand the limit in energy swing for the different RCS designs, hybrid or not

Tentative Parameters

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Are building database with tentative parameters

- To be ready end of August
- Will iterate repeatedly in the future to arrive at consolidated parameters for the ESPPU

Purpose:

- **Define tentative realistic high-level goals for the areas and components**
  - Interface parameters and scalings to make studies more independent
- **Document current designs and assumptions**
  - Not yet a "reference design" but a moving target, we expect them to change soon
  - To be provided by the areas, will be reviewed as needed
- **Identify the important interfaces**
  - Set up (continue) task force teams to address cross-expertise issues

Note: should not consider use of existing infrastructure at this moment

- in conflict with global collaboration, details distract from other key studies

Will consider use of existing infrastructure at a later stage with limited detail

General Status

- **Started to work on many key systems**
  - Started to gain knowledge on driving factors, difference readiness level
- **Are not yet ready to know where exactly to go to**
  - Move targets only if clearly supported by studies
  - Rather set up R&D teams to optimize the design for performance, cost and power
- **Optimisation iterations**
  - Improve information as designs progresses
- **Clarify key studies to make parameter choices more robust**
  - No one can assume that the parameters are final
  - In the coming R&D find the boundaries and dependencies
  - Build simplified performance, cost and power model
    - Have to consider full machine for optimization, not only local systems
    - “Make it as simple as possible but no simpler”

Key Tentative Parameters

- **Overall target performance for physics**
  - E.g. energy and luminosity
- **Beam parameters at the interfaces along the machine**
  - Energy, charge, emittance, …
  - Targets for the accelerator designers
- **Key performance specifications for the components**
  - These define the interface between design and technology
  - Realistic targets for the component designers and basis for the accelerator designers
    - e.g. cross section of the collider ring magnet, shielding and cooling
- **Machine and component parameters and designs**
  - These show snapshot of the current understanding and will change
  - Also important to be aware of all relevant parameters, even if they are not know
  - Internal interfaces etc.
  - Should come from technical experts and area leaders
    - You need to have ownership