Muon Collider – Parameter Consideration

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Parameter Optimisation

- “Top down” optimisation of the low energy complex
  - Look at performance of the muon collider as a function of “low energy complex” parameters
  - Proton beam parameters
  - Target capability
  - Muon cooling system performance
- For this **first pass**, take luminosity as the figure of merit
  - To avoid controversy, I have taken arbitrary normalisation factor
  - Nb: **first pass** – model improvements are welcome (and needed)
- Other FoMs may be important
  - Energy spread at the detector
  - Capital & operating costs
  - Environmental considerations
- Developing better model for muon collider performance
  - Take this all with a “pinch of salt”

Facility Model

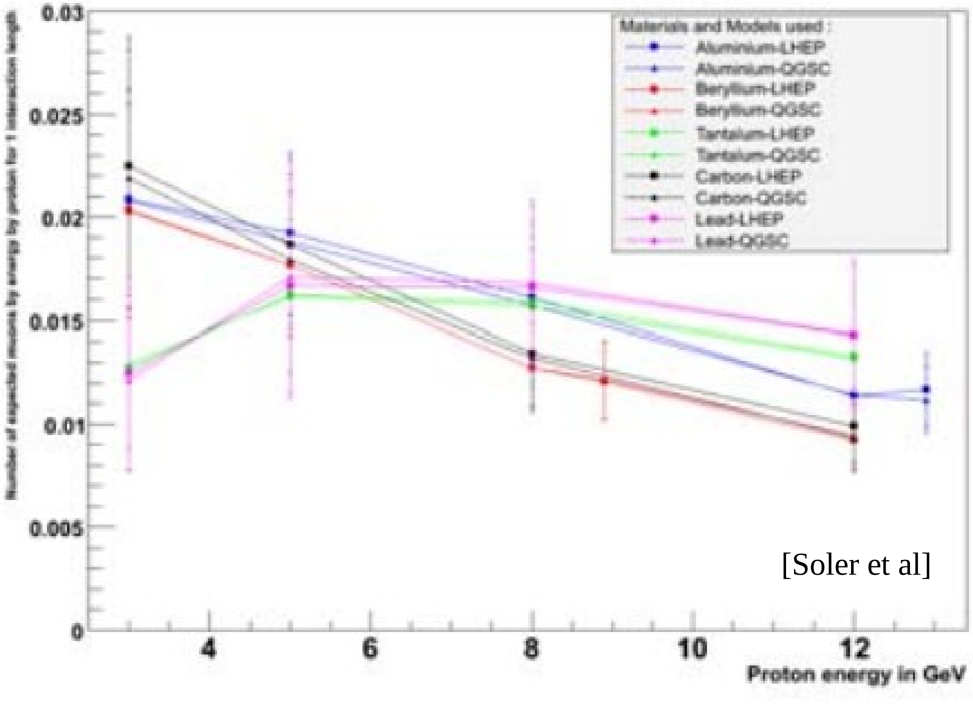
- Facility model is naive python script
  - Assume some proton beam power and rep rate (i.e. charge per proton pulse)
  - Use Soler et al to get proton → muon production yield
    - Normalised to HARP data
    - Other calculations exist, similar to O(factor 2)
  - Cooling performance from papers by Stratakis & Sayed
    - With some bespoke hacking which I will describe
- High energy complex
  - Assume acceleration average 4 MV/m over the whole complex
    - Gives muon survival
  - Assume negligible emittance growth
  - Assume 10 km circumference collider ring (at 5 TeV)
  - Assume β* is 1.5 mm constant
    - Really this depends on longitudinal and transverse emittance

Facility Model (2)

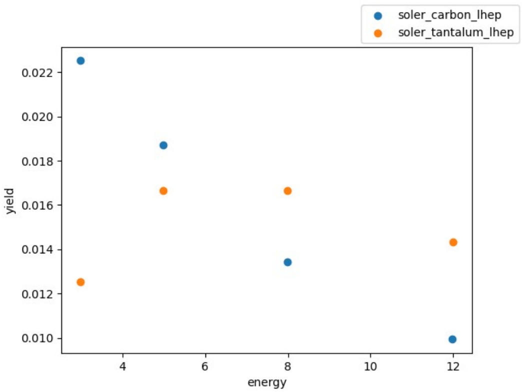
- Relevant proton baseline parameters:
  - Proton energy 5 GeV
  - Beam power 2.0 MW
  - Rep Rate 5 Hz
  - Proton bunch length 2 ns
- Luminosity $L = N_1 N_2 / 4\pi\sigma_x^2$

Proton energy (1)

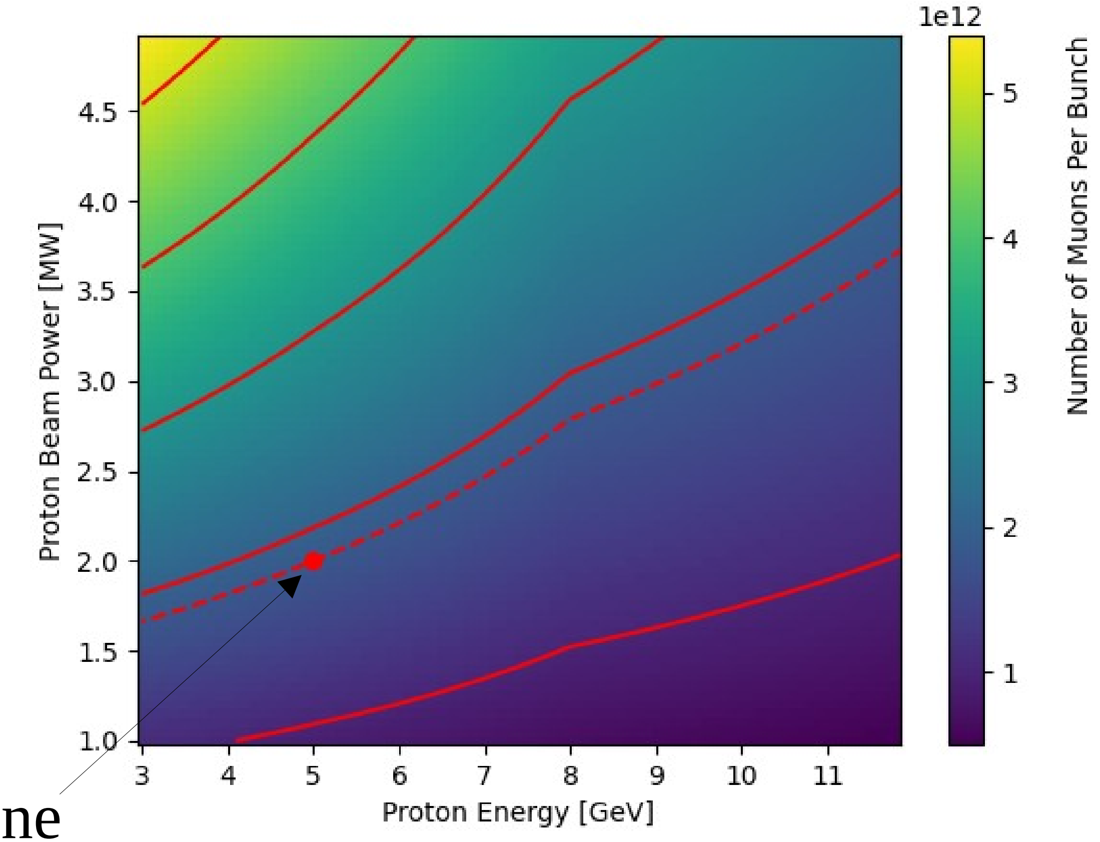
- How sensitive is Muon collider to proton energy?
  - Use data from Soler et al to get muon → proton conversion rate vs energy
  - Normalised i.e. number of muons/proton/GeV
- Note: no data for mu+ vs mu- and carbon and solenoid



[Soler et al]



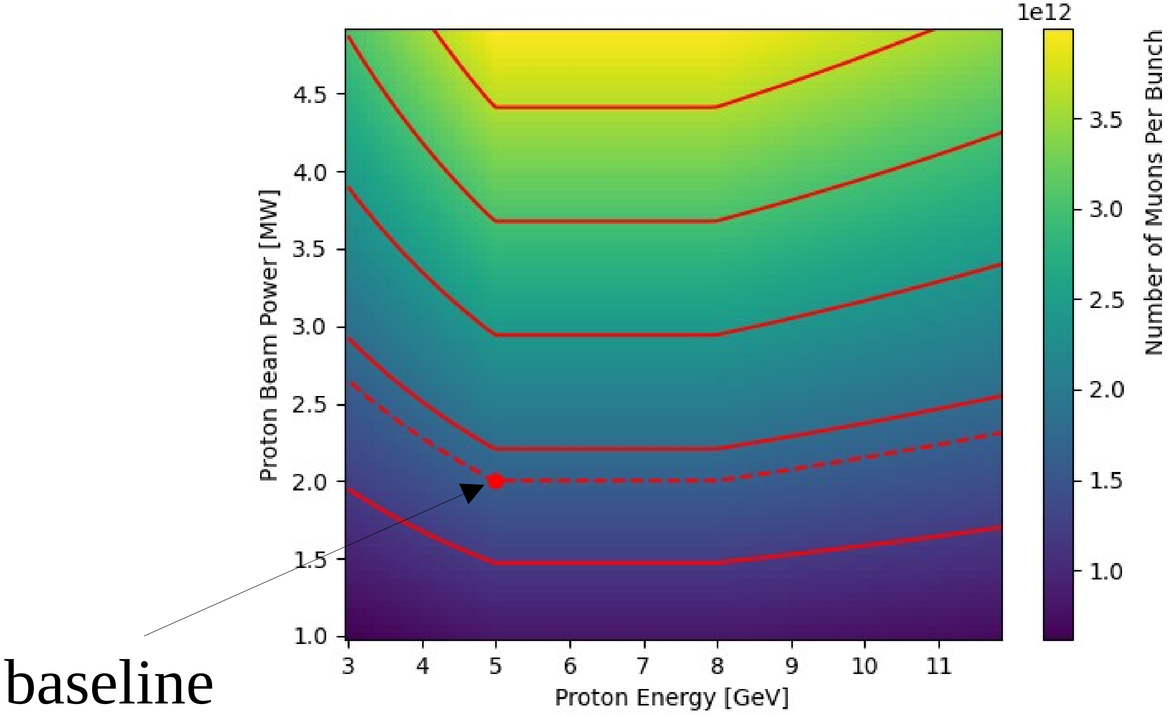
Proton energy - carbon



baseline

- How sensitive is Muon collider to proton energy?
  - Red curves are contours
  - Assumes carbon target

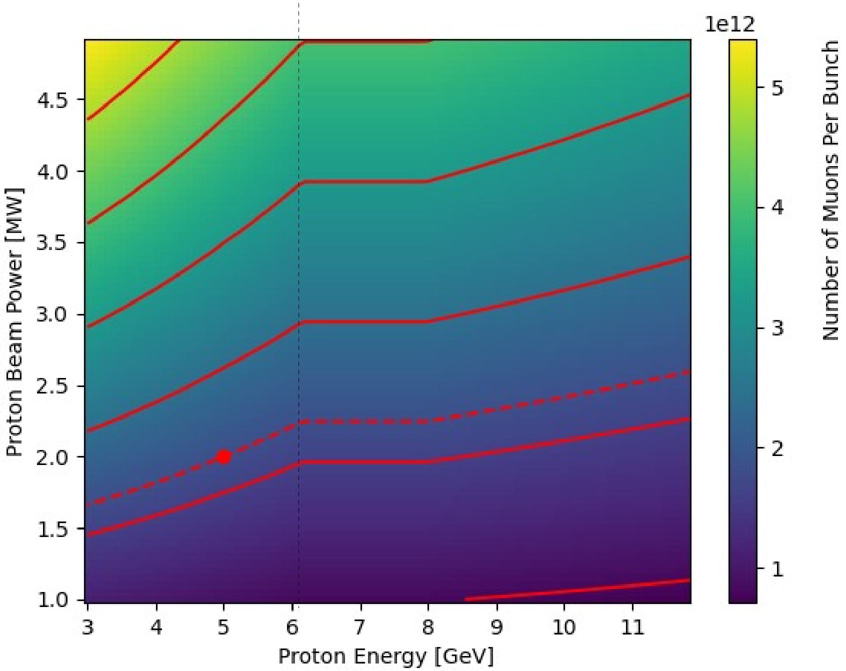
Proton energy - tantalum

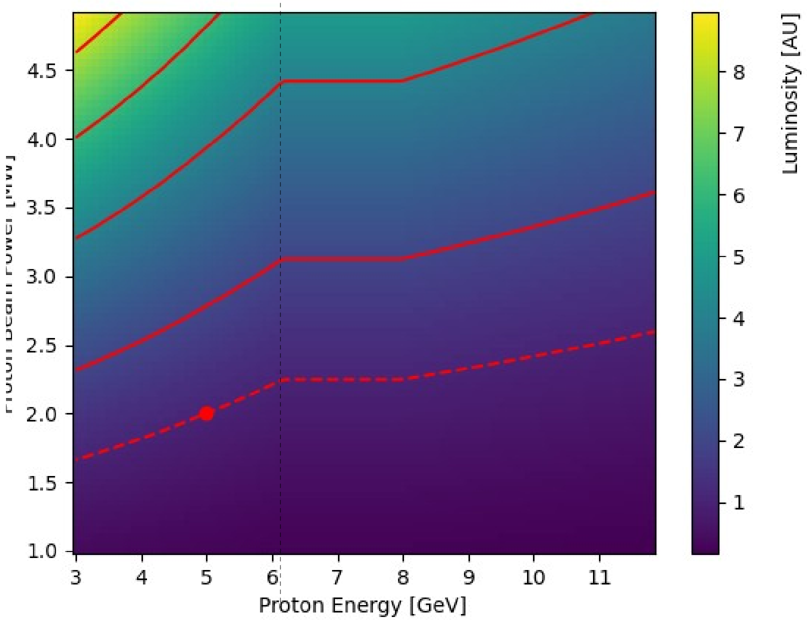


- How sensitive is Muon collider to proton energy?
  - Red curves are contours
  - Assumes tantalum target

Proton energy best

- Consider “luminosity”

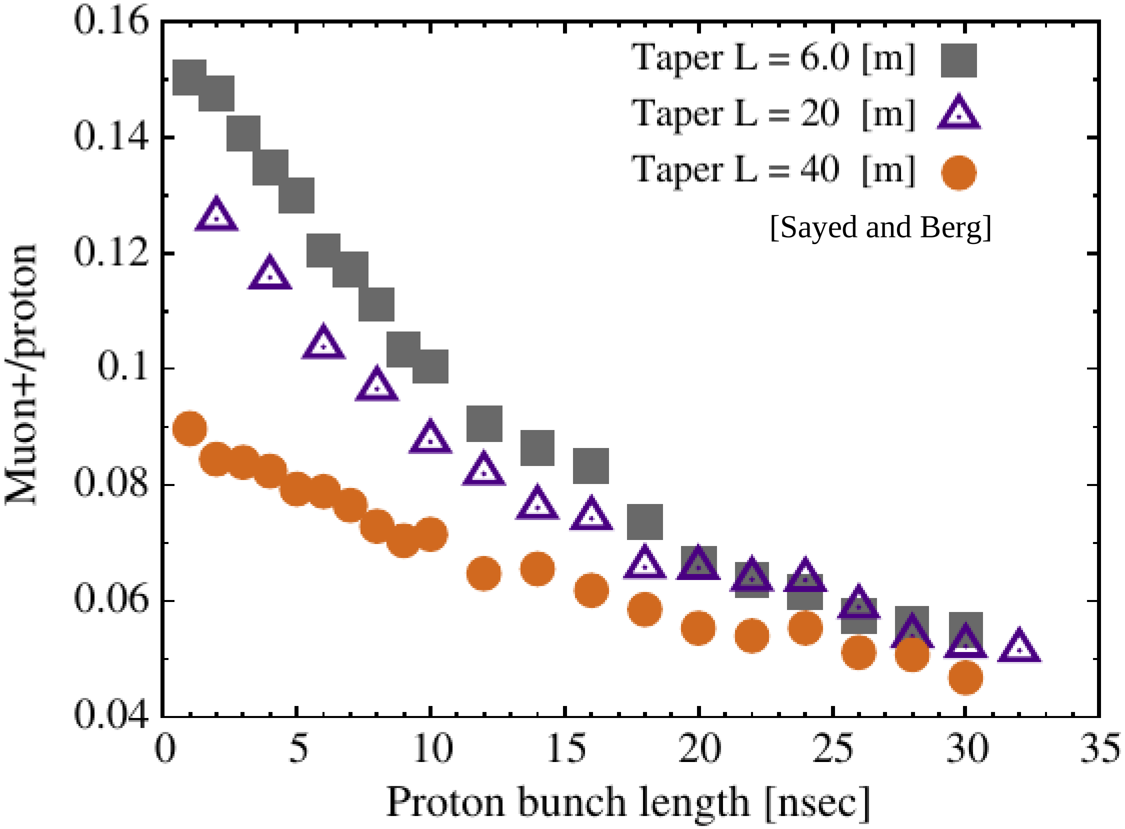


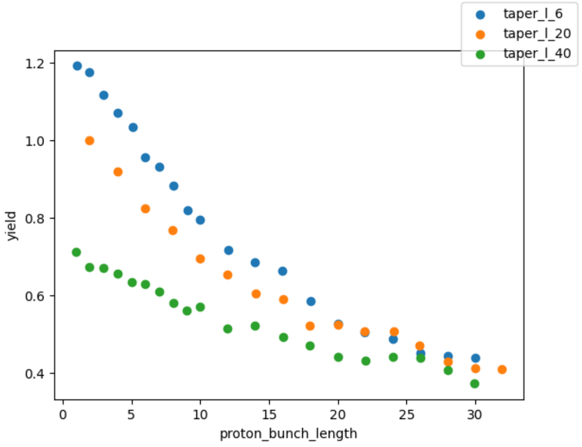


- How sensitive is Muon collider to proton energy?
  - Assumes carbon at low energy
  - Assumes heavy metal target at high energy
  - Red curves are contours

Proton bunch length (1)

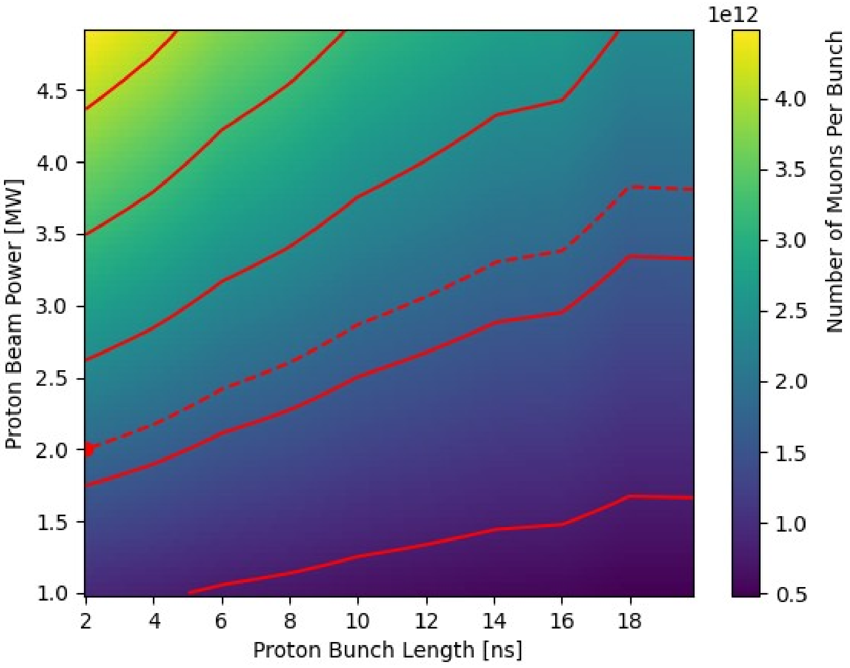
- Consider proton bunch length
  - Sayed and Berg looked at yield for different magnetic tapers and proton bunch length
  - MAP baseline ~ taper length = 20 metres
  - How does the proton bunch length affect yield?

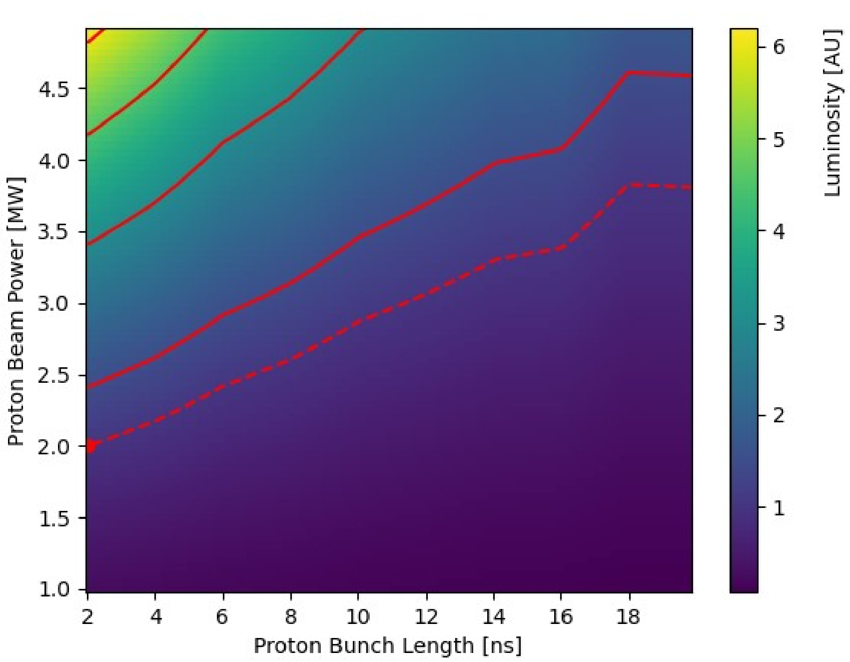




Proton bunch length (2)

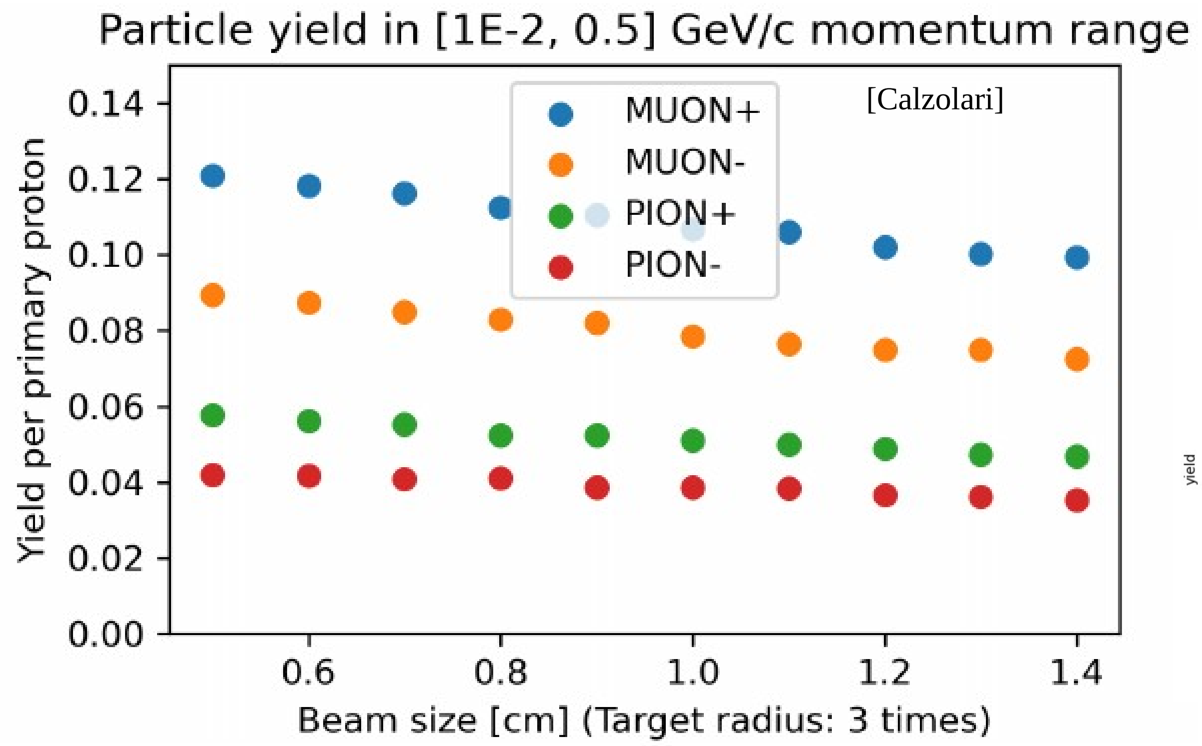
- Muon yield is soft function of proton bunch length
    - Shorter bunch may be harder to achieve than slight uplift in muon beam power

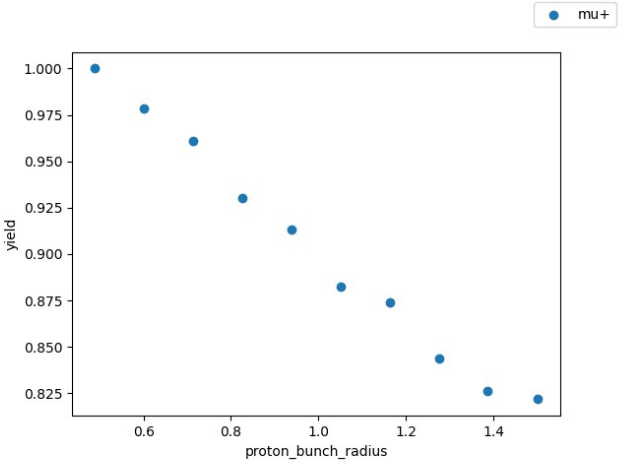




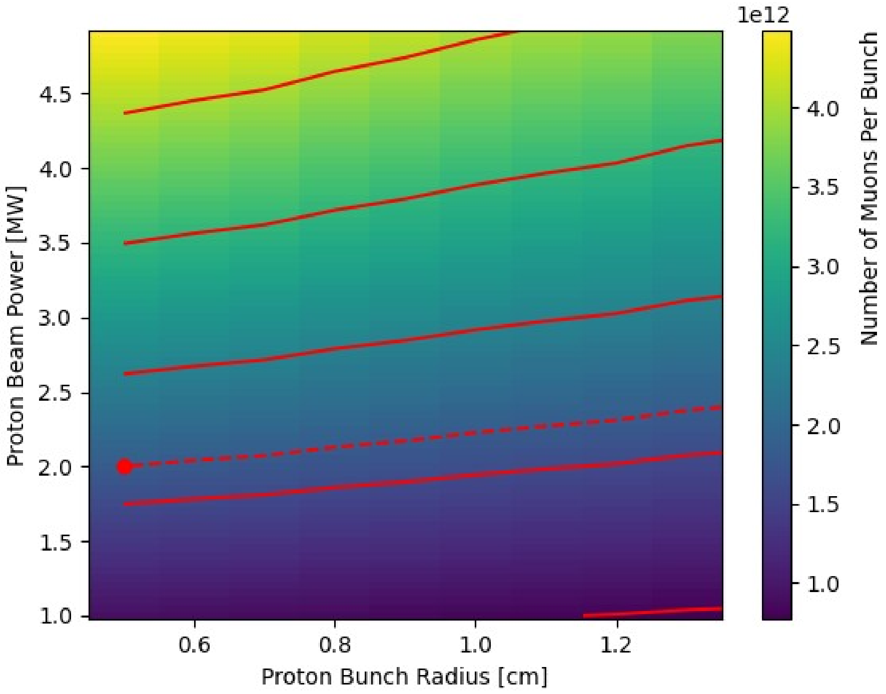
Proton bunch radius (1)

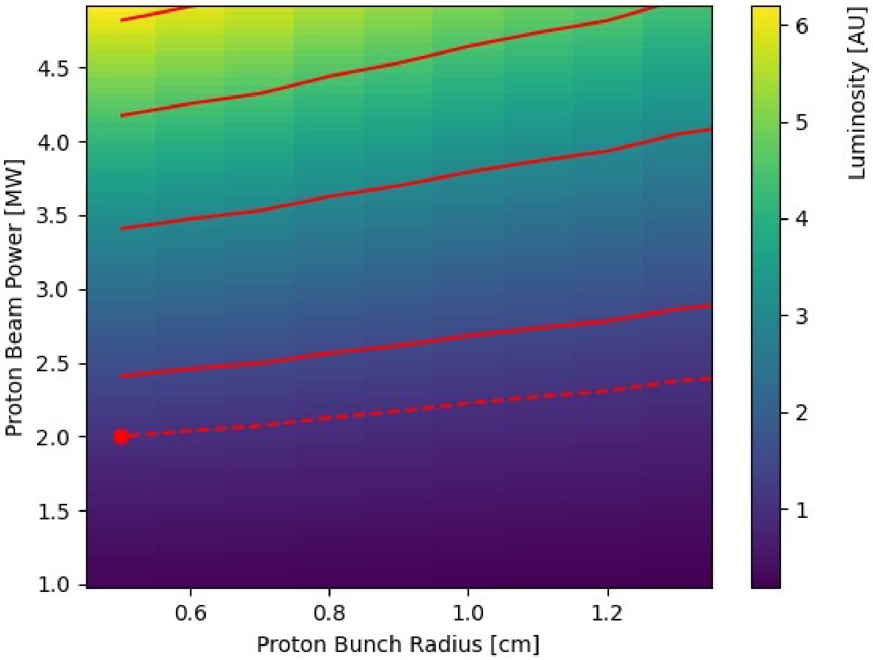
- Consider proton bunch radius
  - Calzolari looked at yield for different bunch radius RMS
  - Baseline ~ 5 mm
  - Target = 3*bunch radius





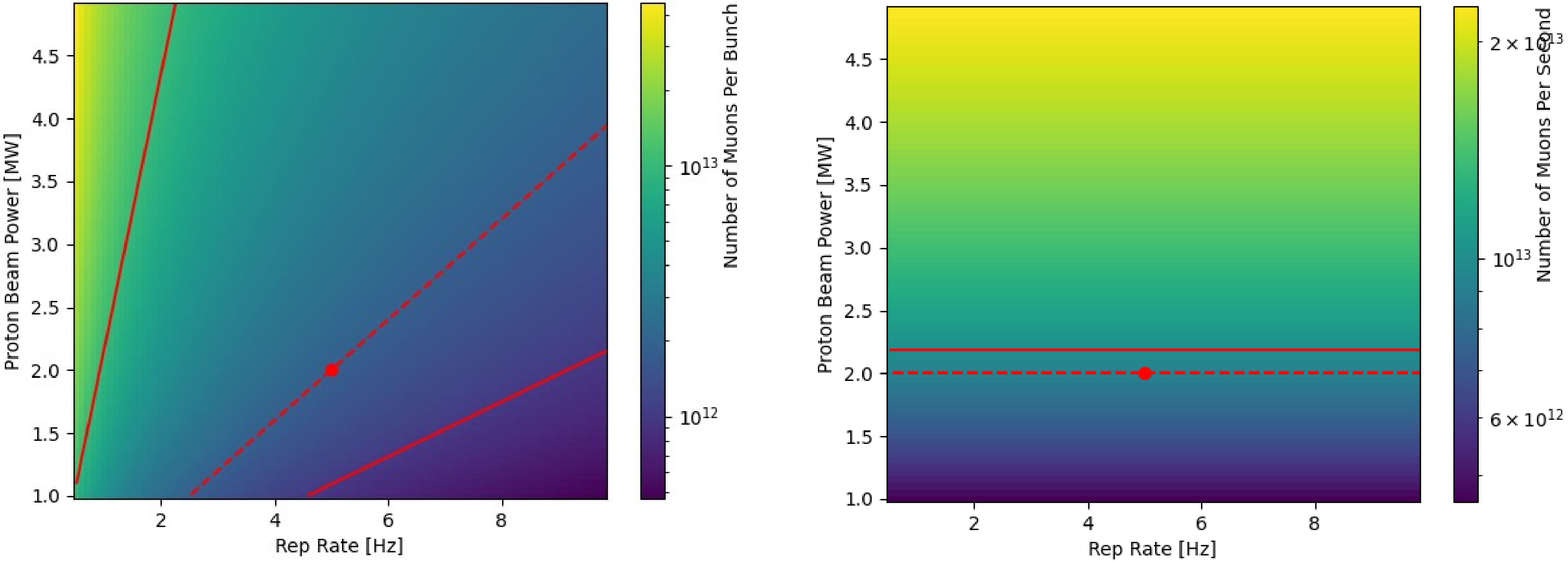
Bunch radius vs performance





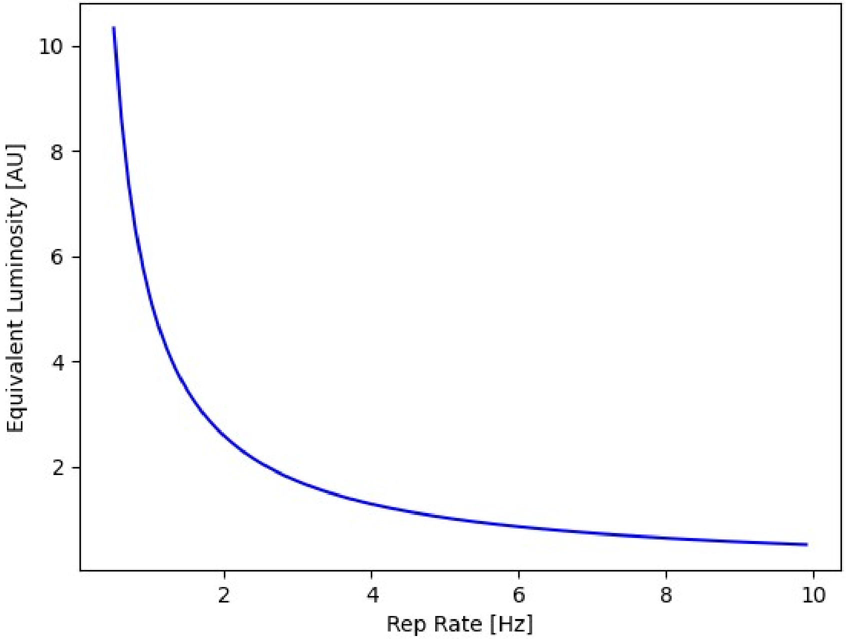
- Small increase in bunch radius → slight degradation in performance
  - Note that bunch structure is more complicated
  - Emittance, beta at the target, etc needs to be considered

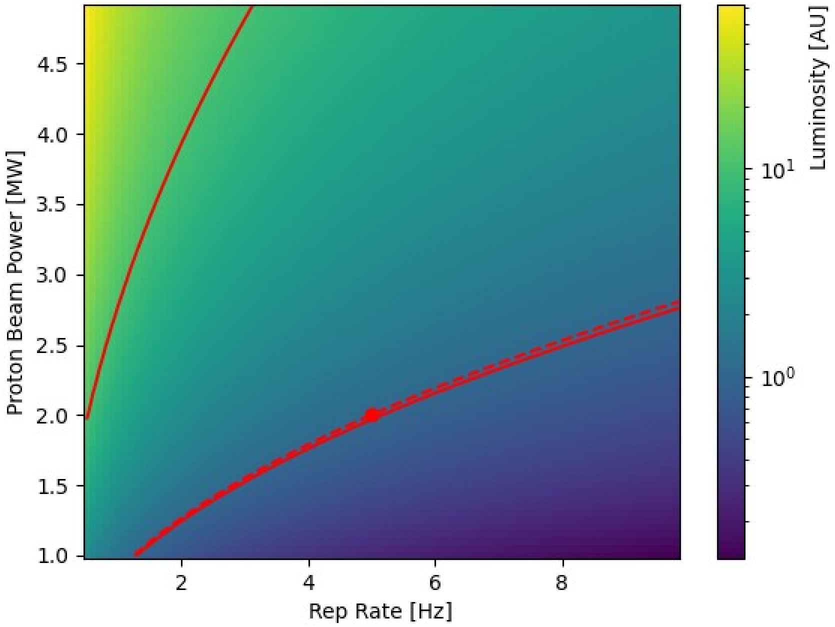
Rep rate vs number of muons



- Reducing the rep rate while holding power constant
  - Number of muons per second is unchanged
  - Number of muons per bunch increases
  - Increased luminosity
  - **Increased collective effects**

Rep rate vs number of muons





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  - Number of muons per second is unchanged
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Cooling Performance

- Use Stratakis paper for rectilinear performance
- Use Fol study for final cooling performance
  - Achieves ~ 25 micron final emittance
  - Not quite closed on a robust baseline

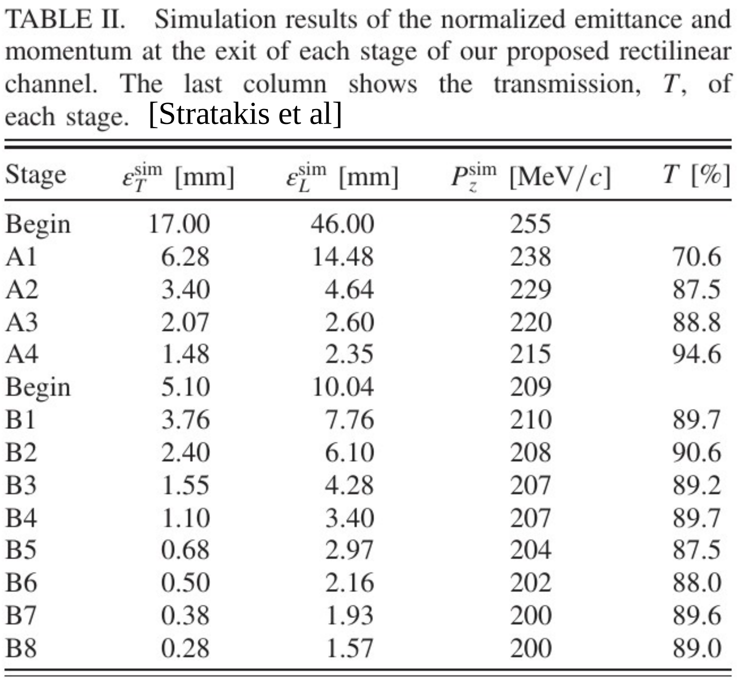
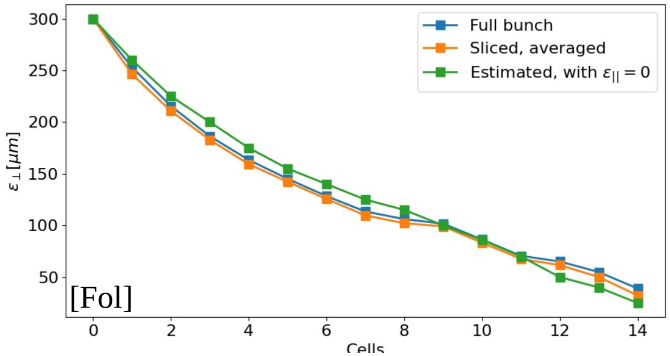
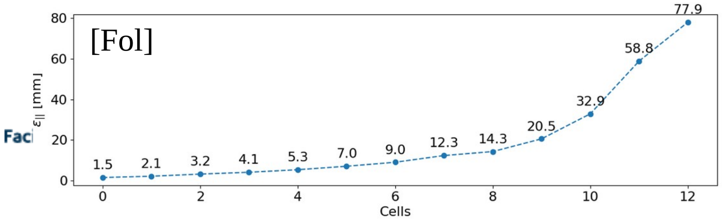


TABLE II. Simulation results of the normalized emittance and momentum at the exit of each stage of our proposed rectilinear channel. The last column shows the transmission, T, of each stage. [Stratakis et al]

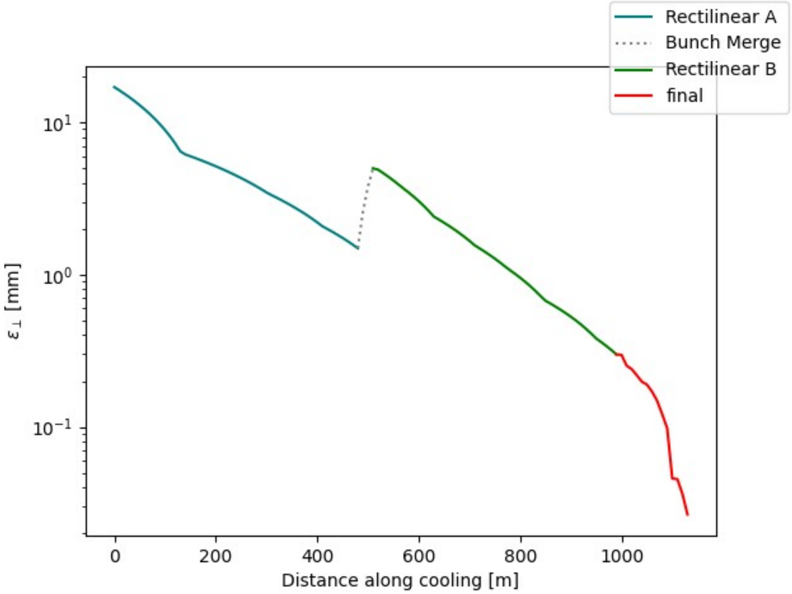
Stage	$\varepsilon_T^{\mathrm{sim}}$ [mm]	$\varepsilon_L^{\mathrm{sim}}$ [mm]	P_z^{sim} [MeV/c]	T [%]
Begin	17.00	46.00	255	
A1	6.28	14.48	238	70.6
A2	3.40	4.64	229	87.5
A3	2.07	2.60	220	88.8
A4	1.48	2.35	215	94.6
Begin	5.10	10.04	209	
B1	3.76	7.76	210	89.7
B2	2.40	6.10	208	90.6
B3	1.55	4.28	207	89.2
B4	1.10	3.40	207	89.7
B5	0.68	2.97	204	87.5
B6	0.50	2.16	202	88.0
B7	0.38	1.93	200	89.6
B8	0.28	1.57	200	89.0

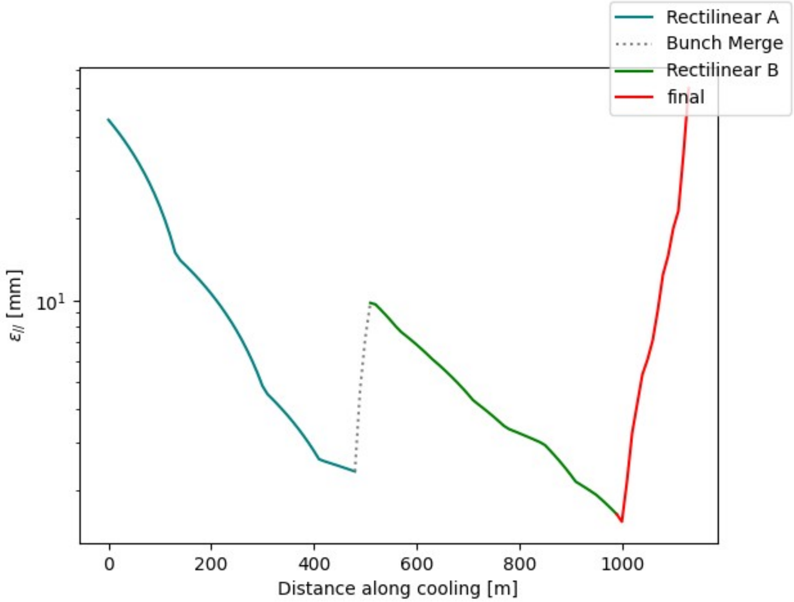




Cooling Emittance

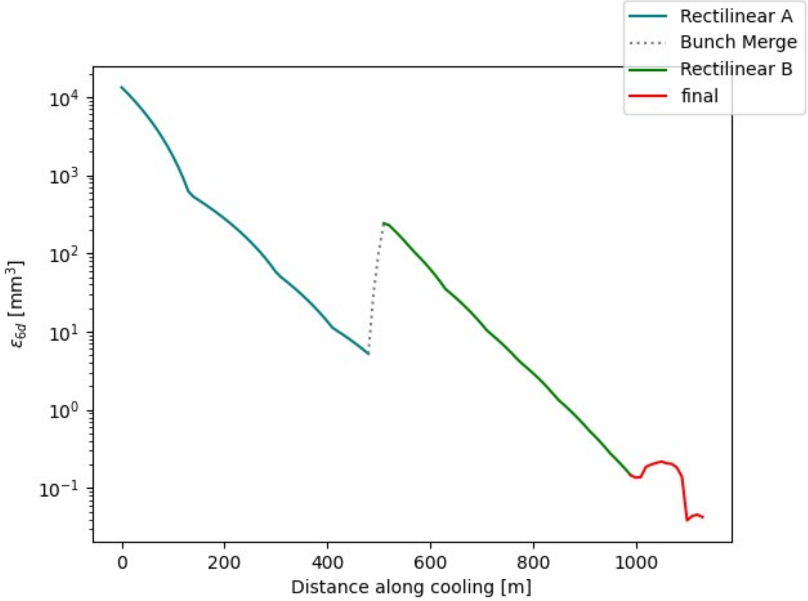
- How does emittance vary along the cooling system?
  - Note – assume each “final cooling” cell is 10 m long
- No correct model for charge separation and bunch merge

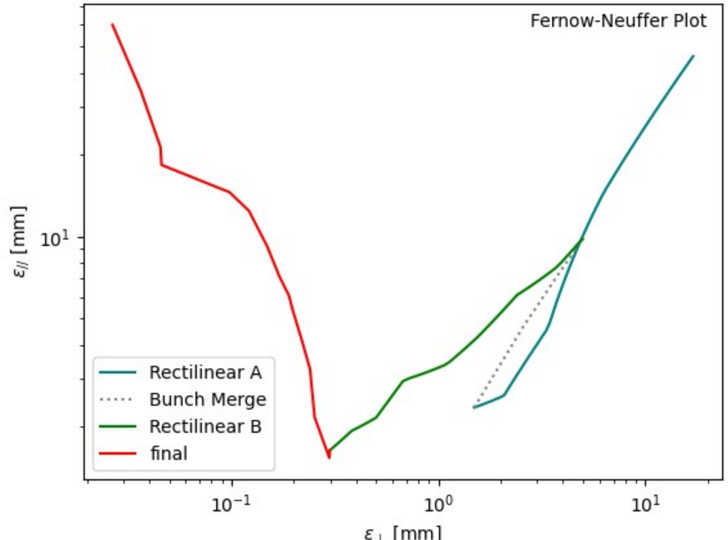




Emittance in Cooling Section

- Significant reduction in 6D emittance
- Longitudinal emittance balances transverse emittance for a lot of final cooling
  - Optimisation continues
- Bunch merge → assume 100 % transmission
  - Needs checking





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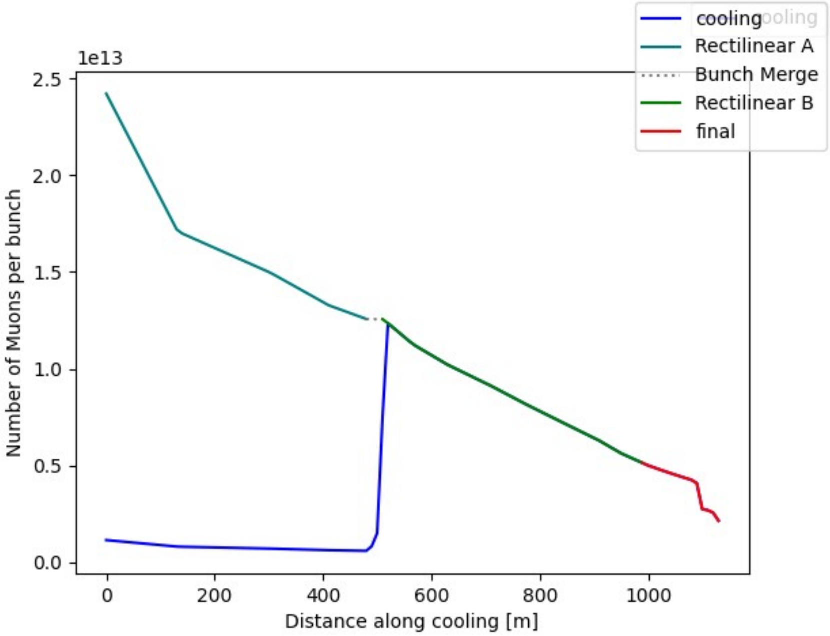

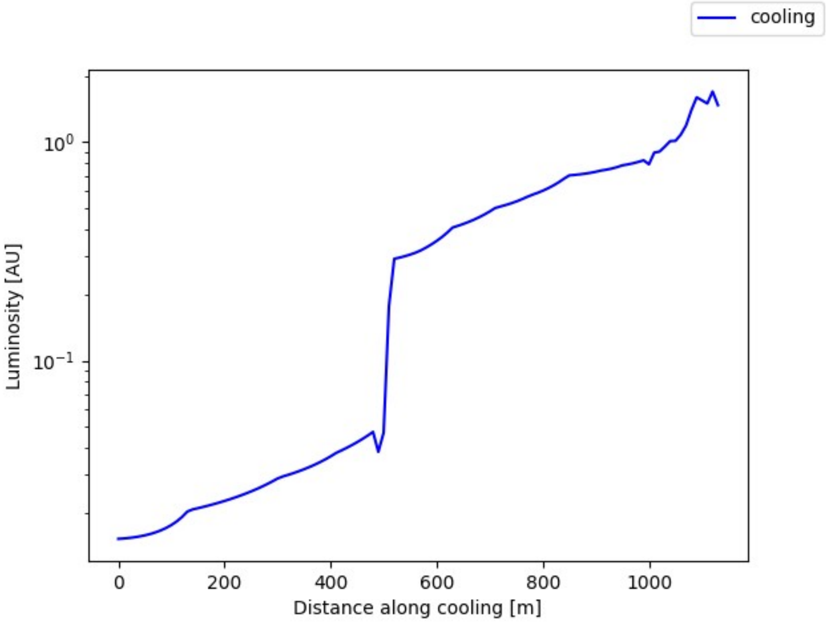

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Conclusions

- Design choices for low energy complex are flexible
- Some areas for trade-offs
  - Can trade proton beam power against other design aspects
    - Add in target radius
  - Can lower rep rate to quickly improve luminosity
    - Where are the intensity/collective effects limits in the facility?
  - Shouldn't get hung up on a particular baseline necessarily
- Some areas for improvement
  - More data on Carbon target yield
  - Bunch merge needs understanding/checking
  - Simulated final cooling performance is improving rapidly
- Knowledge of intensity limits important
  - Target power
  - Beam loading/space charge in cooling system
  - Beam loading in acceleration
  - Beam beam effects in collider
  - Other?