MUON COLLIDERS

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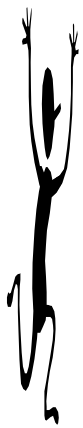
- Review of Muon Collider Motivation & History
- Recent Advances in targetry, cooling, acceleration and final focus design
- Resurrection of 2 Enhancing Technologies: OSC & mu-LCs
- Some scenarios for a rosy future incorporating muon colliders. CAVEAT EMPTOR: speculative scenario-building to illustrate potential only
- Summary

"We need revolutionary ideas in accelerator design more than we need theory. Most universities do not have an accelerator course. Without such a course, and an infusion of new ideas, the field will die."

Samuel C. Ting, quoted in Scientific American, January, 1994.

WHY MUON COLLIDERS?

Colliders that extend the energy frontier provide the most powerful & direct way to advance experimental HEP.



Electrons are too light

Discovery reach of a few TeV ?

Protons are composite & strongly interacting

Discovery reach of some 10's of TeV ?

⇨

Add Muons, though unstable

Discovery reach of ~100 TeV (circular)? ~1 PeV (linear)???

$m_\mu \sim 206 \times m_e$
$\sim m_p / 8.9$

$\mu \rightarrow e\nu\nu$ with $\tau_\mu = 2.2\ \mu s$

Muons have the highest potential discovery reach of all collider projectiles, using clean lepton-lepton collisions.

History of High Energy Muon Collider (HEMC) R&D

60's & 70's $\mu^+\mu^-$ colliders mentioned (Tinlot, Budker, Skrinsky, Neuffer)

1981 ionization cooling (Skrinsky & Parkhomchuk)

1994 high luminosity para. (Neuffer, Palmer); meetings & workshops

1996 "$\mu^+\mu^-$ Collider; a Feasibility Study" (83 authors) E_{CoM} = 0.5, **4** TeV

1997 Muon Collider Collaboration forms, ~20-25 FTE

1998 positive recommendation from Gilman HEPAP sub-panel

1998+ co-existence with neutrino factory R&D

-> Neutrino Factory & Muon Collider Collaboration

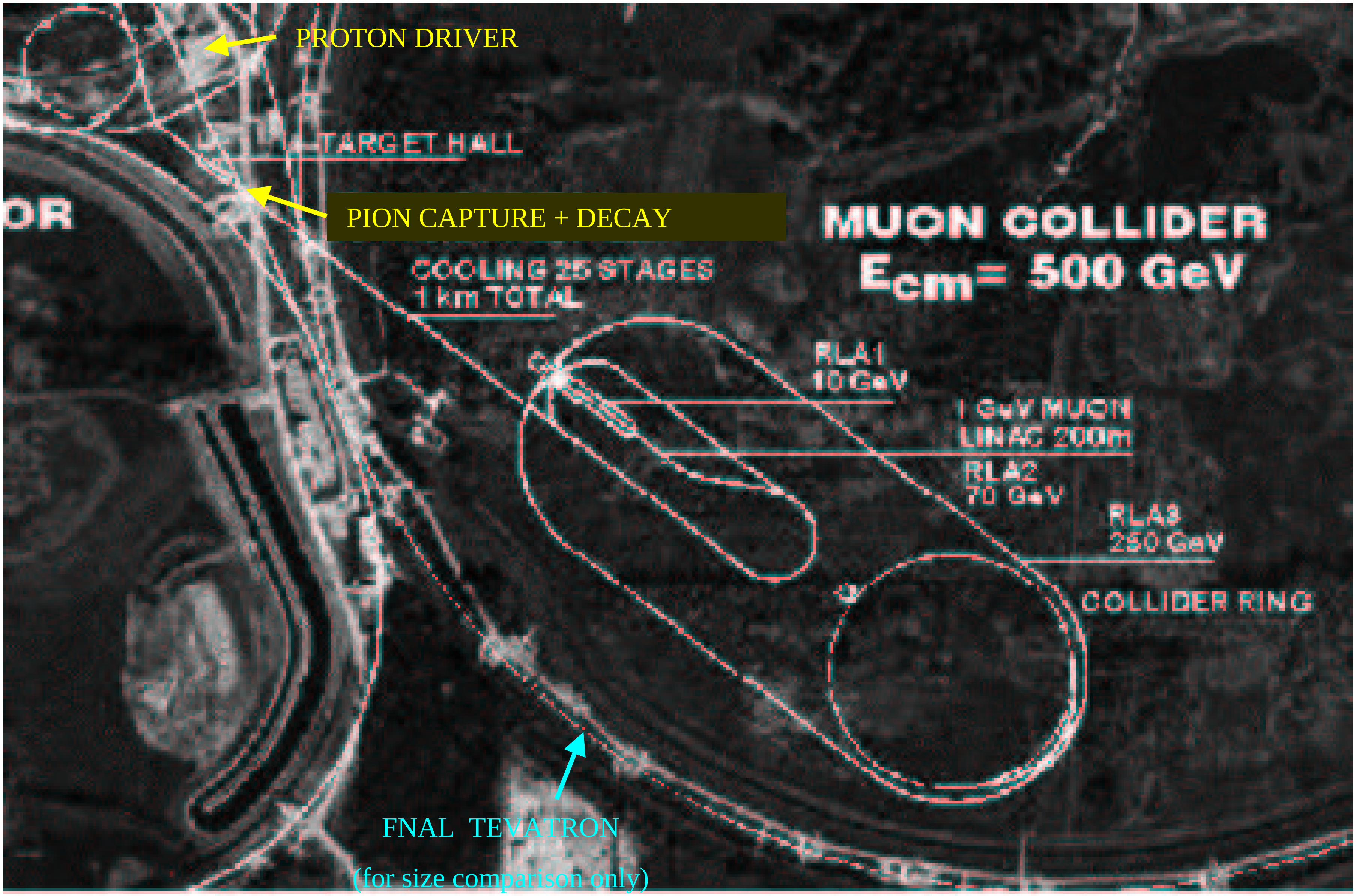
1999 "status report" (108 authors) Phys. Rev. Special Topics, Accel. Beams 2, 081001 (1999)

including E_{CoM} = 100-150 GeV Higgs factory

HEMC'99 workshop E_{CoM} = 10-100 TeV

2000-01 6-Month Feasibility Study on HEMCs ($3000 study)

Example Layout for a "Traditional" Muon Collider

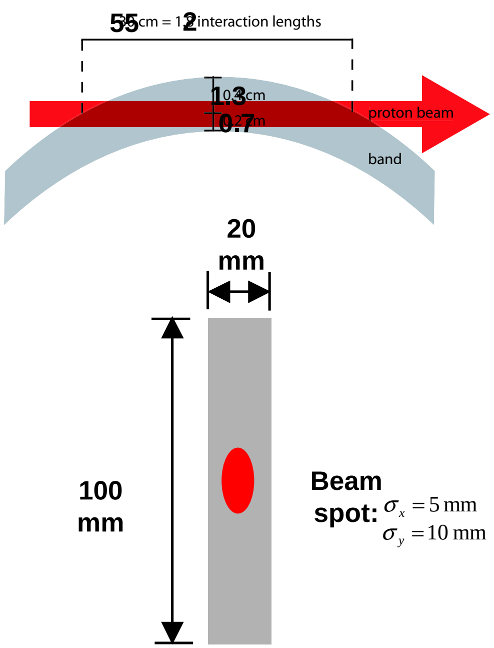


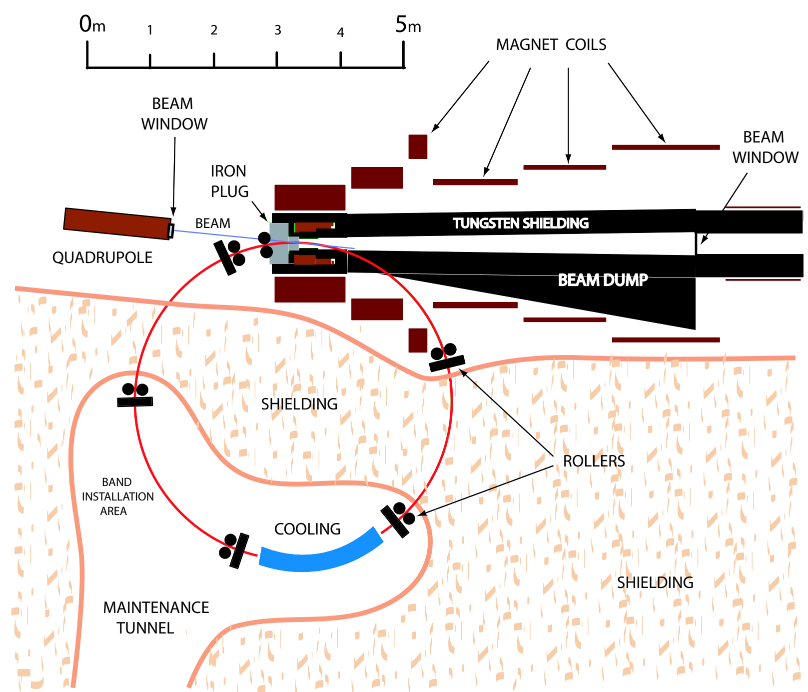
Conventional Pion Production Target Should be OK

Can use large beam spot size on target to produce pion "cloud" => shock heating stresses can be managed.

Continuous rotation to new target material allows convenient cooling and dilutes the radiation damage. Such target designs can comfortably handle pulsed proton beams of several MW, e.g.:

Ti-alloy band



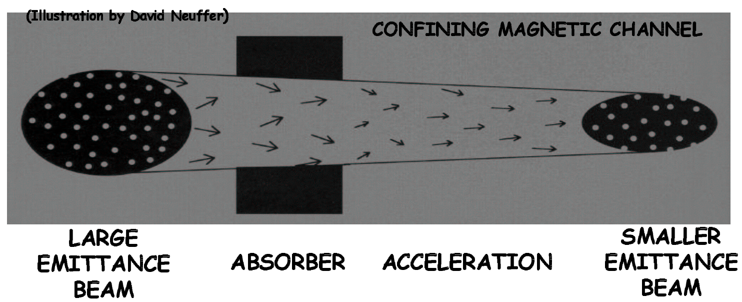


Ref. BJK, Mokhov, Simos & Weggel, "A Rotating Metal Band Target for Pion Production at Muon Colliders", *Proc. 6-Month Study on HEMC's* (available on CD here at Snowmass)

IONIZATION COOLING CHANNEL (1 of 2)

The high-performance ionization cooling channel has been the signature technology and dominant technical challenge for muon colliders.

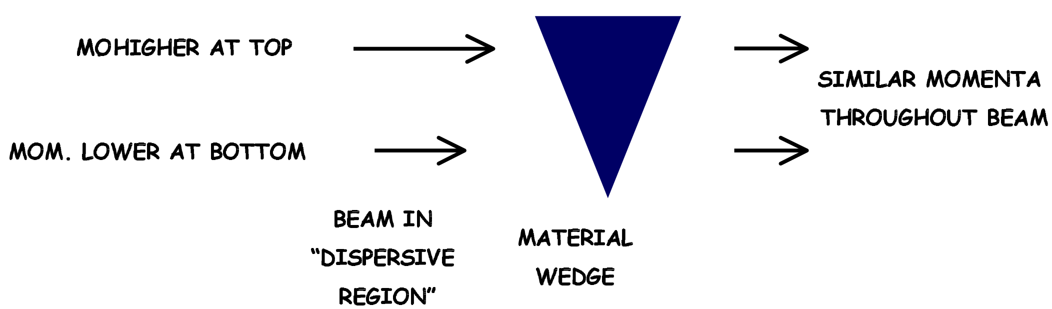
Simple concept for transverse cooling:



However, Coulomb scattering and energy straggling compete with cooling,

A) confines cooling to a difficult region of parameter space (low energy, large angles)

B) need to control beam energy spread to obtain large reduction (10^4-10^6) required in 6-D phase space:



"emittance exchange"

IONIZATION COOLING CHANNEL (2 of 2)

So far we have:

a) general theoretical scenarios & specs. to reach the desired 6-D emittances

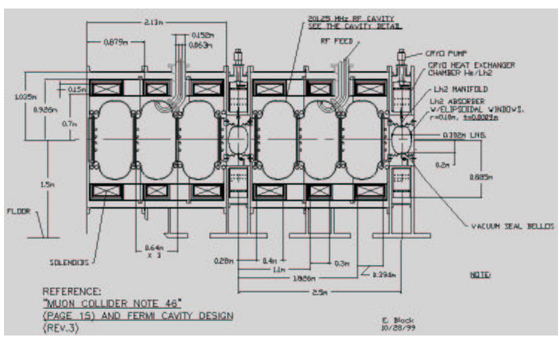
b) detailed particle-by-particle tracking codes (modified GEANT,ICOOL) & (new) higher order matrix tracking code (modified COSY-infinity) + (new) wake field code interface

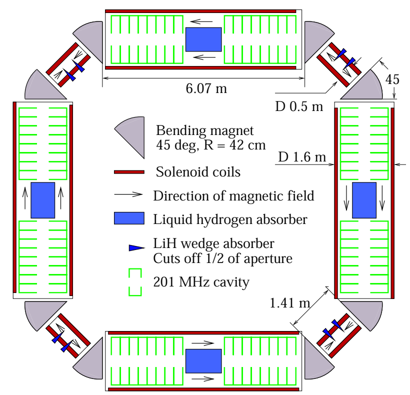
c) engineering designs of pieces

d) neutrino factory designs for first factor of ~10 *transverse* cooling

e) "ring cooler" design progressing for MUCOOL expt. with predicted full 6-D cooling by factor of ~32 (c.f. muon collider may need up to ~10^6 ~ 32^4)

2 sub-units of a cooling stage (Black, IIT)





"ring cooler"

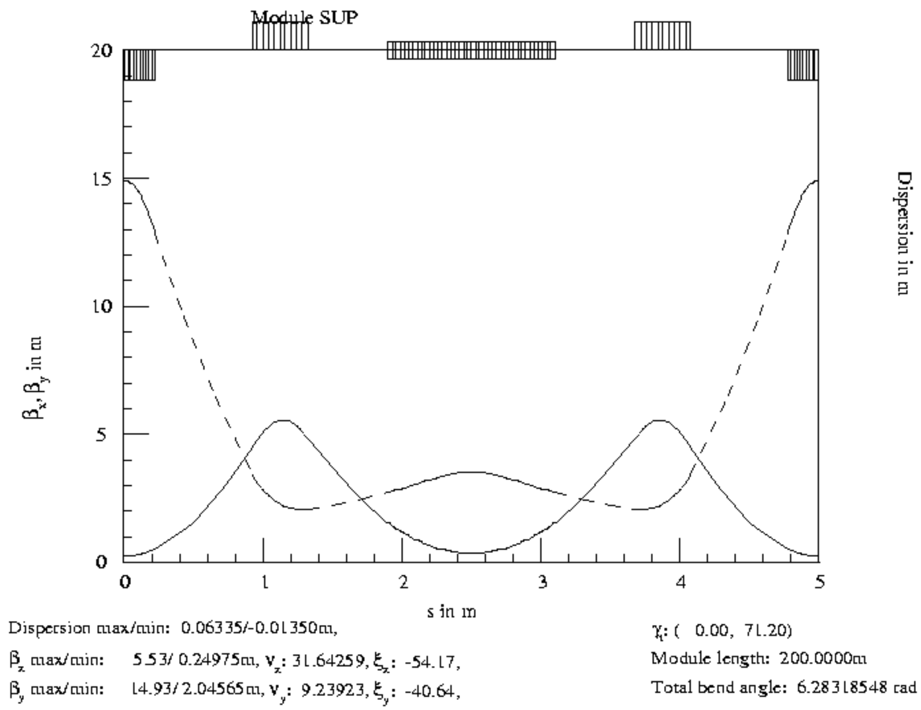
(Balbekov, FNAL)

But we have yet to put the pieces together to "build the muon collider cooling channel on a computer". The most difficult and expensive parts will be the initial stages (huge beam emittance) and the final stages (push parameters for minimum final emittance).

ACCELERATION

Require average accelerating gradient >> $m_\mu c/\tau_\mu$ = 0.16 MeV/m

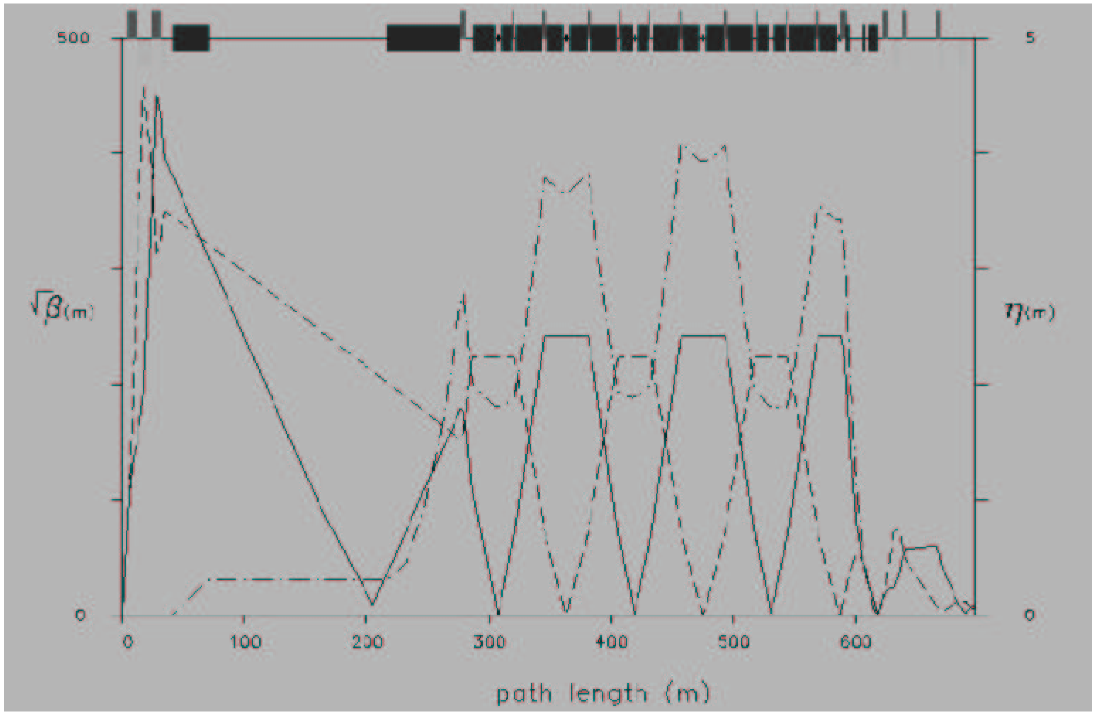
Acceleration will be the largest cost component for energy frontier muon colliders
Cost reduction -> recirculate with multiple passes through (e.g.) FFAG lattices.



The figure shows a module of an FFAG lattice for 10->20 GeV by Trbojevic (+ Courant & Garren). Unfortunately, the scaling of FFAG lattices to multi-TeV energies is given a low R&D priority at the moment.

COLLIDER RING

The design of the final focus is a major challenge for energy frontier muon colliders.



The figure shows a 4 TeV final focus design by Johnstone & Garren for E_{μ}=2 TeV, β^*=3 mm, σ_{θ}^*=0.7 mrad. As well, the CD for the recent 6-month study includes an attractive final focus design by Raimondi (+Zimmermann) for E_{μ}=15 TeV, β^*=4.8 mm, σ_{θ}^*=0.5 mrad.

Magnet Costs: The Dominant Financial Challenge

Slides from Mike Harrison (BNL)

"Magnet Challenges: Technology and Affordability"

HEMC'99 Workshop,

Montauk, NY, Sept'99

Affordability

Caveat: collider ring only; acceleration may be more expensive..

- RHIC Dipoles 8cm, 10m, 4T, FY95 cost $110K each
- HEMC Dipole
  - 8cm -> 15cm 50%
  - 4T -> 7T 50%
  - 10m -> 15m 40%
  - FY95 -> FY00 15%
  - Estimate HEMC Dipole $400K or $26K/m based on RHIC
- 10 Tev needs 15km circumference -> magnet costs ~$400M. Ring costs = dipoles x 3(or4) = $1.2(6)B (probably a lower bound since HEMC dipoles are more complex than RHIC)

⇦ Encouraging

Conclusions

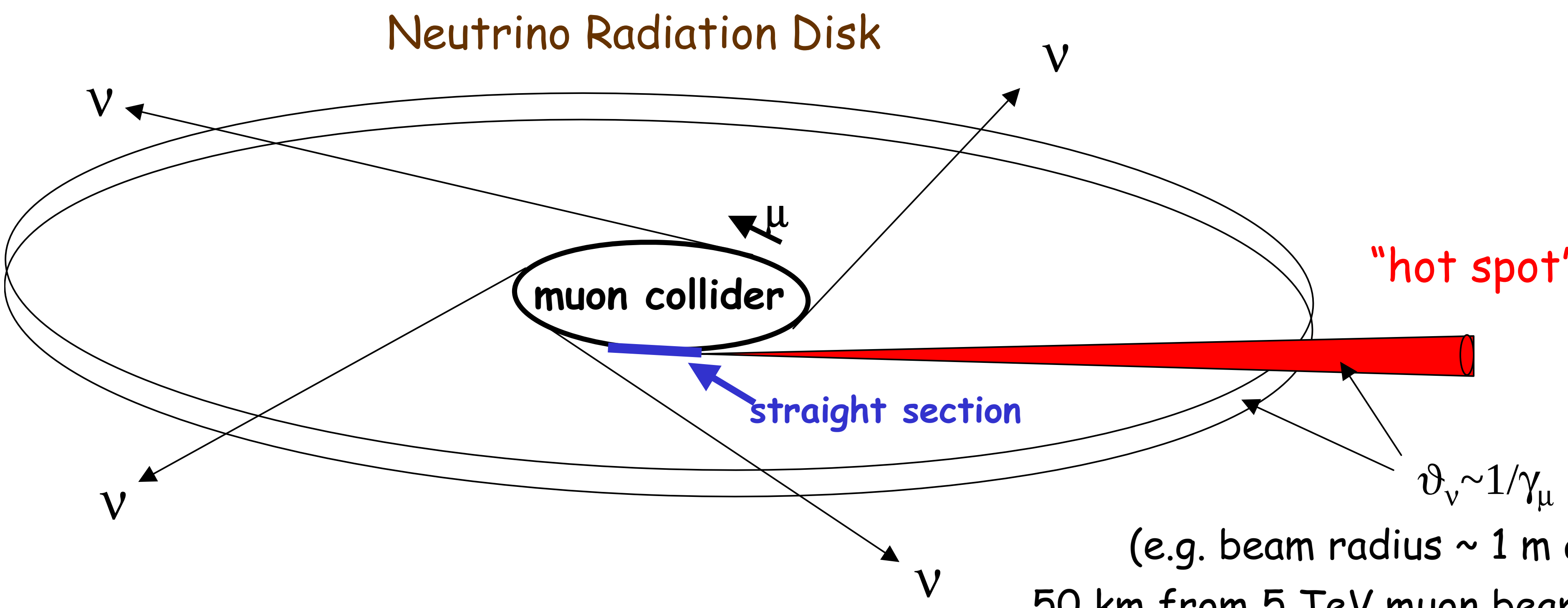
- A 10 Tev machine based on Nb-Ti magnets (7T dipole) is challenging but possible
- A 100 Tev machine does not look feasible based on 10T cosine theta dipoles
- A different magnet design (no mid plane cryogenics) would help
- Newer technologies (Nb3Sn, HTS) would be beneficial assuming that costs are reasonable and they work

⇦ work in progress for neutrino factory;

not relevant for low current colliders

NEUTRINO RADIATION ISSUES

NEUTRINO RADIATION

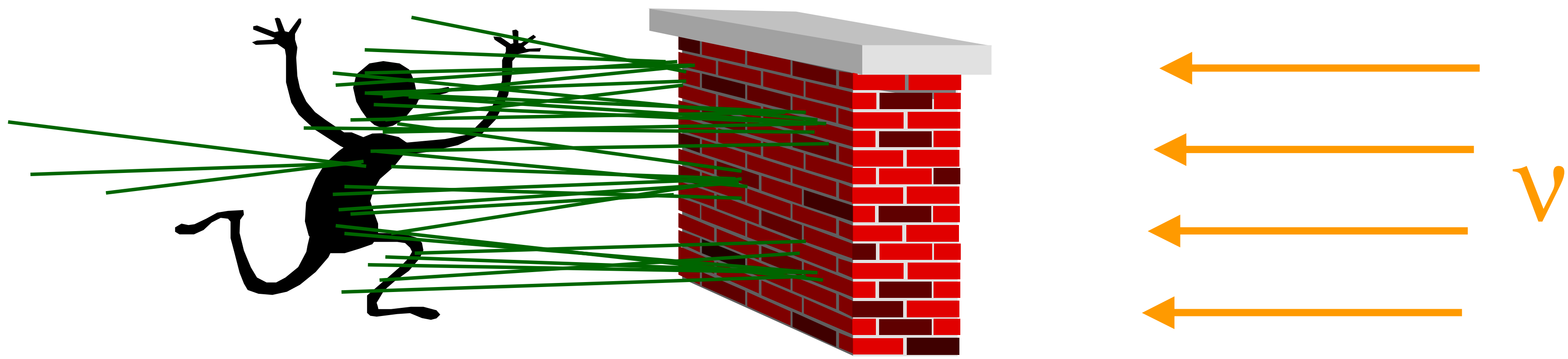


(e.g. beam radius ~ 1 m at 50 km from 5 TeV muon beam)

neutrino production: $\mu \to e\nu\nu$

THE OFF-SITE RADIATION CONSTRAINT

Neutrino interactions in the surroundings initiate the charged particle showers that lead to the radiation constraint ...



Predicted Radiation Dose up to ~TeV Energies*

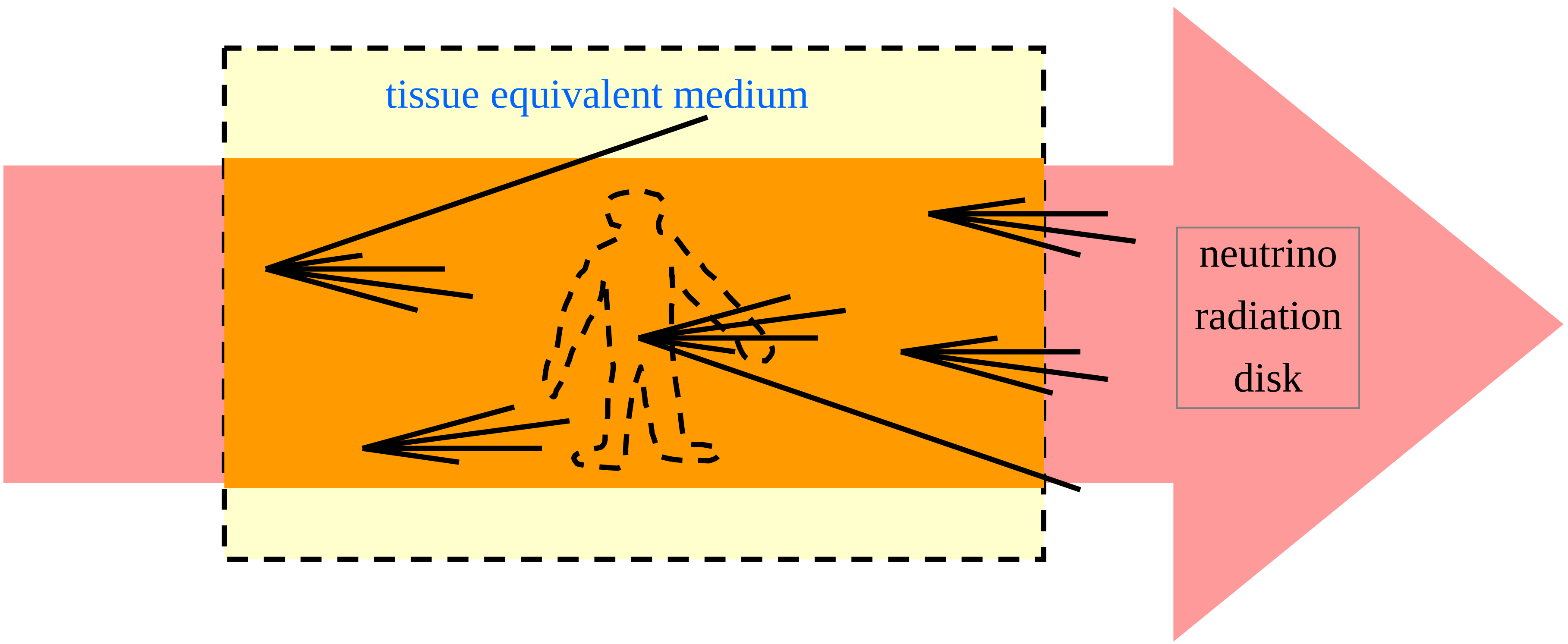
$$\text{Radiation Dose[mSv]} \cong 0.4 \times N_{\mu+}[10^{20}] \times \left(\frac{\text{length of str. section}}{\text{collider depth}}\right) \times \left(E_{\text{CoM}}[\text{TeV}]\right)^3$$

1 mSv/yr = U.S. Federal off-site limit ~ natural background

- a conservative, worst case, order-of-magnitude analytic calculation
- collider depth ~ (distance to surface)^2 for a non-tilted ring and locally spherical Earth
- the formula overestimates the dose close-by & at many-TeV energies

*ref. BJK, "Neutrino Radiation Hazards at Muon Colliders", physics/990817

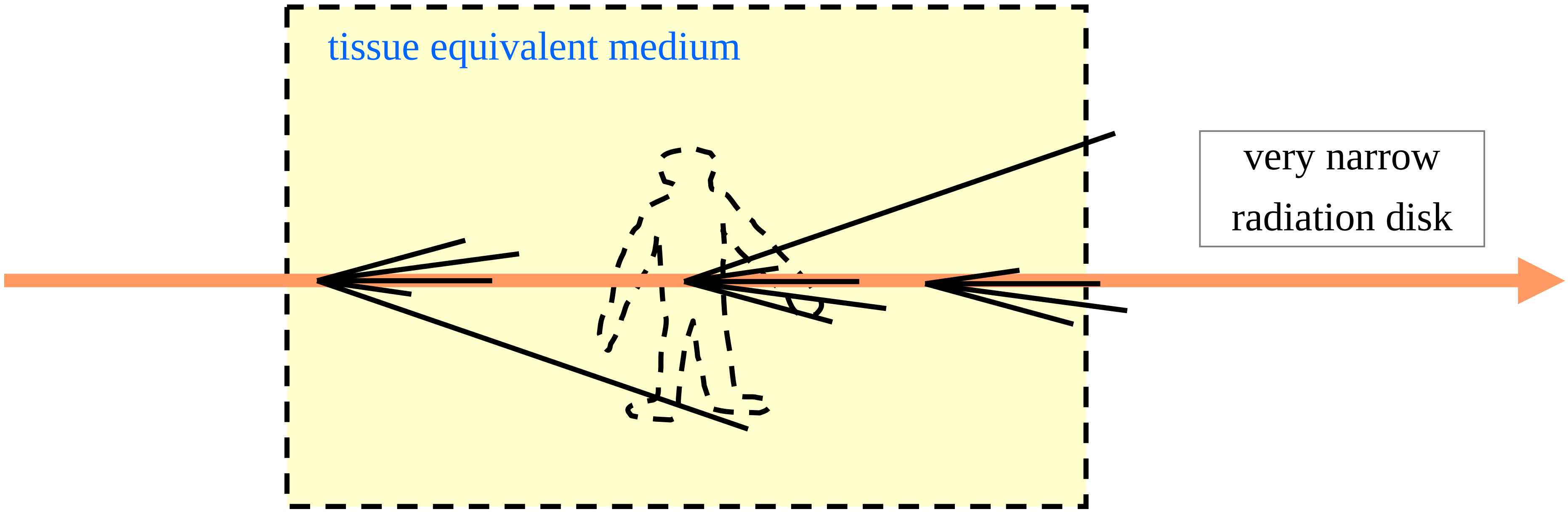
"Equilibrium Approximation" for Dose Calculation



Max. dose absorbed = energy of neutrino interactions in person

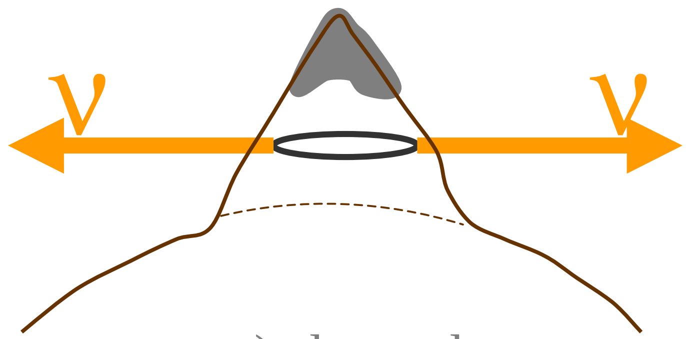
N.B. breaks down close-by & at many-TeV energies (next slide)

1) equilibrium approximation breaks down:



2) neutrino cross-section levels off:

$$\frac{\left(\frac{\sigma_\nu}{E_\nu}\right)_{E=100\,\mathrm{TeV}}}{\left(\frac{\sigma_\nu}{E_\nu}\right)_{E=1\,\mathrm{TeV}}} = 0.33$$



a) elevated

b) isolated

OPTICAL STOCHASTIC COOLING (OSC)

SPECULATIVE NEW PROMISE FOR REALLY COOL MUON BEAMS

- proposed in A. Mikhalichenko and M. Zolotorev, Phys. Rev. Lett. **71**, 4146 (1993)
- optical analog of microwave stochastic cooling: vastly higher frequency light => much faster cooling is suitable for muons
- ionization cooling has potential only for moderately cool beams; OSC might cool the 6-D emittance a further ~10 orders of magnitude until limited by intra-beam scattering (c.f. linear collider beams)
- further developed in "Optical Stochastic Cooling of Muons", A. Zholents, M. Zolotorev & W. Wan, Phys. Rev. ST - Acc. and Beams, **4**, 031001 (2001); includes a example muon collider parameter set with E_{CoM}= 4 TeV and L=10^{35} $cm^{-2}.s^{-1}$.
- still very speculative. However, concept can be tested experimentally with GeV-scale electron beams (much easier). Conclusion of ZZW:

"Overall, we conclude that OSC of muons is difficult and expensive. Further studies are needed to decide whether the benefit of the additional cooling outweighs the great complexity and considerable cost associated with its implementation."

[Include ZZW plot]

1) header + abstract

2) cooling scheme figure

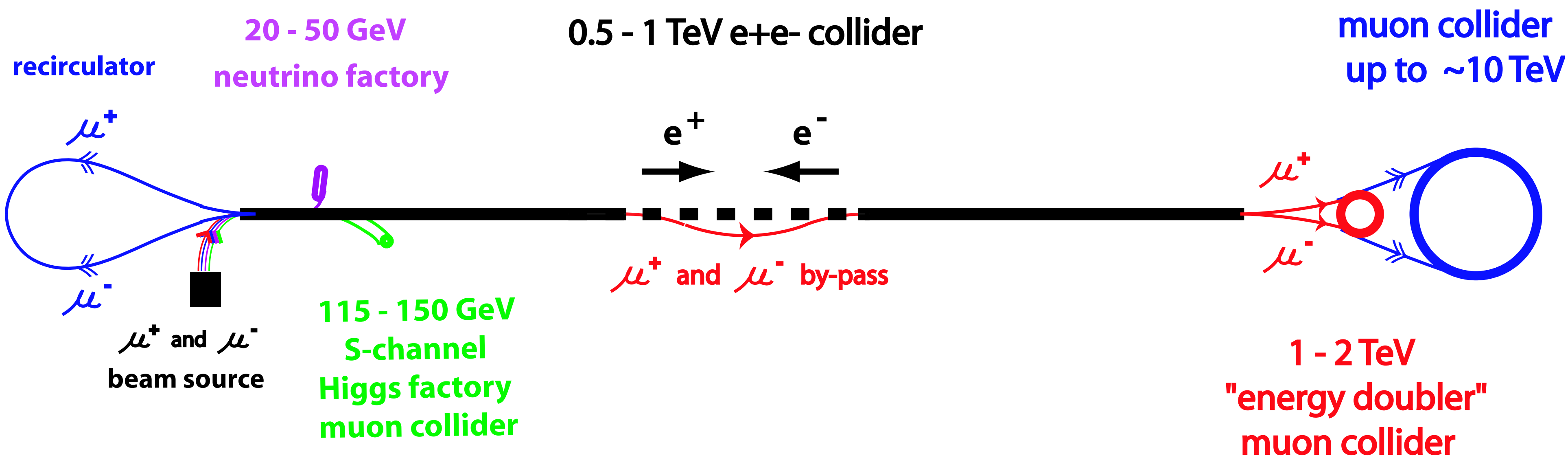
3) 4 TeV parameters: reduce current by 4.4e3

[Include BJK parameter sets]

Mu-LCs to ~10 TeV

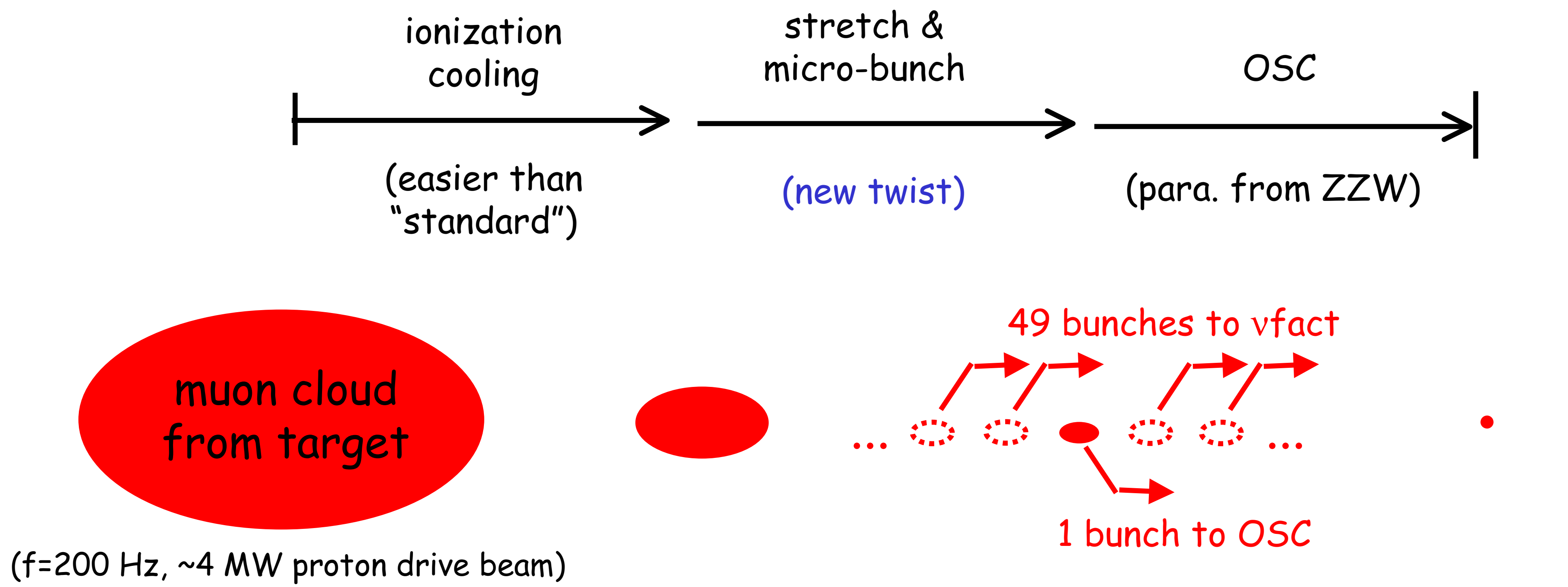
- mu-LCs = accelerate muons for muon collider in linacs of e+e- collider as an energy upgrade
- concept presented in Proc. Snowmass'96 in "An Energy Upgrade from TESLA to a High-Energy Muon Collider", D. Neuffer, H. Edwards and D. Finley
- examined again in Snowmass 2001 linear collider session, assuming the feasibility of a high-performance ionization cooling channel. Conclusions were that mu-TESLA continues to look very promising and (new!) mu-NLC has a chance (P. Tenenbaum)
- scenarios become much more attractive if muon OSC is also available - both the muon bunch charges and currents are then much smaller than the baseline electron parameters. The remaining concerns are then A) for mu-NLC need multiple pulsing of klystrons on microsecond timescale, B) for mu-TESLA may need big increase in rep. rate over default parameters.

Example of a mu-LC & Potential Add-ons

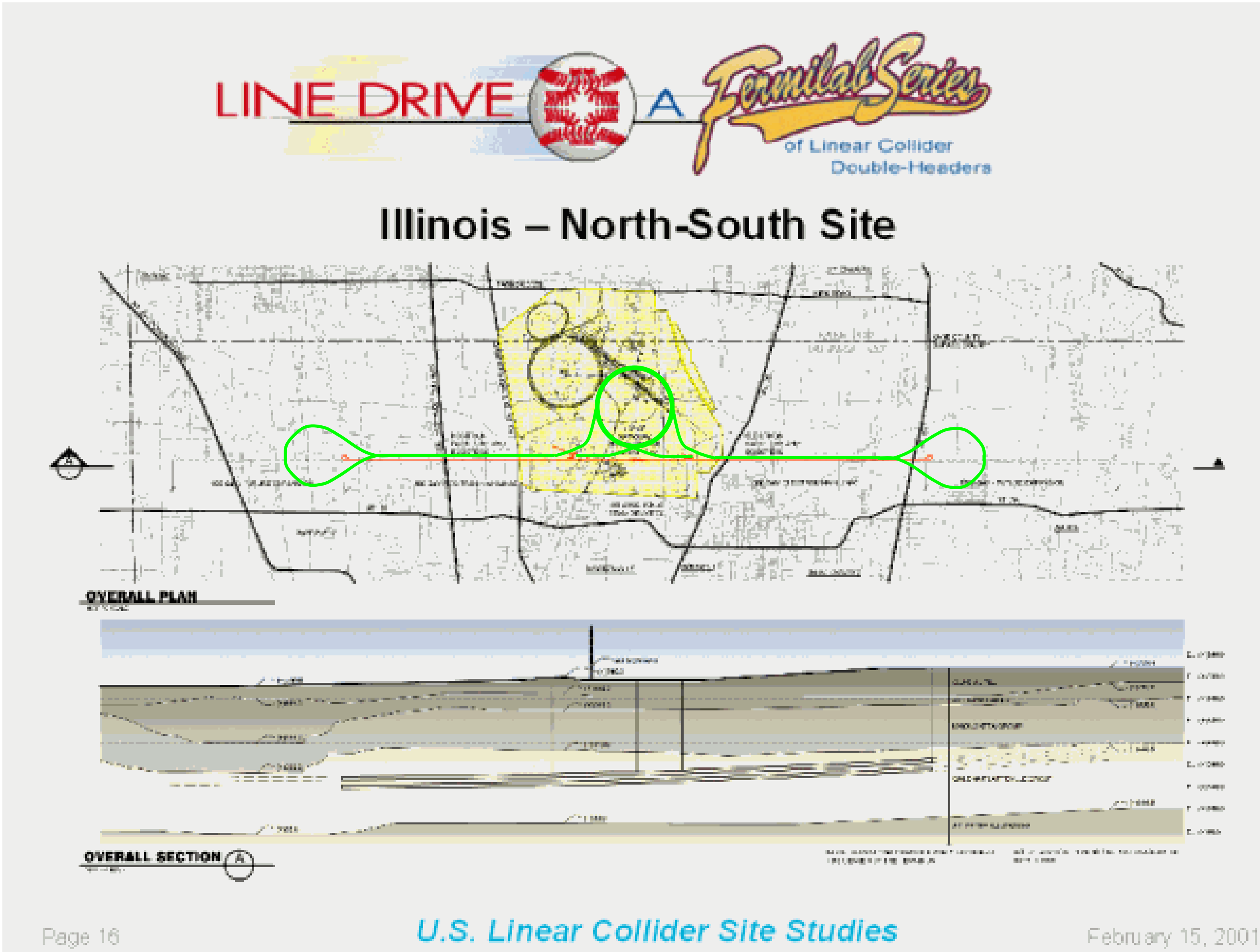


N.B. a high performance neutrino factory would fit in naturally with an attractive cooling scenario using OSC (next slide) and so could be added on for a MINOS-scale price tag. The cold muon beam would produce an even better characterized neutrino beam than at a stand-alone neutrino factory.

Example Cooling Scenario with Re-Bunching

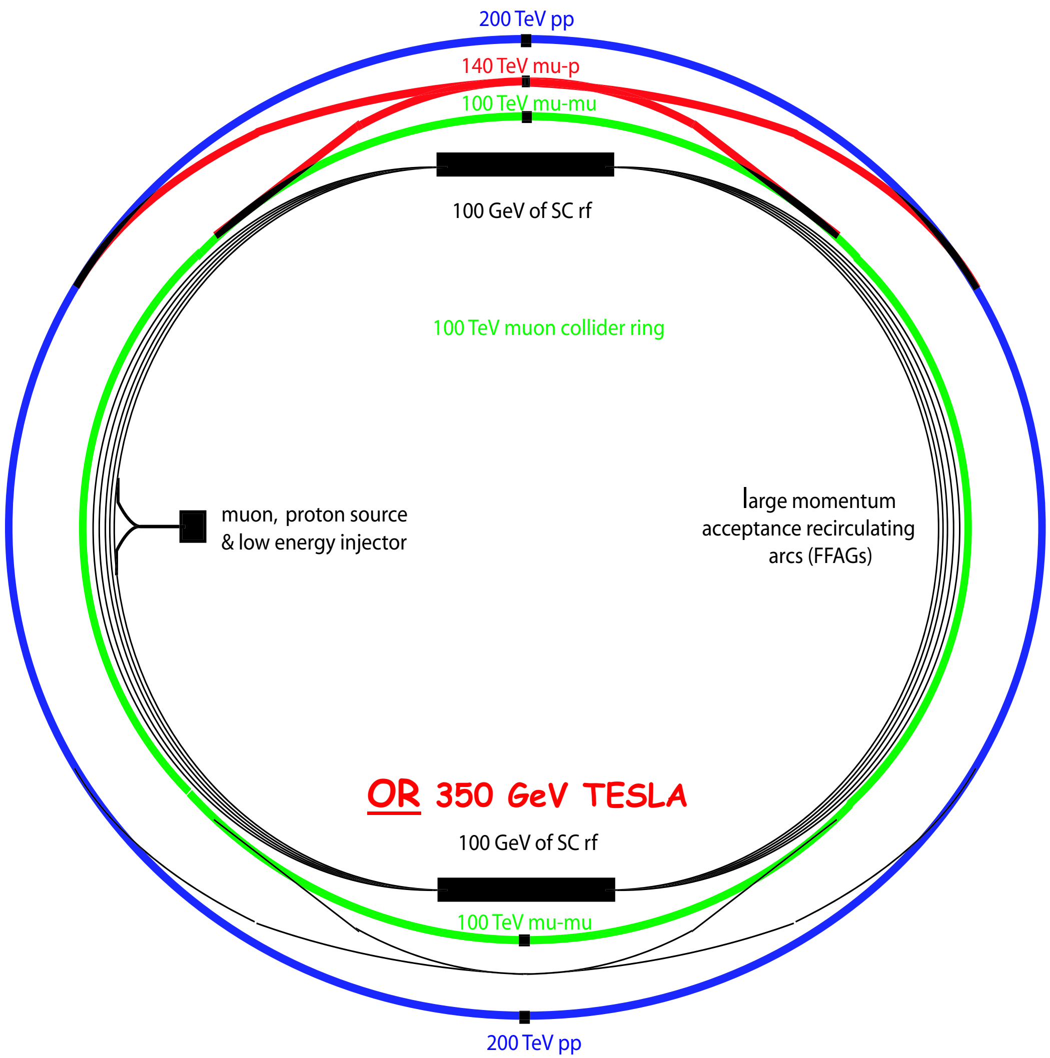


N_{μ}^{+}	8×10^{11}	4×10^{11}	4×10^{9}	4.5×10^{8}
$\varepsilon_{6N}[m^3]$	1×10^{-4}	8×10^{-9}	8×10^{-11}	1.8×10^{-21}


LINE DRIVE
A
Fermilab Series
of Linear Collider
Double-Headers
Illinois – North-South Site
OVERALL PLAN
OVERALL SECTION
Page 16
U.S. Linear Collider Site Studies
February 15, 2001

VLMC @ VLHC (@ TESLA?)

Schematic Layout showing Acceleration,
Muon Collider, Proton Collider & mu-p Collider



Plausible potential for

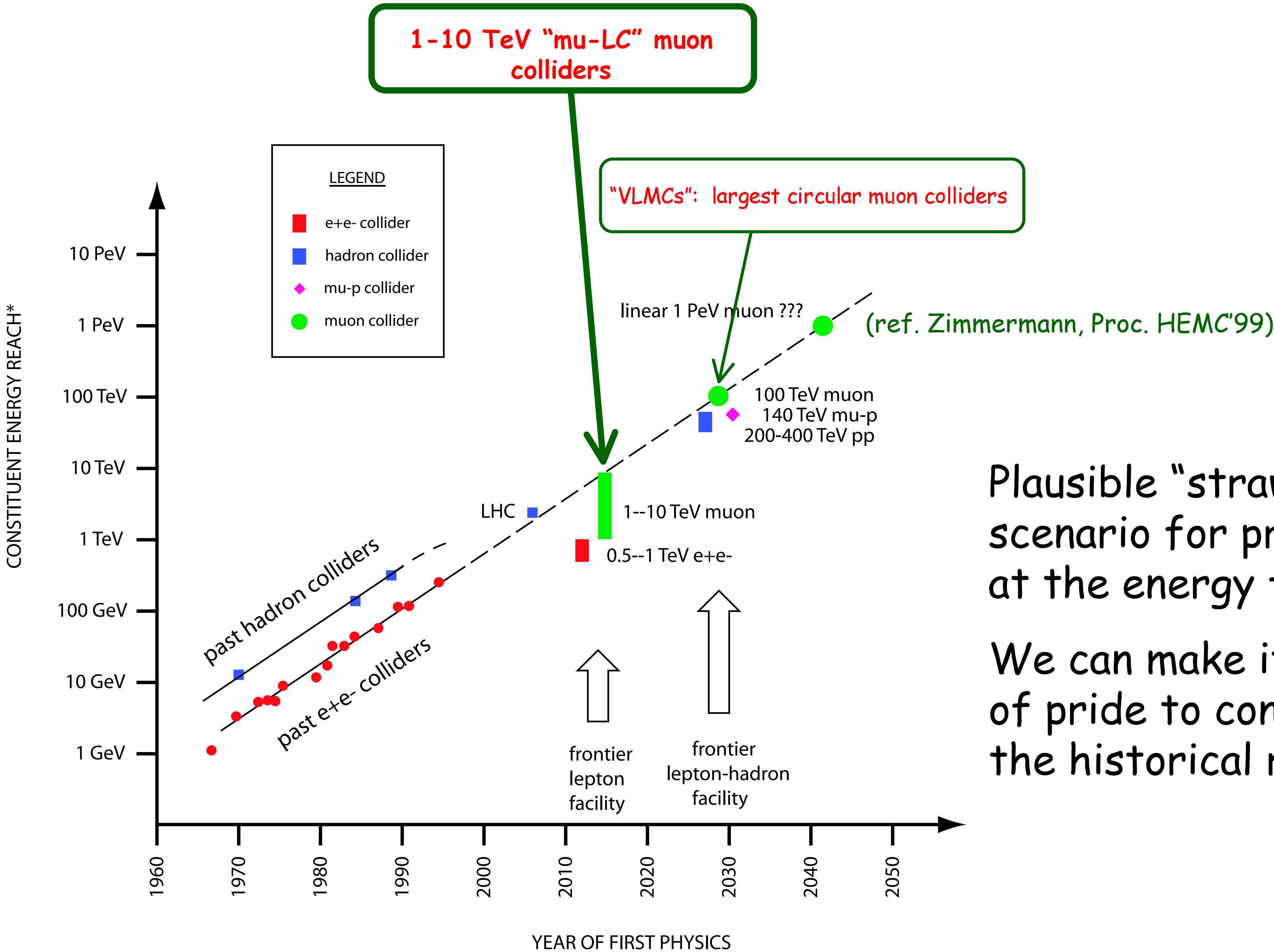
- ✓ common magnet R&D
- ✓ same tunnel
- ✓ common acceleration to ~50 TeV/beam
  - ➢ full energy for muon collider
  - ➢ ~½ energy for hadron collider
- ✓ mu-p collisions at E_{CoM} ~ 140 TeV
- ✓ with OSC, low-current VLMC @ Fermilab VLHC with E_{CoM}=100 TeV, L=10^{34}-10^{35} $cm^{-2}s^{-1}$
- ✓ TESLA linacs provide the acceleration

ULTIMATE HEP COLLIDER COMPLEX?

What is the time-scale to muon collider physics?

- if feasible then "technology-limited" timescale must surely be less than a decade, c.f. man on the moon in the 1960's
- current rate of progress => infinity (recall Ting warning)
- assuming 0) feasible in software, then timescale is determined by 1) hardware challenges, 2) cost and 3) resources. We can reliably estimate 1 & 2 if and only if we have 0.
- in Proc. Snowmass'96, Palmer, Sessler & Tollestrup hypothesized a 0.5 TeV muon collider in around 2010. Restoring our momentum will take some time so for the sake of argument assume around 2015.

CONTINUING THE GREATEST VOYAGE OF EXPLORATION IN SCIENCE



Plausible "straw-man" scenario for progress at the energy frontier.

We can make it a point of pride to continue at the historical rate.

What Would we Learn from Such a Voyage?

We don't know in detail - that's why it is called exploration!

For comparison, the previous 3 1/2 energy decades cover all known elementary particles other than electrons, photons and neutrinos.

The last 3 1/2 energy decades have revolutionized our understanding and led to the well-tested but stop-gap Standard Model. **We can expect further revolutions in understanding the fundamental organizing principles of our universe, all within the career-span of a student entering the field!**

SUMMARY

• muons have the highest "energy rating" of any collider projectile and so muon colliders at the energy frontier have **magnificent potential to advance experimental HEP**. The field will be the poorer if that potential is not realized

• despite a lack of resources, simulations and paper studies have continued to provide significant **advances in targetry, cooling, acceleration & final focus**.

• though it appears extremely challenging, **optical stochastic cooling** has a chance to provide muon beams with comparable brightness to e+ and e- beams for linear colliders – a potential gain of 10 orders of magnitude over ionization cooling. This allows us to consider the possibility of, e.g., a 100 TeV muon collider with acceptable off-site neutrino radiation levels

• speculative scenarios can be built up where muon colliders perform a central role in advancing the energy frontier while also enhancing the potential of future electron and proton colliders. An example is mu-LCs. Such scenario-building is a step towards a coherent future vision for experimental HEP and needs to be further developed under the constraints of scientific peer review.