10 TeV com Collider Ring
Parameters and Requirements

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- Luminosity
- Nominal 10 TeV com Collider Parameters
- Consequences on Collider Lattice
- Neutrino Radiation Issue
- Muon Decays causing Radiation and Heat Load
- Options to simplify by changing main Parameters?
- Summary

Luminosity

- Luminosity per IP given by: $L = \dfrac{f_r N^2}{8\pi\, \varepsilon_{ph} \beta^*} f_{hg} \dfrac{\gamma\, T_\mu}{T_{rev}}$

  for round muon beams and one bunch per beam and with
  - f_r the complex repetition rate, N the number of muons in bunch
  - $\varepsilon_{ph} = \varepsilon_n/\gamma$ the physical rms emittance with $\varepsilon_n = 25\ \mu\mathrm{m}$ the normalized rms emittance and γ the relativistic Lorentz factor
  - β^* the Twiss betatron function at the IP, σ_z the rms bunch length
  - $T_\mu \approx 2.2\ \mu s$ the muon life-time at rest, T_{rev} the revolution time
  - f_{hg} the “hourglass” luminosity reduction factor a function of σ_z/β^* (for short bunches $f_{hg}(\sigma_z \ll \beta^*) \approx 1$)
- Assumptions
  - Bunch length $\sigma_z = \varepsilon_L/(\gamma\ \sigma_\delta)$ expressed by geometric longitudinal rms emittance ε_L and rms relative momentum spread
  - $\beta^* = \sigma_z$ giving moderate luminosity loss due to hourglass effect $f_{hg} = 0.758$
  - Revolution time $T_{rev} = 2\pi \dfrac{\gamma\ E_\mu}{e\ c^2\ \bar{B}}$ with $E_\mu = 105.658\ \mathrm{MeV}$ the muon rest energy and $\bar{B}$ the average bending field

  → gives luminosity per IP $L = \dfrac{e\ c^2\ T_\mu}{16\ \pi^2\ E_\mu} \dfrac{f_r\ N^2\ \gamma^2\ \sigma_\delta\ \bar{B}\ f_{hg}}{\varepsilon_n\ \varepsilon_L}$

Luminosity

Incoming beam

- Emittances determined by ionization cooling
- Luminosity per beam power increase with beam power ∝ $(f_r\,N\,\gamma)$ under assumptions made
- Large bunch population N gives higher lumi and corresponds to lower repetition rate for given beam power => nominal N/ε_n close to beam-beam limit

Constant $11.83\ \mathrm{T}^{-1}$

$$L = \overbrace{\frac{e\,c^2\,T_\mu}{16\,\pi^2\,E_\mu}}\ \overbrace{\frac{(f_r\,N\,\gamma)\,N\,\gamma}{\varepsilon_n\,\varepsilon_L}}\ \underbrace{\sigma_\delta\,\bar{B}\,f_{hg}}$$

Few collider parameters to maximise luminosity

- Large (average bending) magnetic field helps
- Large longitudinal acceptance to operate with large rms momentum spread σ_δ => corresponds to small $\beta^* = \sigma_z$ - both a challenge for lattice design

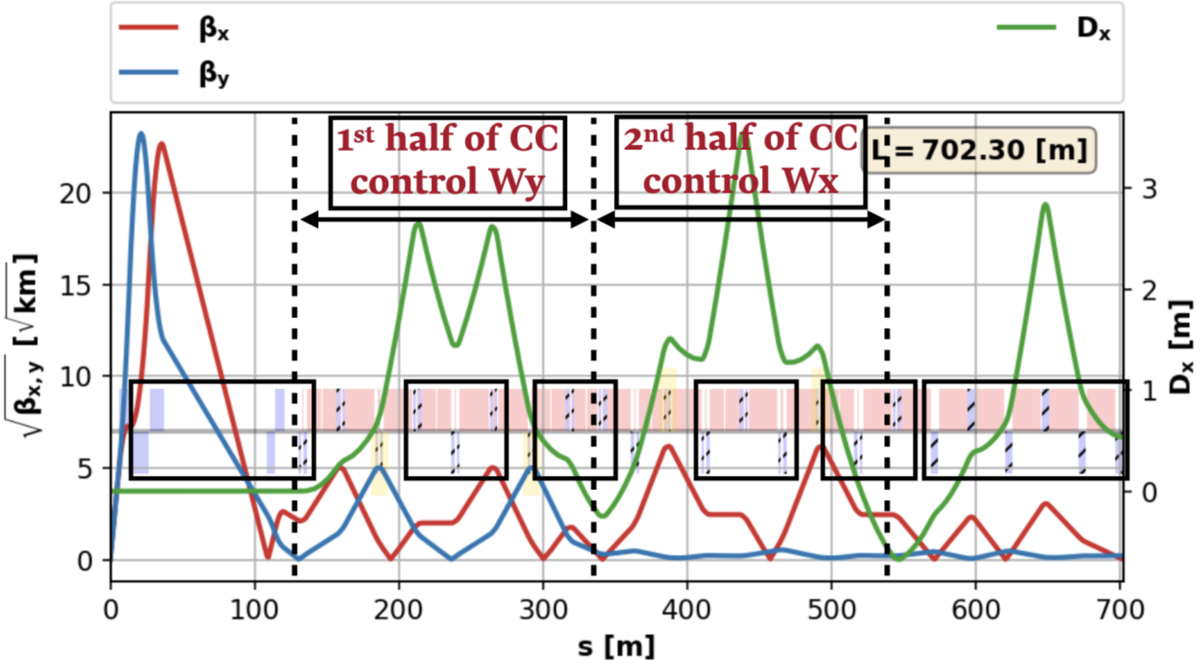
- Consequence of assumption and optimizations made:
  - Bunch length σ_z and β^* decrease with energy
  - Divergence at IP independent of energy!
  - Lattice design becomes more difficult for higher energies (higher beam rigidity, longer innertriolet, more chromatic effects …)

Nominal 10 TeV com Collider Parameters

Parameter	Symbol	Value
Beam energy	E	$5000\ \mathrm{GeV}$
Relativistic Lorentz factor	γ	$47\,322$
Circumference	C	$\approx 10\,000\ \mathrm{m}$
Magnetic (average bending) field	$\bar{B}$	$\approx 10.48\ \mathrm{T}$
Repetition rate	f_r	$5\ \mathrm{Hz}$
Bunch intensity (one bunch per beam)	N_μ	$1.8 \cdot 10^{12}$
Beam power per beam	P_B	$7.2\ \mathrm{MW}$
Normalized transverse rms emittance	ε_n	$25\ \mu\mathrm{m}$
Physical transverse rms emittance	ε_{ph}	$0.528\ \mathrm{nm}$
Long. geometric rms emittance $\gamma\ \sigma_z\ \sigma_\delta$	ε_L	$70\ \mathrm{mm}$
Rms relative momentum spread	$\sigma_\delta = \sigma_p/p$	$1 \cdot 10^{-3}$
Rms bunch length	σ_z	$1.5\ \mathrm{mm}$
Twiss betatron function at the IP	β^*	$1.5\ \mathrm{mm}$
Rms beam size at IP	$\sigma_{\perp,IP}$	$0.89\ \mu\mathrm{m}$
Luminosity	L	$19.5 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
Beam-beam tune shift per IP		0.078

Consequences on Collider Lattice

10TeV Muon Collider - Extended Final Focusing Schemes

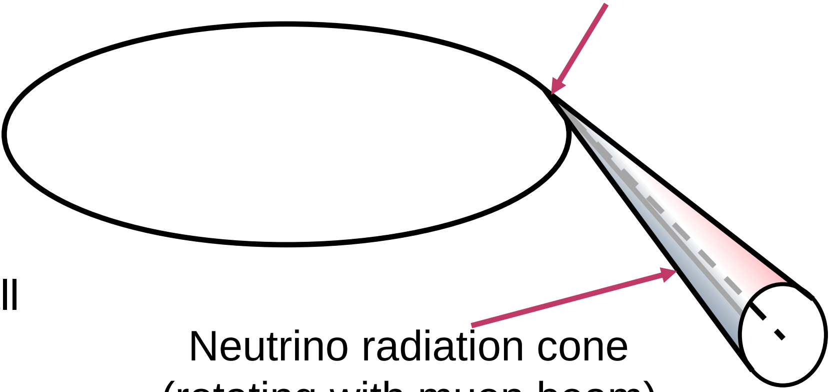


Slide from Presentation by K. Skoufaris

- Strong quadrupoles at locations with large Twiss betas and large momentum spread
    - Strong chromatic aberrations from IP to be corrected by local compensation
    - Sensitivity to unwanted mutipolar components and
        - Short beam life-time helps for slow diffusion driven by high orders
    - Sections with large beam sizes and, thus, apertures

Neutrino Radiation Issue

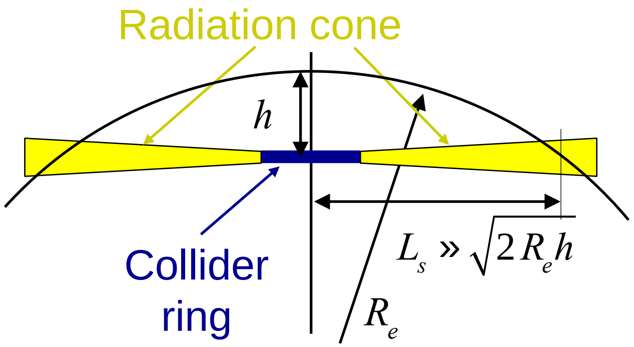
- Radiation due to neutrino beam reaching the earth surface
  - Narrow radiation “cone” for a short piece of the machine
  - Very small interaction cross sections
    - Earth does not act as shielding (very small cross sections)
    - Showers from neutrinos interacting close to earth surface generate dose seen at surface



Muons decay (say in some straight section)

Neutrino radiation cone (rotating with muon beam)

- Strong increase of maximum dose with muon energy
  - Cross sections about proportional to energy
  - Typical energy per interaction of neutrino with matter proportional to muon energy
  - Opening of radiation cone inversely proportional to muon energy

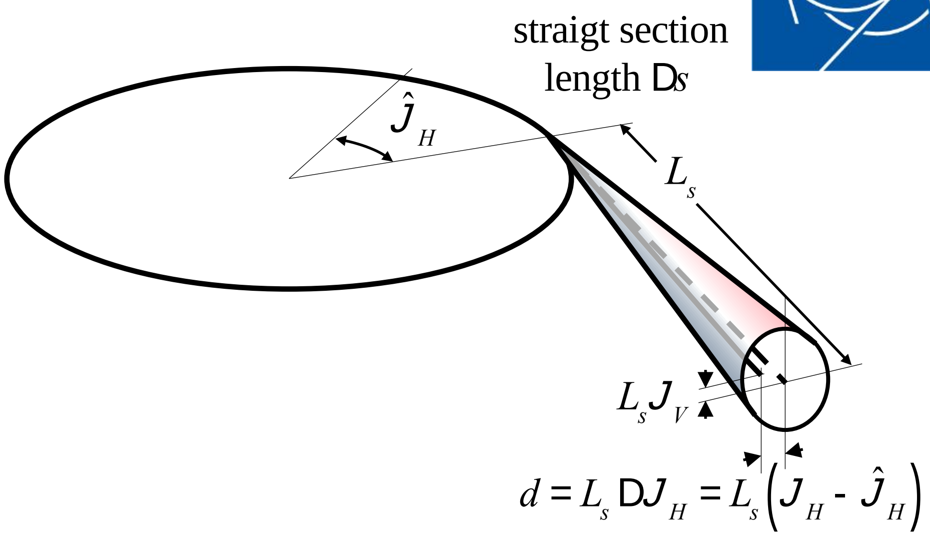


Radiation cone

Collider ring

$L_s \gg \sqrt{2 R_e h}$

Neutrino Radiation Issue



- Without mitigation measures gives

$$\frac{dH}{dt} = (1.104\cdot 10^{-28}\ \mathrm{Gy\ m^2})\ w_{R,eff}\frac{4\gamma^4 f_r N_\mu}{\pi\ L_s^2\ C}\int ds\ \frac{1/(6\gamma^2)}{\sigma_{\vartheta_H}\cdot\sigma_{\vartheta_V}}\exp\left[-\frac{\left(\vartheta_H-\hat{\vartheta}(s)\right)^2}{2\sigma_{\vartheta_H}^2}-\frac{\vartheta_V^2}{2\sigma_{\vartheta_V}^2}\right]$$

  - “Source term” from analytical estimates and fit to FLUKA results by G. Lerner et al.
    - Effective weighting factor $w_{R,eff} = 1.3\ \mathrm{Sv/Gy}$
  - Integral w.r.t. longitudinal position s in ring and taking details of lattice into account

$$\sigma_{\vartheta_H}^2 = \frac{1}{6\gamma^2} + \varepsilon_{ph}\gamma_H(s) + \left(\sigma_\delta^2\cdot D'(s)\right)^2$$

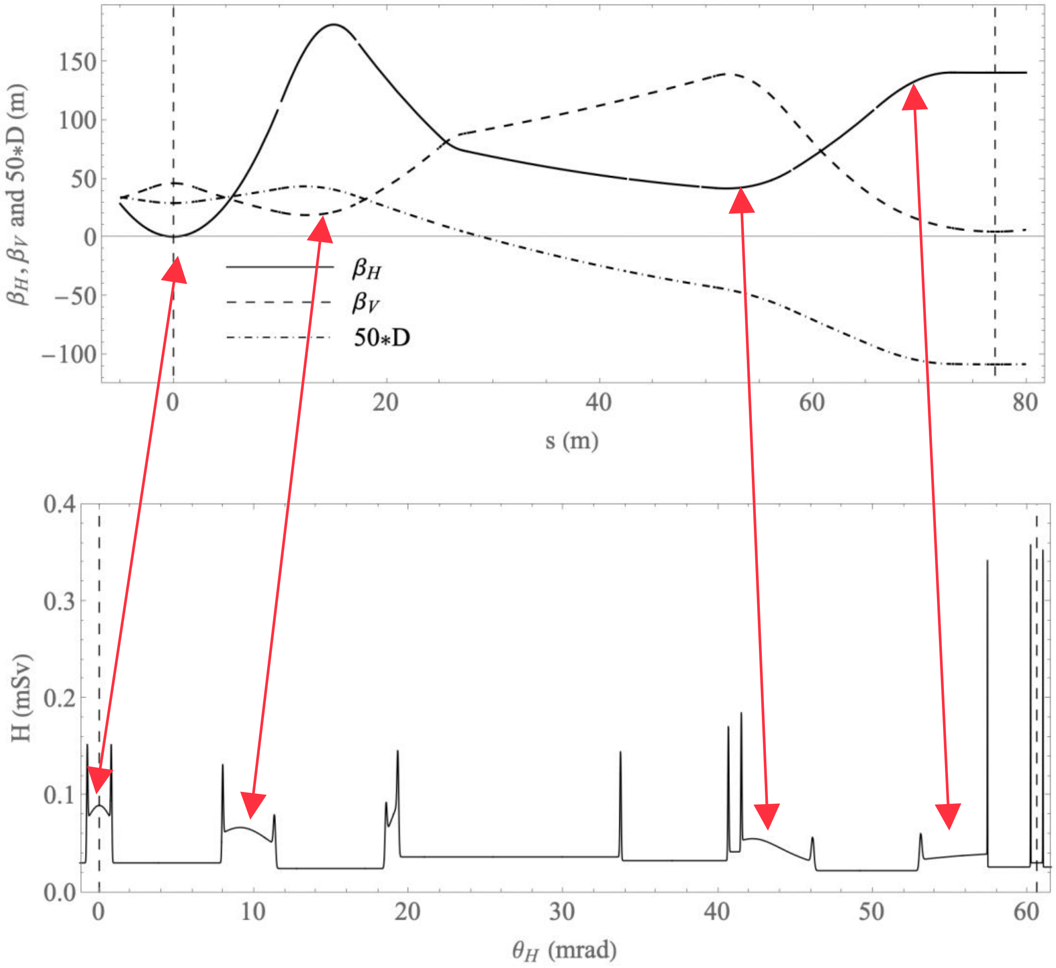
$$\sigma_{\vartheta_V}^2 = \frac{1}{6\gamma^2} + \varepsilon_{ph}\gamma_V(s)$$

with γ_H and γ_V the Twiss γ function in the horizontal and vertical plane and $D'(s)$ the derivative of the dispersion

Neutrino Radiation Issue

- Integrals evaluated for present (work in progress by K. Skoufaris) 10 TeV collider arc half cell
  - In collider mid-plane as function of J_H (i.e., $J_V = 0$) for one year (5000 h operation)

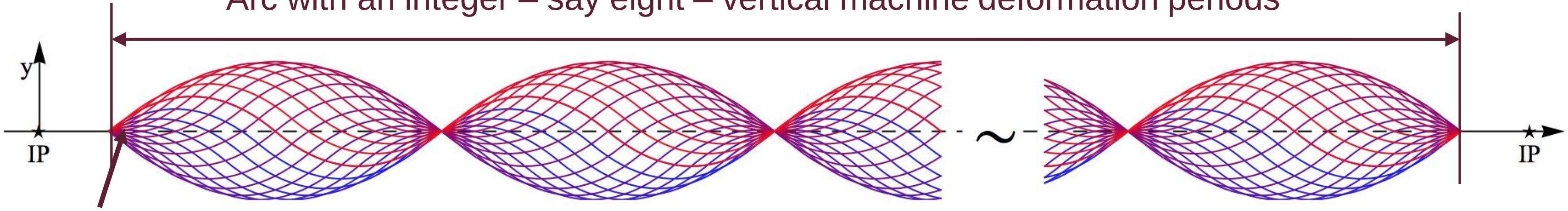
Peaks from 30 cm straight sections
=> Some lower due to beam
divergence (D’ or betatron motion)
Longer regions with higher radiation
from quadrupoles and X-poles
=> Lower dipolar magnetic field



Neutrino Radiation Issue

Mitigation by “Wobbling”

- Wobbling of machine in vertical direction – part of MAP proposal
  - High precision movement system for time-dependent mechanical deformation of ring around arc (including chromatic compensation, matching section and FMC arc cells
  - Vertical slope modulation within $\pm 1\ \mathrm{mrad}$ reduce peak dose by factor ~100
- For 10 TeV com collider with 10 km circumference and say 3.6 km arcs



Arc with an integer – say eight – vertical machine deformation periods

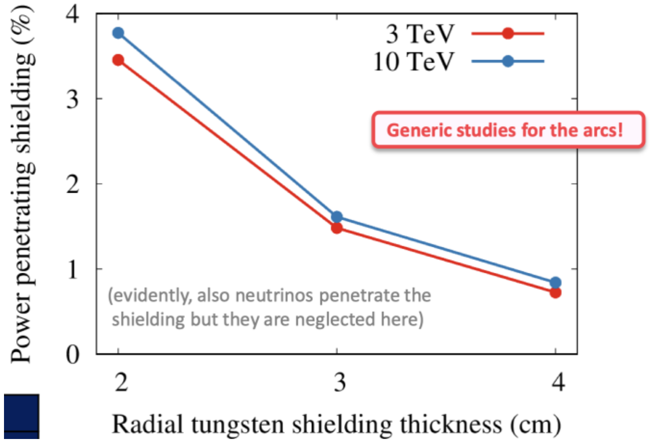
Vertical bend ±16.7 Tm

  - Combination of pieces of parabola – two pieces with opposite curvature one period
- Initial proposal
  - Say 8 periods ~600 m long periods leading to vertical position excursions ±150 mm
  - Horizontal magnetic field (average) of ±0.11 T needed for vertical deflections (in addition and independent from main bending and multipolar fields!!)
- Proposal for reduced vertical position excursions
  - More periods about 100 m long leading to vertical position excursions ±25 mm
  - Horizontal magnetic field (average) of ±0.67 T needed for vertical deflections

Muon Decay causing radiation and heat load

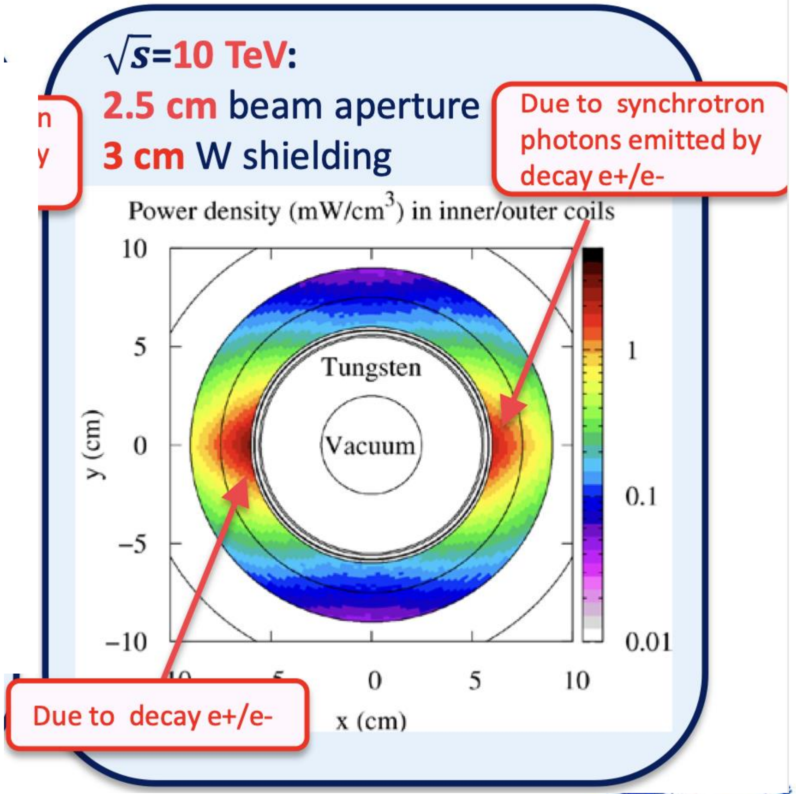
- Almost all (assuming no dumping of “residual intensity”) injected muons decay
- Electrons and positron generate shower
  - W absorber to intercept most of shower (~500 W/m with nominal C and average field)

Study by G. Lerner, A. Lechner, D. Calziolari



Generic studies for the arcs!

(evidently, also neutrinos penetrate the shielding but they are neglected here)



$\sqrt{s}$=10 TeV:

2.5 cm beam aperture

3 cm W shielding

Due to synchrotron photons emitted by decay e+/e-

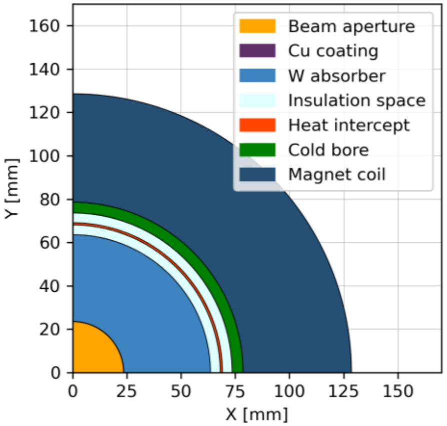
Due to decay e+/e-

  - Residual power ”leaking” into cold mass
    - □ Cryo load, radiation damage etc. “under control” with 30 mm to 40 mm
  - Thickness 40 mm assumed in recent discussion Impact of muons lost on apertures?
  - May localized (at acceptance limitation) losses generate significant additional cryogenic load?

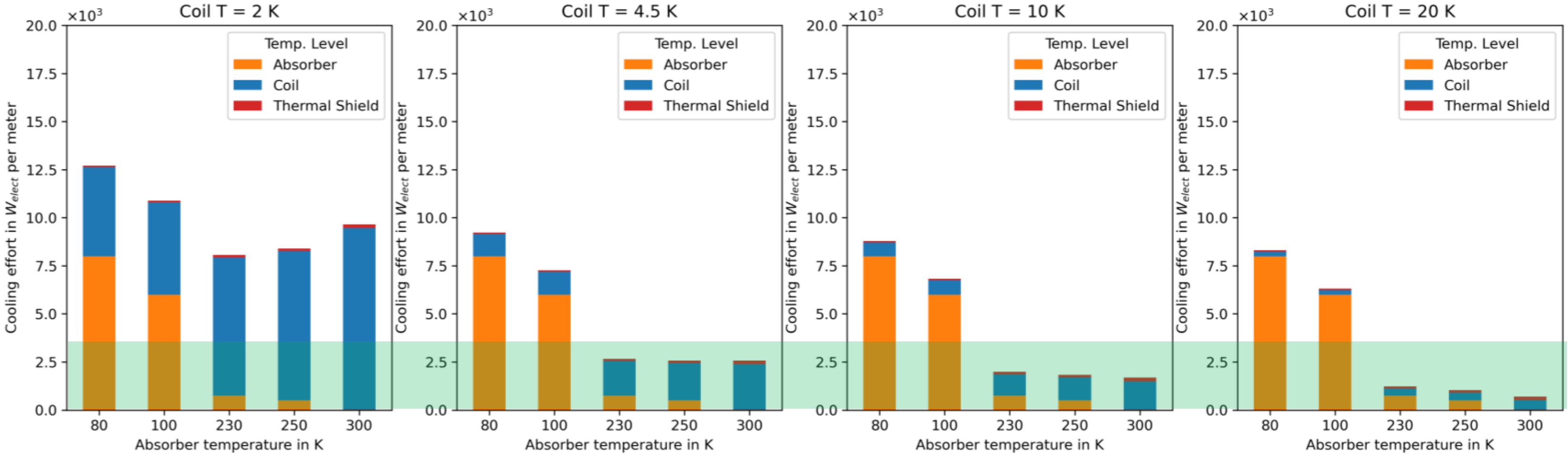
Conclusion of Cryogenic System Study

Study by P. Borges de Sousa,
M. Rhandi, T. Koettig, R. van Weelderen

- Baseline 40 mm W absorber and nominal parameters
- Warm W absorber (otherwise excessive power for refrigerator)
- Thermal shield at ~80 K between absorber and cold bore (otherwise excessive heat load by thermal radiation to cold bore)
- Heat loads to cold mass due to beam and conduction through supports similar
- Cold mass at 2 K leads to excessive power for refrigerator
  => Choice of cold mass temperature and conductor(s) to be discussed



Cooling effort at refrigerator I/F, w/o distribution, vs. absorber T, absorber thickness = 0.04 m, th. shield = 80 K, w/ thermal intercept between absorber and coil at T = 80 K



- Many more details (cooling fluid options, 30 mm absorber …) studied and in presentation by Patricia

Considerations on main collider parameters
Any option to reduce challenge and improve?

- Lower magnetic fields
  - Immediate impact on luminosity
    - Larger circumference, reduced beam induced heat load normalized to length
    - Even more difficult to design optics (β^* and chromatic correction ..)
- Change of time structure
  - Lower repetition rate and larger intensity (unchanged beam power)
    - Limitation all along the chain (drive beam, cooling, acceleration, beam-beam ..)
    - (ruling out larger emittances – would not result in luminosity increase)
- Apertures
  - Limited margin to reduce aperture in FF (less than 5 rms beam sizes for beam?)
  - May-be beam size reduction in CC and matching sections (larger than in arc, for which discussions concentrated so far)?
  - Little margin to reduce aperture in arc dominated by W absorber
- Smaller emittances
  - Present emittances a challenge for cooling – no blow-up along accelerator chain
  - Beam-beam effect to be watched with smaller transverse emittances
  - Smaller longitudinal emittances would help if used to reduce momentum spread
- Asymmetric colliding beams
  - Natural to have round beams with equal emittances in both planes

Summary

- Collider design challenging
  - Optics for small β^* with large beam rigidity and momentum spread - chromatic effects
  - Energy deposition and radiation from muon decay products
  - Radiation due to neutrinos reaching Earth's surface
    - ☐ "Wobbling" scheme – challenging mechanical system, impact optics design
  - Beam induced background to experiment
- Some impact on hardware
  - High field, large aperture magnets, most of the them combined function (e.g., horizontal bending, quadrupolar component and small vertical bending for "wobbling")
    - ☐ Stringent field quality requirements for some magnets conflicting with feasibility
    - ☐ Short straight sections between magnets – Feasible field versus position profiles?
  - Tunsten absorber inside magnet aperture
  - Cryogenic system has to and can cope with heat load
    - ☐ Conclusion to be drawn from study (cold mass temperature, which superconductor, cooling fluid)?
  - Precise (how?) mechanical magnet movement system for wobbling .. feasibiliy?
- Little margin to change parameters keeping nominal luminosity
  - E.g., reduction of magnetic field immediately impacts luminosity
  - Finalize collider lattice design for present nominal parameters and discuss feasibility and required changes