High Energy Muon Collider
Technology needs

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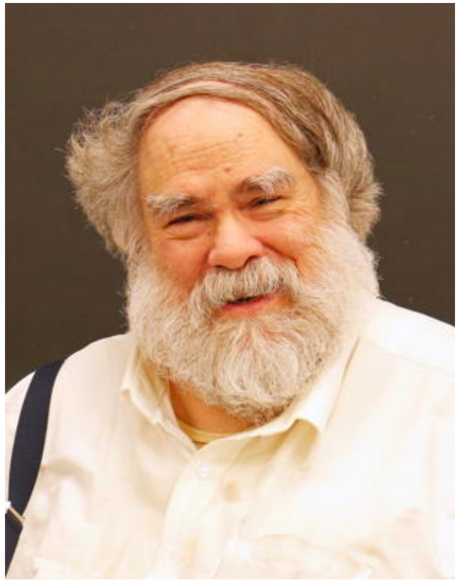
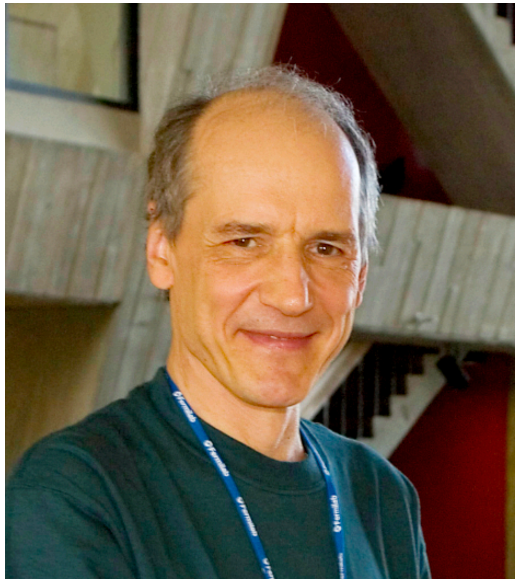
Fermilab

Great thank to Don, Yuri, Sergei, and Alvin

They inspired me good life and good science.



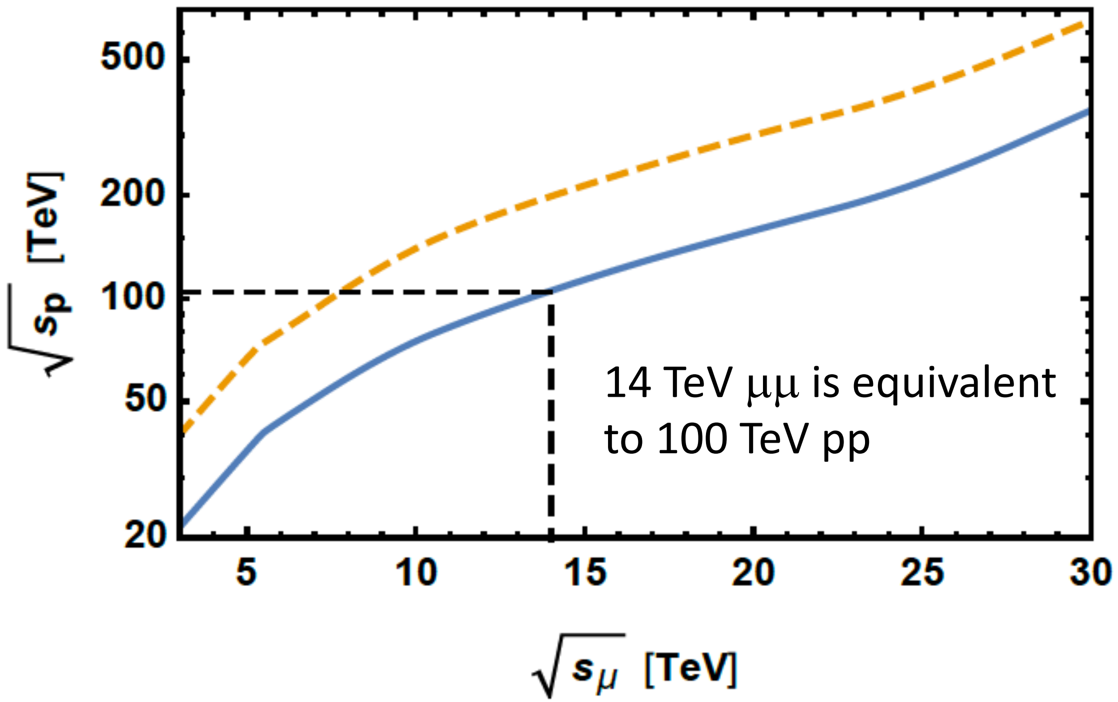


Outline

- Motivation of HEP muon colliders
- Collider table from MAP
- Final cooling channel (possible “game changer”)
  - 30-Tesla solenoid channel
  - Parametric resonance Ionization Cooling channel (introduce low emittance scheme)
- Beam component with low emittance scheme
- Extend COM and Luminosity for 10 TeV MC (Neuffer’s speculation)
- Summary

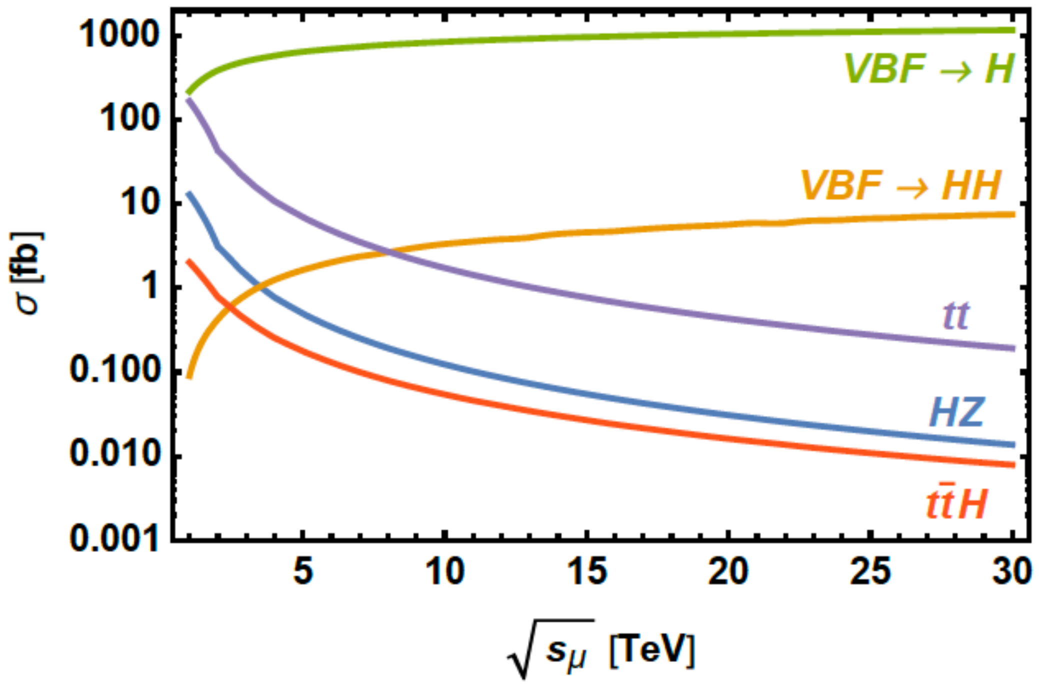
Physics in HEP muon collider[1]

Equivalent COM energy of μμ and pp



Cross section of various HEP events in μμ

VBF = Vector boson fusion



μμ is one of the best tools to study Beyond Standard Model

We've already seen violations of the SM in LHCb and g-2 experiments!

Scenarios from Muon Accelerator Program

Table 1: Main parameters of the proton driver muon facilities

Parameter	**Units**	**Higgs**	**Multi-TeV**		
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13'500	37'500	200'000	820'000
Circumference	km	0.3	2.5	4.5	6
No. of IP's		1	2	2	2
Repetition Rate	Hz	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1	0.5	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	μm-rad	200	25	25	25
Norm. Long. Emittance, ε_{LN}	μm-rad	1.5	70	70	70
Bunch Length, σ_{S}	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

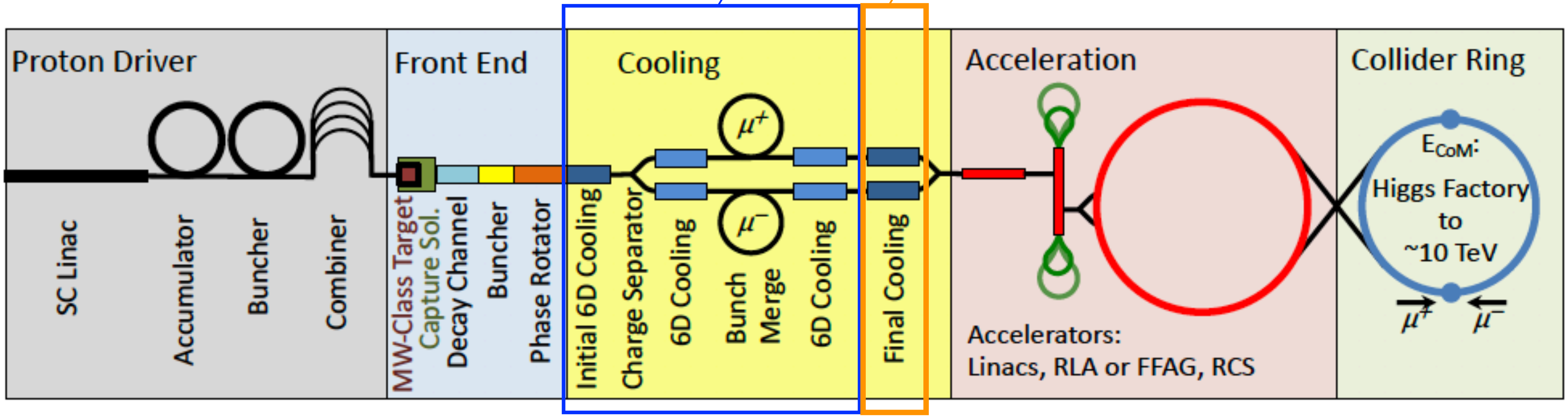
$$\mathcal{L} = \frac{f_{col} \cdot n_{\mu_+} \cdot n_{\mu_-} \cdot \beta \cdot \gamma}{4\pi\left(\varepsilon_{x,n} \cdot \beta_x^*\right)^{1/2} \cdot \left(\varepsilon_{y,n} \cdot \beta_y^*\right)^{1/2}}$$

Beam components are designed to realize COM energy and Luminosity

MAP baseline design

Decay process is involved in an efficiency calculation

Cooling
- Transmission efficiency of 6D cooling is **20 %**
- Transmission efficiency of Final cooling is **50 %**



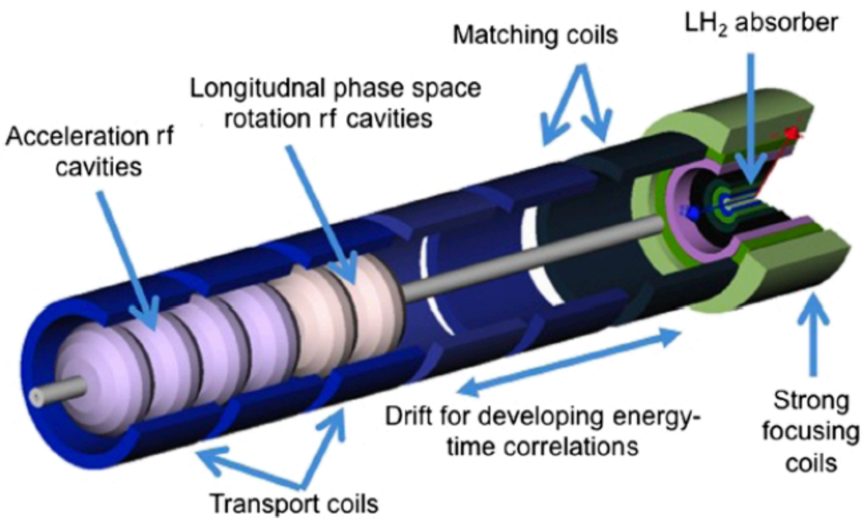
Proton driver
4 Mega-Watt 8 GeV protons
N_p = **3.13E15** protons on target

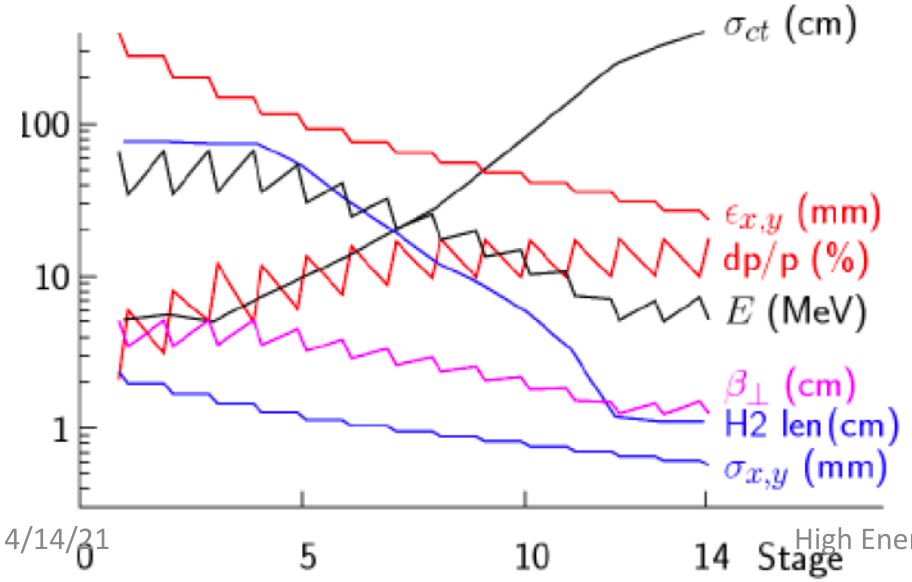
Front End
Proton to muon conversion efficiency is **10-15 %** for each sign

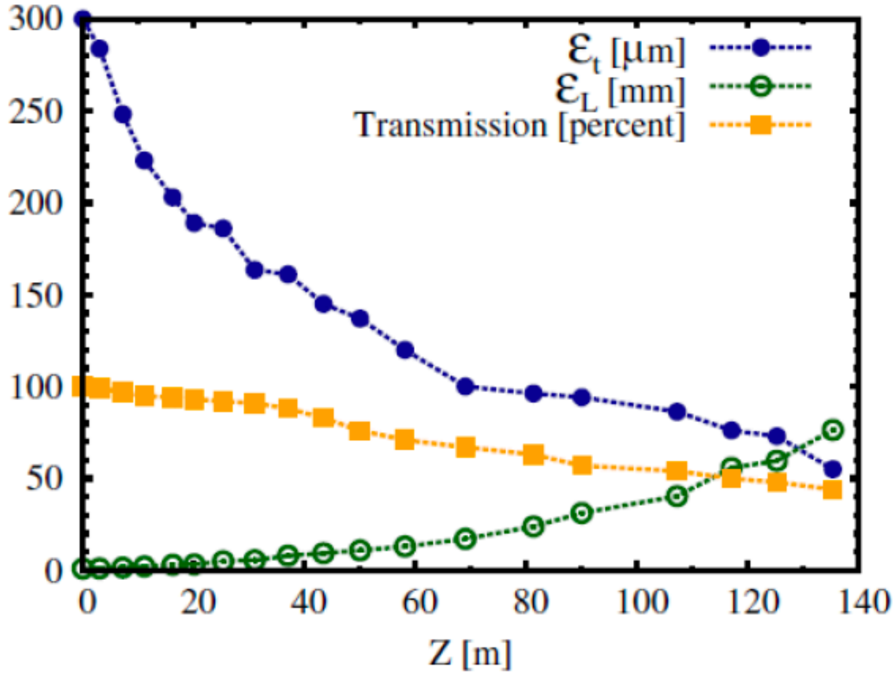
Acceleration & Collider Ring
Total transmission efficiency is **70-80 %**

In the next few slides, I will focus on the Final Cooling channel which is a key element to improve the quality of muon beam

Final Cooling Channel (MAP baseline design)[2]

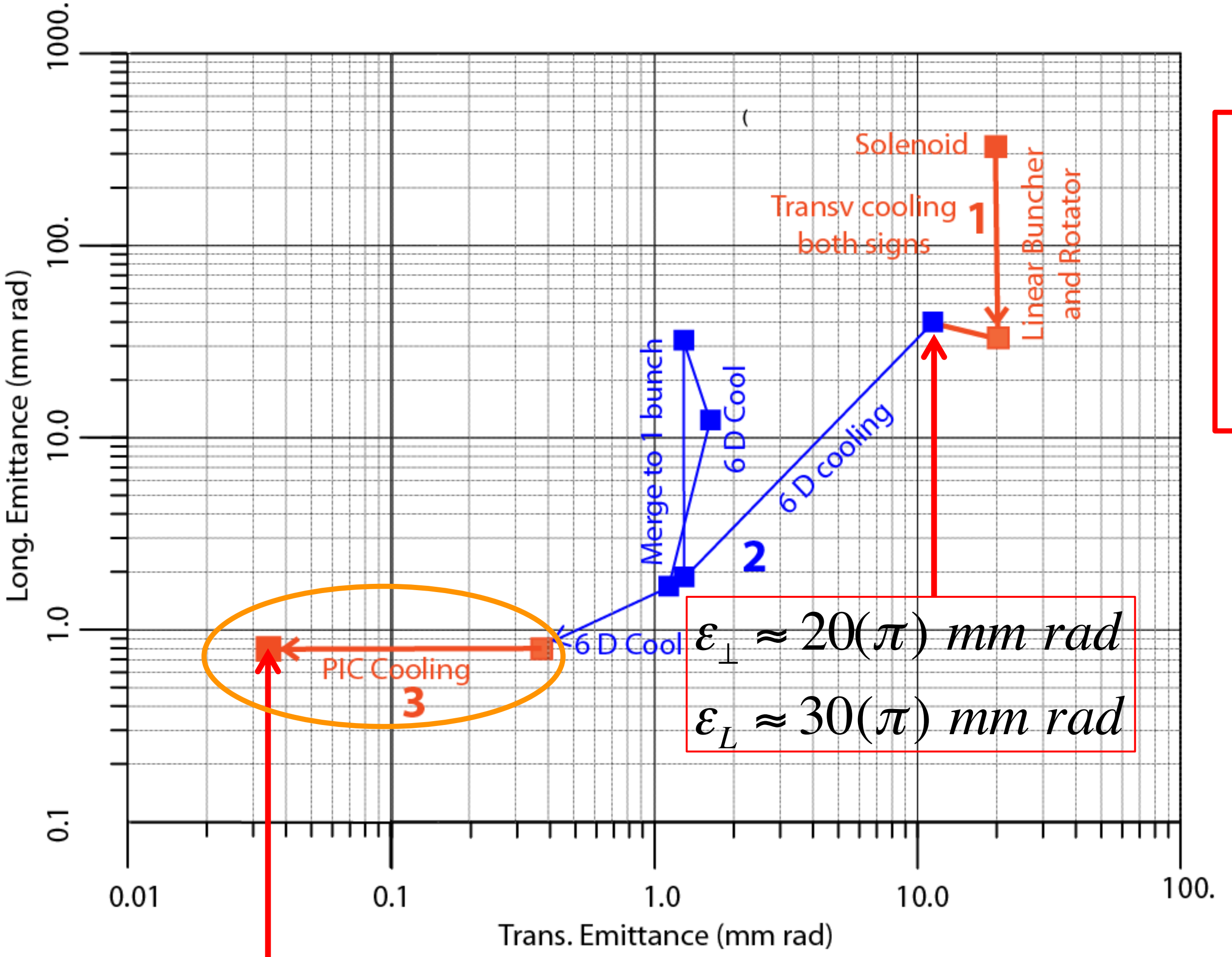






- 30-Tesla solenoid channel
- 14 segments (10 m-long each)
- Muons lose a kinetic energy to gain a low beta function
- Transverse emittance goes down while longitudinal one goes up (reverse emittance exchange)
- Transmission is 50 %

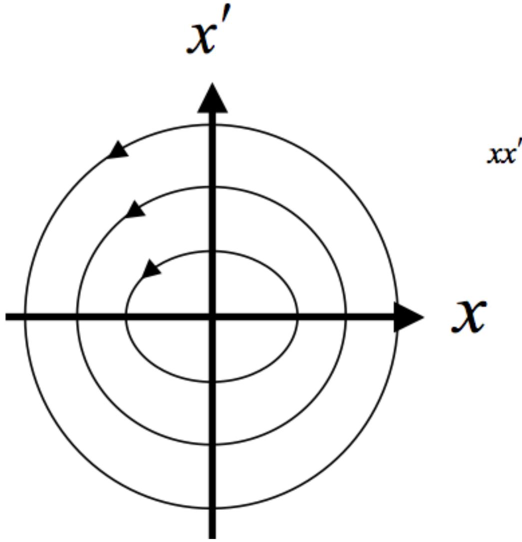
Introduce Parametric resonance Ionization Cooling channel[3]



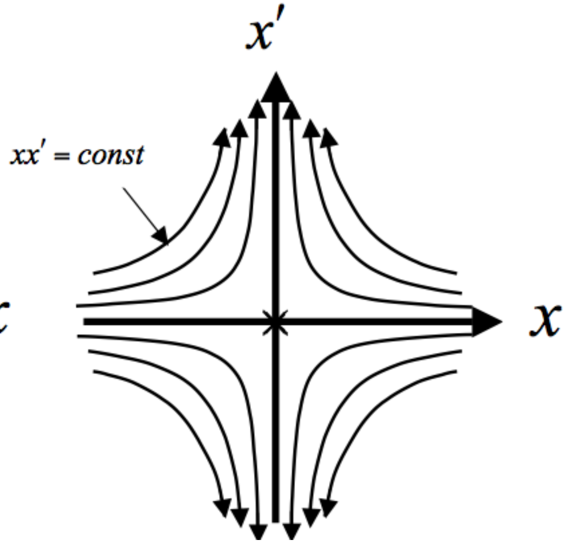
$\varepsilon_\perp = 0.04(\pi) mm\,rad \quad \varepsilon_L = 1.0(\pi)\ mm\ rad$

Shrink transverse emittance by factor 10 while maintaining longitudinal emittance in PIC

Concept of PIC[4]



Ordinally 2D phase space oscillation



Excited 2D phase space by a half-integer resonance

- Ionization cooling shrinks beam angular spread (x').
- Conventional ionization cooling channel generates a low beta function with ordinally phase space oscillation (top left picture). Thus, a very strong magnetic field is needed for a final cooling.

Equilibrium beam size $\sigma_a^2 = \frac{1}{8}\frac{(Z+1)}{\gamma\beta^2}\frac{m_e}{m_\mu}w^2,$

Equilibrium angular dist. $\theta_a^2 = \frac{3}{2}\frac{(Z+1)}{\gamma\beta^2}\frac{m_e}{m_\mu},$

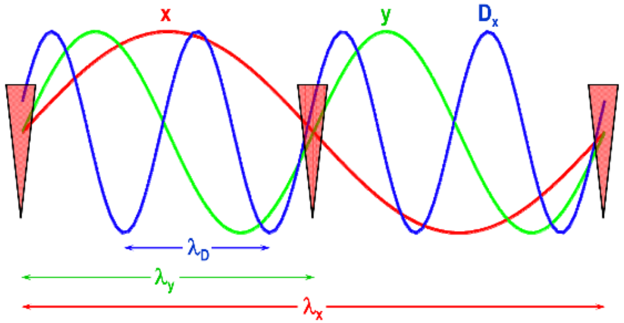
Equilibrium momentum sp. $\left(\frac{\Delta p}{p}\right)^2 = \frac{3}{8}\frac{(\gamma^2+1)}{\gamma\beta^2}\frac{m_e}{m_\mu}\frac{1}{log},$

- In PIC scheme, a half-integer resonance is applied to excite the phase space in hyperbolic motion (top right picture).
- As a result, the achievable transverse emittance is lower than the conventional cooling channel, and **independent from strength of magnetic field**

$\beta = v/c$, γ is a Lorentz factor, w is a thickness of cooling material, log is the Coulomb logarithm.

Cooling simulation

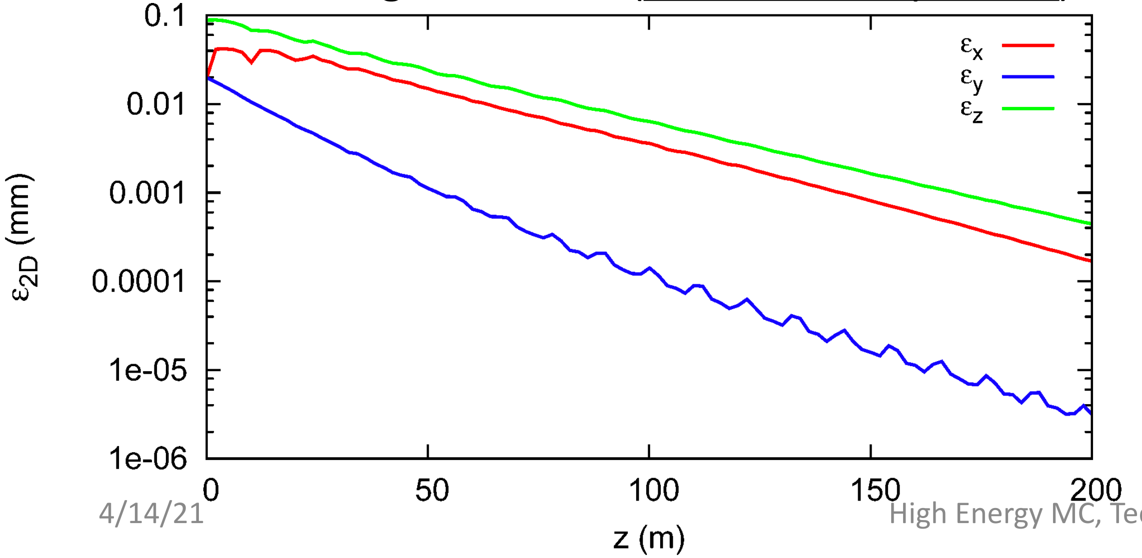
$$\lambda_x = 2\lambda_y = 4\lambda_D$$



Analytical estimation

Parameter	Unit	Initial	Final
Muon beam momentum, p	MeV/c	250	250
Number of particles per bunch, N_b	10^{10}	1	1
Be ($Z = 4$) absorber thickness, w	mm	20	2
Normalized transverse emittance (rms), $\varepsilon_x = \varepsilon_y$	µm	230	23
Beam size at absorbers (rms), $\sigma_a = \sigma_x = \sigma_y$	mm	0.7	0.1
Angular spread at absorbers (rms), $\theta_a = \theta_x = \theta_y$	mrad	130	130
Momentum spread (rms), $\Delta p/p$	%	2	2
Bunch length (rms), σ_z	mm	10	10

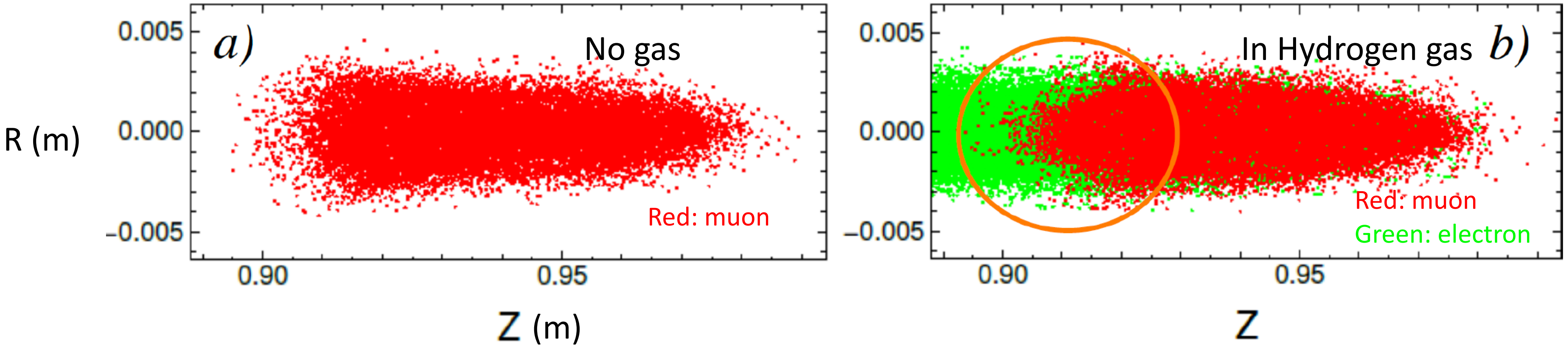
Cooling simulation (<u>no stochastic process</u>)



- So far, the cooling simulation is made without stochastic process (no energy straggling, no multiple scattering).
- Skew-PIC is the most up-to-date lattice, which realizes a large dynamic aperture as designed.
- Plasma focusing (see next slide) significantly mitigates the aberration which is caused in a cooling absorber

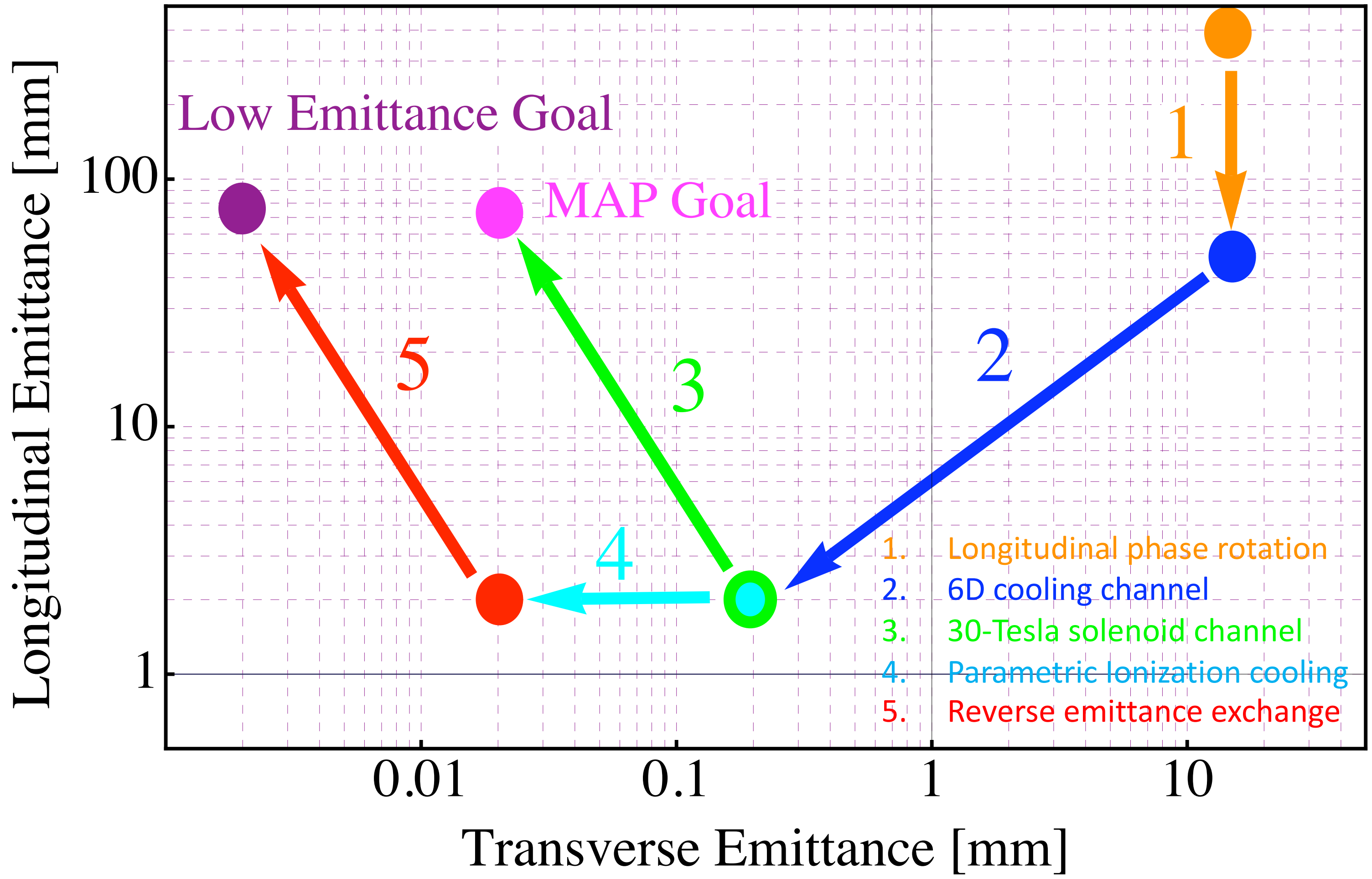
Plasma focusing[5]

- Strong radial beam focusing will appear in a dense Hydrogen gas-filled RF cavity
  - Space charge is neutralized by dielectric polarization of gas plasma, as a result, beam induces a toroidal self-focusing field

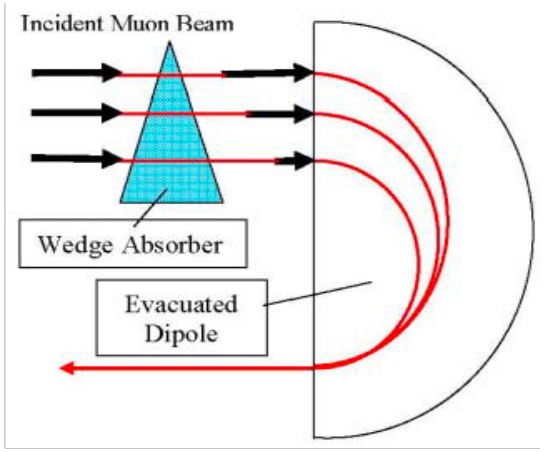


- Can this effect be adopted for cooling channel design?
- Easy to induce a resonance in a channel of azimuthally symmetric lenses
  - Focal parameter of each lens must be less than 1/4th of the distance between adjacent lenses
- Will strong radial plasma focusing allow one to tame the beam smear and take advantage of parametric resonance ionization cooling?

Reverse emittance exchange[6]



Schematic diagram of reverse emittance exchange



Analytical estimation of final emittance with PIC lattice (no magnetic field dependence)

Parameter	*Unit*	*Initial*	*After 1st stage*	*After 2nd stage*
Momentum	MeV/c	100	100	2500
Bunch length	cm	.5	10	10
Momentum spread	%	3	3	3
Longitudinal norm. emittance	cm	1.5×10^{-2}	.15	7.5
Transverse norm. emittance	µm	25	8	2

*2nd stage with high energy muons is proposed to obtain a positive dEdx slope (upper limit is determined by energy straggling)

Low emittance scheme and high transmission efficiency

$$\mathcal{L} = \frac{f_{col} \cdot n_{\mu_+} \cdot n_{\mu_-} \cdot \beta \cdot \gamma}{4\pi\left(\varepsilon_{x,n} \cdot \beta_x^*\right)^{1/2} \cdot \left(\varepsilon_{y,n} \cdot \beta_y^*\right)^{1/2}}$$

Goal of low emittance scheme

- $\varepsilon_{x,y,n} = 25$ μrad → 2 μrad (Low emittance scheme)
- Transmission efficiency in 6D cooling = 20 % → > 30 %
- Transmission efficiency in final cooling = 50 % → > 70 %
- Luminosity = 25 × Original luminosity
- Use the luminosity gain to reduce the beam power

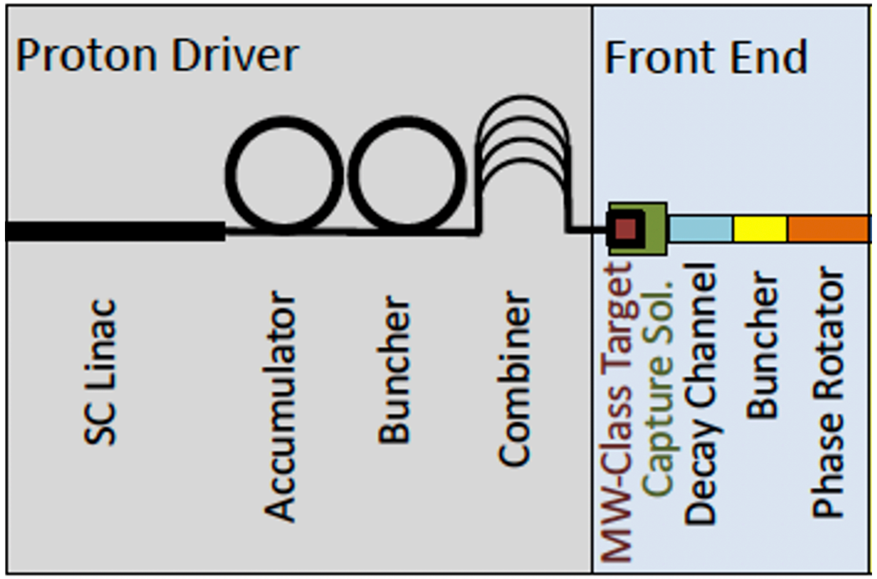
Proton Driver & Front end

MAP baseline

- 4 Mega-Watt 8 GeV proton beam
- Hg target

Low emittance scheme

- Probably < 1 Mega-Watt 8 GeV proton beam
- Conventional graphite target will be available
- Maybe create pions outside capture solenoid which will significantly mitigate radiological problems



Cooling

MICE and MTA RF measurements are very positive for ionization cooling design

MAP baseline

Helical FOFO Snake channel[7]

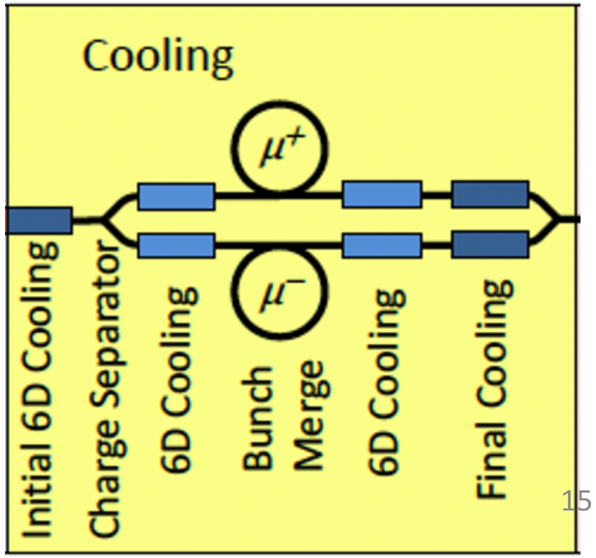
- Accept both sign muons
- Simple alternate solenoid lattice
- Ready for initial engineering study
- Appropriate for Initial 6D cooling

Rectilinear channel[8]

- Alternate solenoid makes a beta function half
- Initial engineering study done
- Cooling performance is limited by space charge

Helical channel[9]

- Shortest length (high transmission)
- No longitudinal limit because of negative slip factor (no space charge issue)
- Extra transverse focusing by self-induced toroidal field
- Poor matching scheme



Low emittance scheme

- Significantly reduce space charge effect
- Matching issue will be mitigated if pions/muons are not magnetized

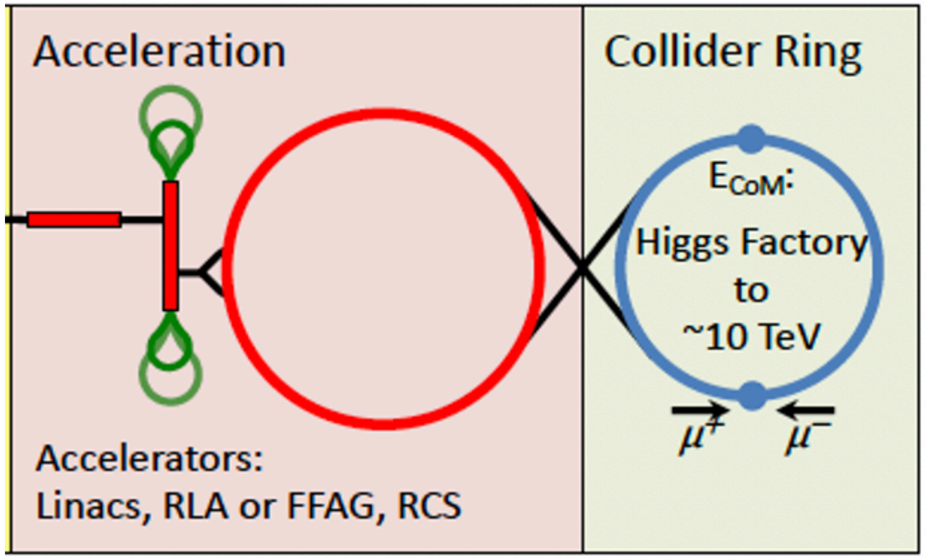
Acceleration & Collider ring

MAP baseline

- Quick acceleration to minimize muon decay
- Challenge to accelerate a short bunch length intense muon beam
- Decay electron & Neutrino radiation are intrinsic issue

Low emittance scheme

- Space charge effect is reduced
- Muon lifetime still issue; quick acceleration needed
- Decay electron & Neutrino radiation are still an issue (though the risk is significantly reduced)



Conceptual design study of Large bore Nb_3Sn dipole magnet[10]

17 Tesla dipole magnet

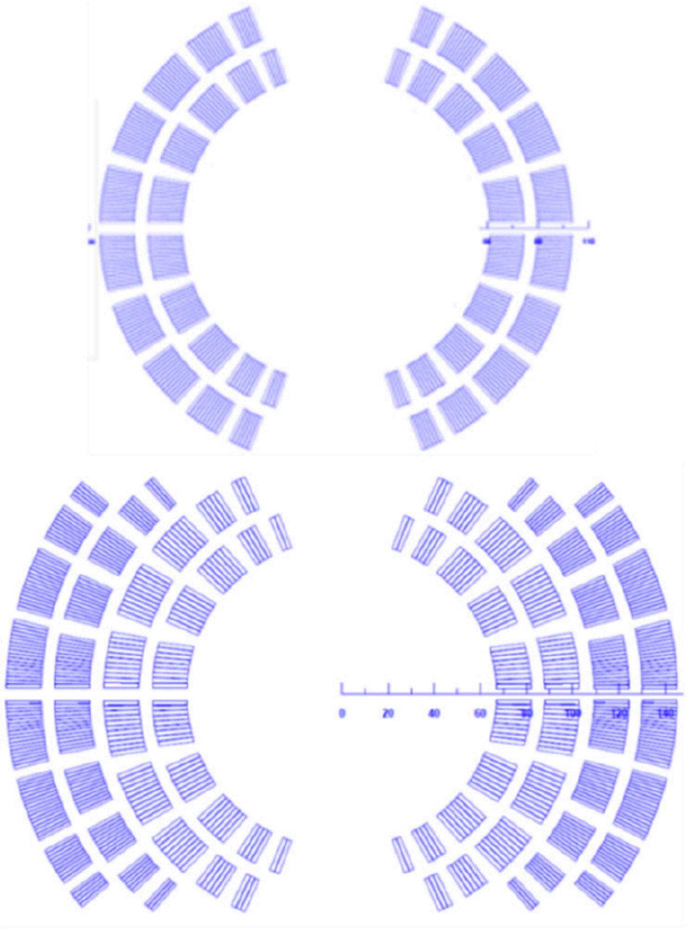
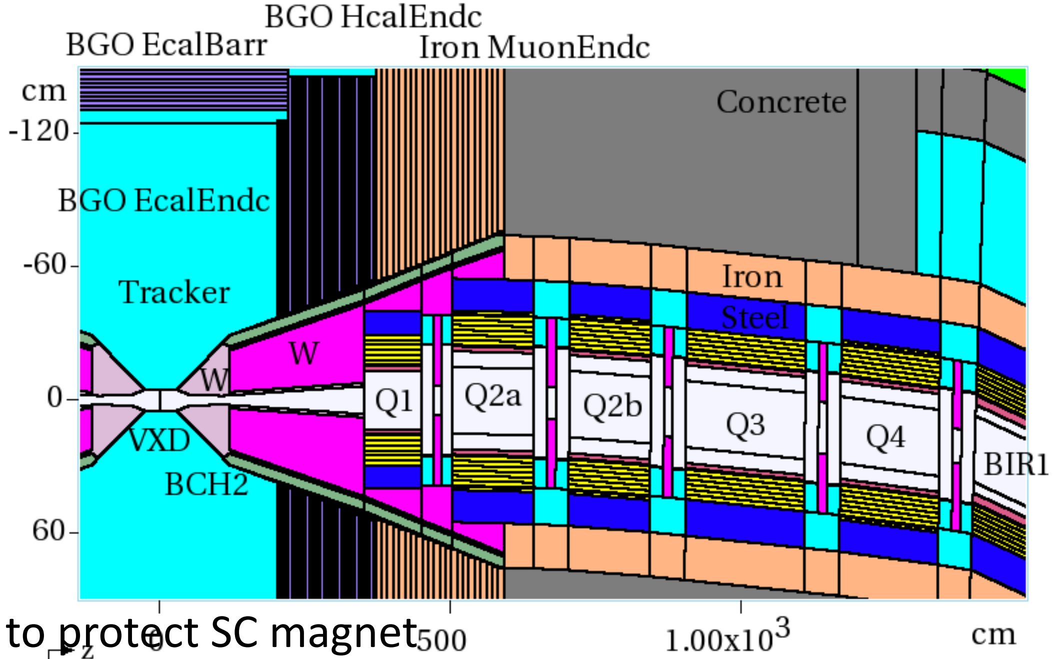


Figure 1: Cross-sections of Design 1 and Design 2 coils with 120-mm aperture.



Need W mask to protect SC magnet at IR (This design for 0.126 TeV ring)

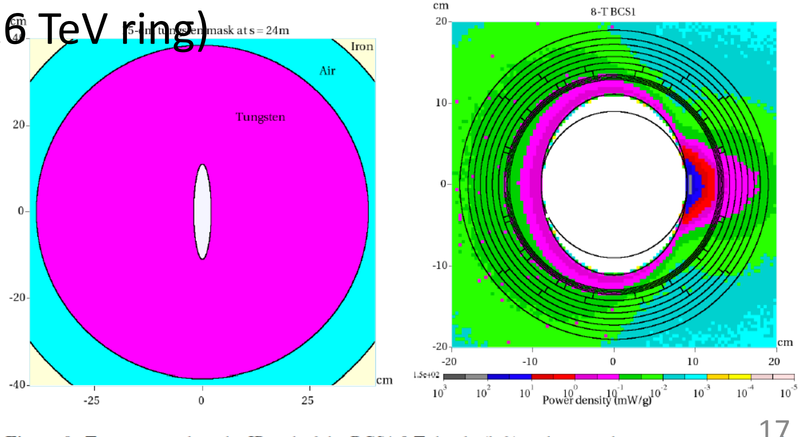


Figure 9. Tungsten mask at the IP end of the BCS1 8-T dipole (left) and power density isocontours in this dipole (right). The ring center is to the right in these figures.

Important relationships

D. Neuffer

➢Muon Lifetime:

- 2.2 γ μs = 0.0208 E (TeV) s
  - 0.104 s at 5 TeV

➢Bending Radius

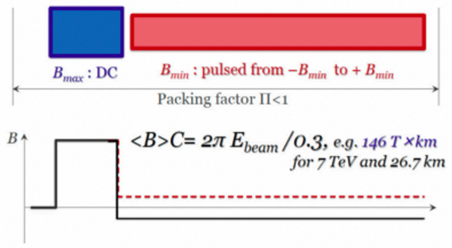
$$R = \frac{B\rho}{B} = \frac{P(GeV/c)}{0.3B(T)}\,m = \frac{P(TeV/c)}{0.3B(T)}\,km$$

➢Path Length

- 660 βγ m -> 6250 E (TeV) km

➢**Rapid Cycling Synchrotron**

- B_{typ} = ~1.5 T, 15- 60 Hz



Hybrid – High field + pulsed

- **Example:**
  B_{max}=8T B_{pulsed}=2.0, f= 0.25
  → 3.5 / 0.5 T

$$B_{ave} = f\,B_{max} + (1-f)B_{pulsed}$$

- **Number of Turns (ring)**

$$\frac{\text{path length}}{\text{circumference}} = \frac{660\,P_\mu}{m_\mu}\,\frac{0.3\,B_{ave}}{2\pi P_\mu} \cong 300\,B_{ave} \quad \text{turns}$$

In 2.2γ μs

- (luminosity lifetime/pathlength a factor of 2 less because both μ decay)

Bending, Accelerating fields:

D. Neuffer

- **Conventional (Ferric)**
  - ~ 2T
- **Superconducting –NbTi**
  - Tevatron ~4 T
  - LHC ~8 T
- **Superconducting Nb_3Sn**
  - HL-LHC + → 16T
- **HTS superconductor …**
  - REBCO → 40 T ?
- **Pulsed magnets**
  - ±2 T → ± 4 T ?? ~200T/s
    - 20T/s HTS record
    - Piekarz et al. NIM A 943, 162490 (2019)

- **SRF accelerating fields**
  - 17 MV/m (650 MHz PIP-II)
  - 30 MV/m (1300 MHz SLS-2)
- **Future upgrades**
  - 40 → 50 MV/m → 80??
- **Pulsed rf – Cu → ??**
  - 50 → 100 MV /m

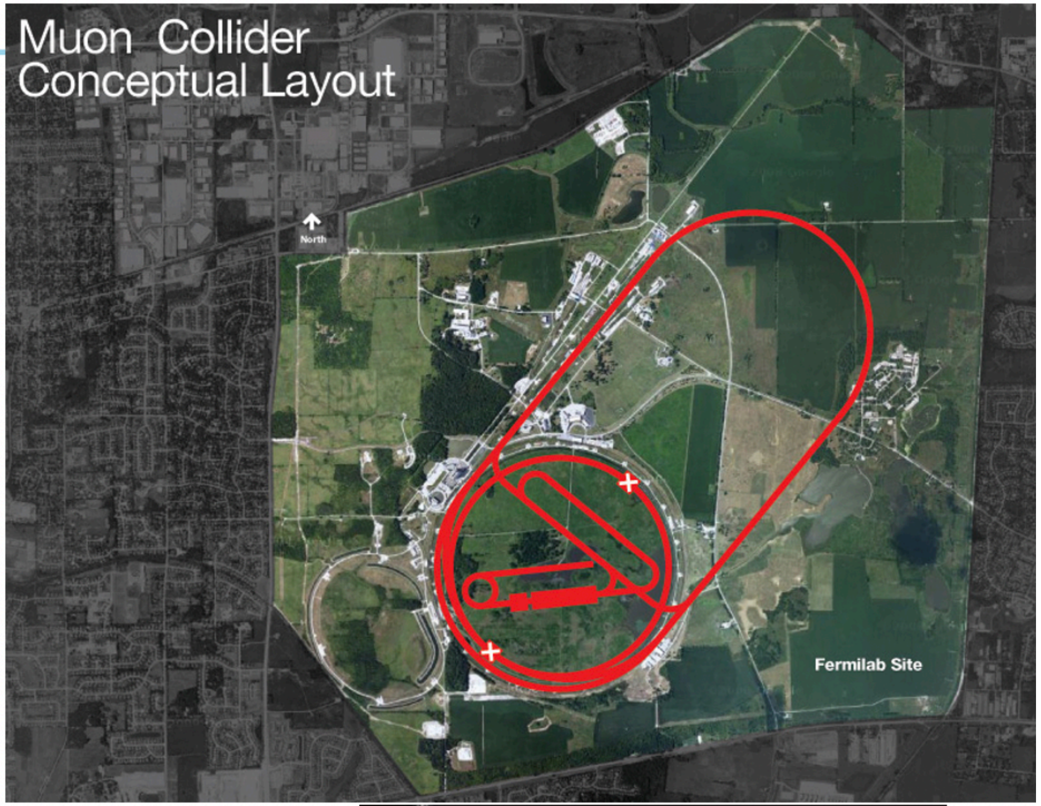
~4 TeV (2 x 2) Muon Collider (~2005)

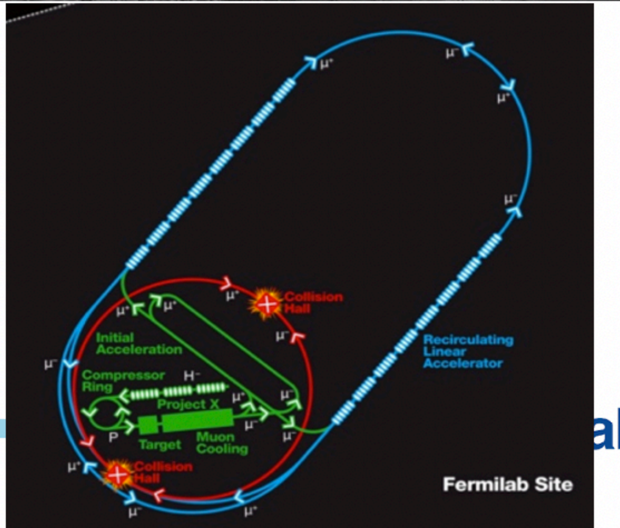
D. Neuffer

- **Muon Collider**
  - 2 TeV ring (~8T magnets)

  - RLA accelerator
  - ~18 turns
    2km linacs -50 GeV each
    ~30 MV/m rf
    Arcs are ~8T magnets each
- **Not quite site filler**
  - Easily expand to 2.5x2.5
  - (5 TeV)

- **Double gradients, B_{max}**
  - 10 TeV (5 x 5) – (16 T – 60 MV/m)





Summary

- Many benefits by improving final cooling channel
  - Most radiological issues will be mitigated
  - Beam design becomes more realistic
- Variable goal COM and Luminosity
  - Depends on available magnetic field strength and RF gradients
  - COM 5 TeV Collider is relatively accessible goal (D. Neuffer)
  - COM 10 TeV is a stretch goal (D. Neuffer)
    - Require 16 T dipoles, +/- 4 T rapid cycling, SRF 60 MV/m

Reference

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