Overview of Muon Collider Radiation Issues

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Outline

- The Issues
- Useful Papers
- Summary

Disclaimer: I was asked to prepare this talk on short notice. I am reviewing work done by others, about which I am not an expert.

The Issues

1. Protection of magnets from muon-decay radiation
2. Suppression of muon-decay backgrounds in detectors
3. Protection of people from off-site neutrino-induced radiation

Some Useful Papers

1. **The Higgs Factory Muon Collider Superconducting Magnets and Their Protection Against Beam Decay Radiation**, N.V. Mokhov, V.V. Kashikhin, S.I. Striganov, I.S. Tropin, and A.V. Zlobin, arXiv:1806.08883; JINST, to appear
2. **A Study of Muon Collider Background Rejection Criteria in Silicon Vertex and Tracker Detectors**, V. Di Benedetto, C. Gatto, A. Mazzacane, N.V. Mokhov, S.I. Striganov, N.K. Terentiev, arXiv:1807.00074; JINST, to appear
3. **Ultra-Fast Hadronic Calorimetry**, Dmitri Denisov, Strahinja Lukić, Nikolai Mokhov, Sergei Striganov, Predrag Ujić, arXiv:1712.06375v2, NIM A **898** (2018) 125–132
4. **Muon Colliders**, R.B. Palmer, Reviews of Accelerator Science and Technology **7** (2014) 137–159
5. **Neutrino Radiation at Muon Colliders and Storage Rings**, N. Mokhov, A. Van Ginneken, J.Nucl.Sci.Tech. **37** (2000) 172
6. **Mitigating radiation impact on superconducting magnets of the Higgs Factory muon collider**, N.V. Mokhov et al., TUPRO030, Proc. IPAC2014, Dresden, Germany, June 2014, p. 1084; Fermilab-CONF-14-175-APC-TD
7. **JINST Special Issue on Muon Accelerators**, http://iopscience.iop.org/journal/1748-0221/page/extraproc46 (work in progress)

Repository for final MAP and MICE papers

The Issues

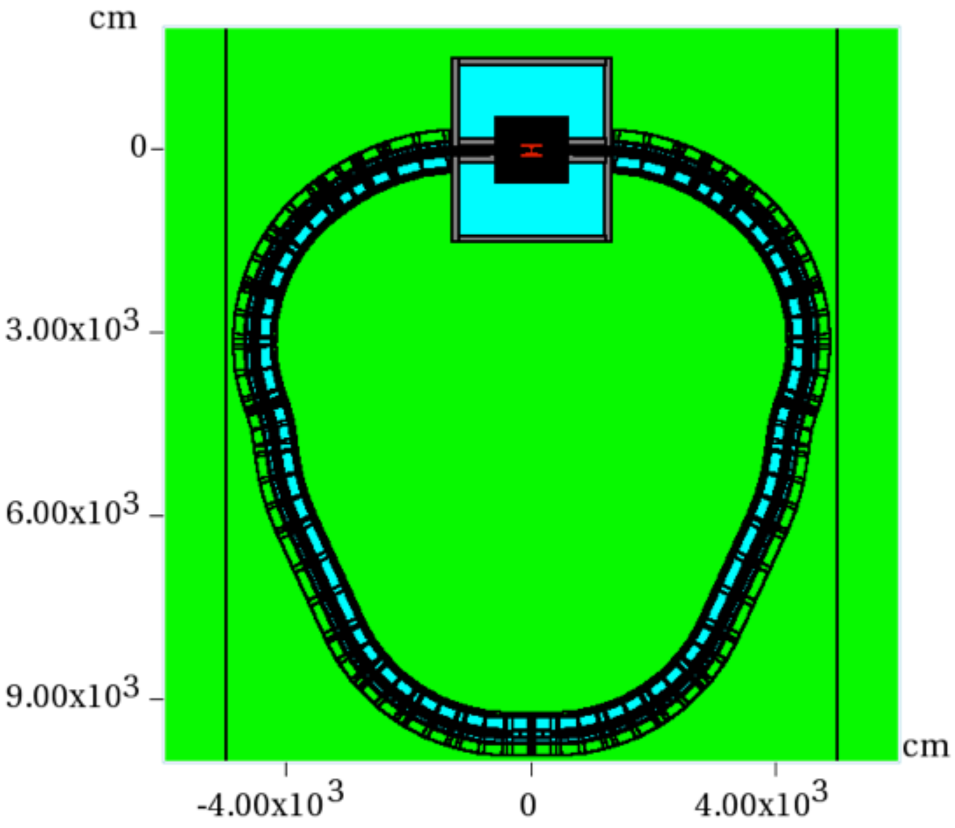
1. Protection of magnets from muon-decay radiation

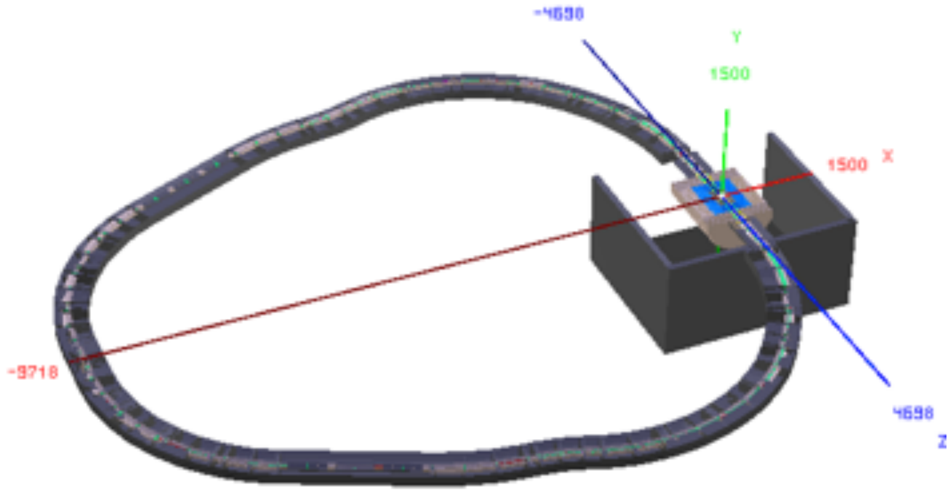
- muon decays are "benign": EM-shower *E* deposition ≪ hadronic
  - by ~ 4(?) orders of magnitude
- however – "Electrons from muon decays will deposit more than 300 kW in superconducting magnets of the HF collider ring." (MARS calculation) [N.V. Mokhov et al., arXiv:1806.08883]
  - Higgs Factory is example, applies to higher-*E* muon colliders as well (MAP studied 1.5, 3, and 6 TeV muons collider as well as HF)
  - potentially cause quenches & drive up cryo costs
- solved by novel magnet layouts
  - with internal W liners cooled at LN_2 temp

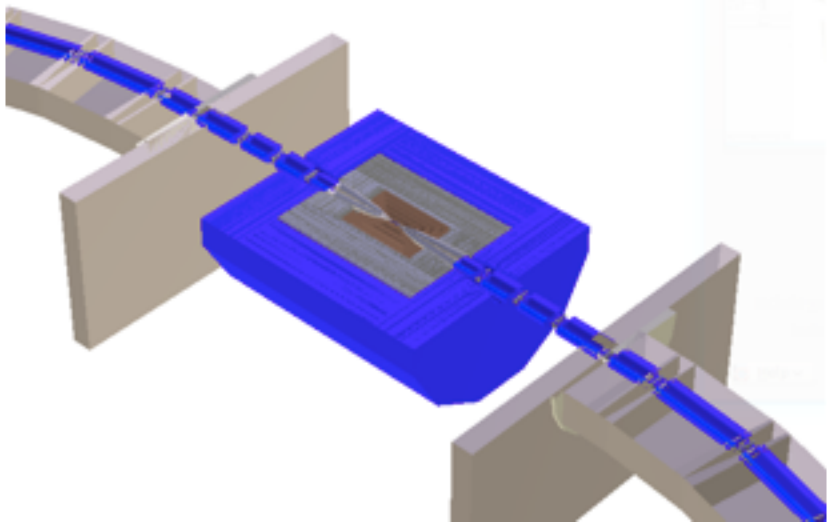
HF Storage Ring Layout

[**The Higgs Factory Muon Collider Superconducting Magnets and Their Protection Against Beam Decay Radiation**, N.V. Mokhov, et al., arXiv:1806.08883; JINST, to appear]

- MARS15 3D model:

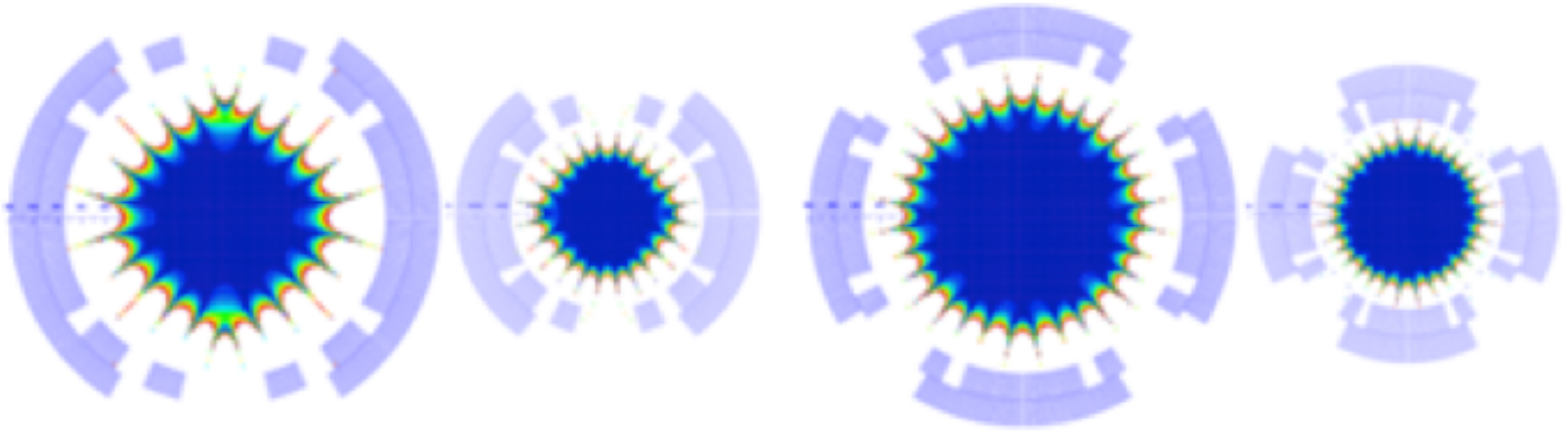






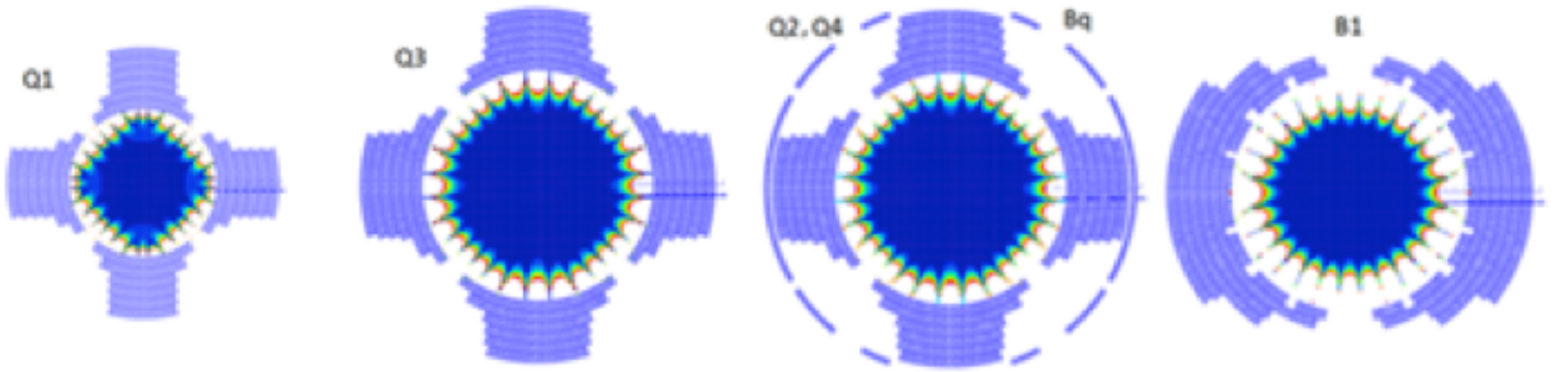
HF Storage Ring magnet cross-sections

- Ring:



D1, 270 mm D2, 160 mm Q1, 270 mm Q2, 160 mm

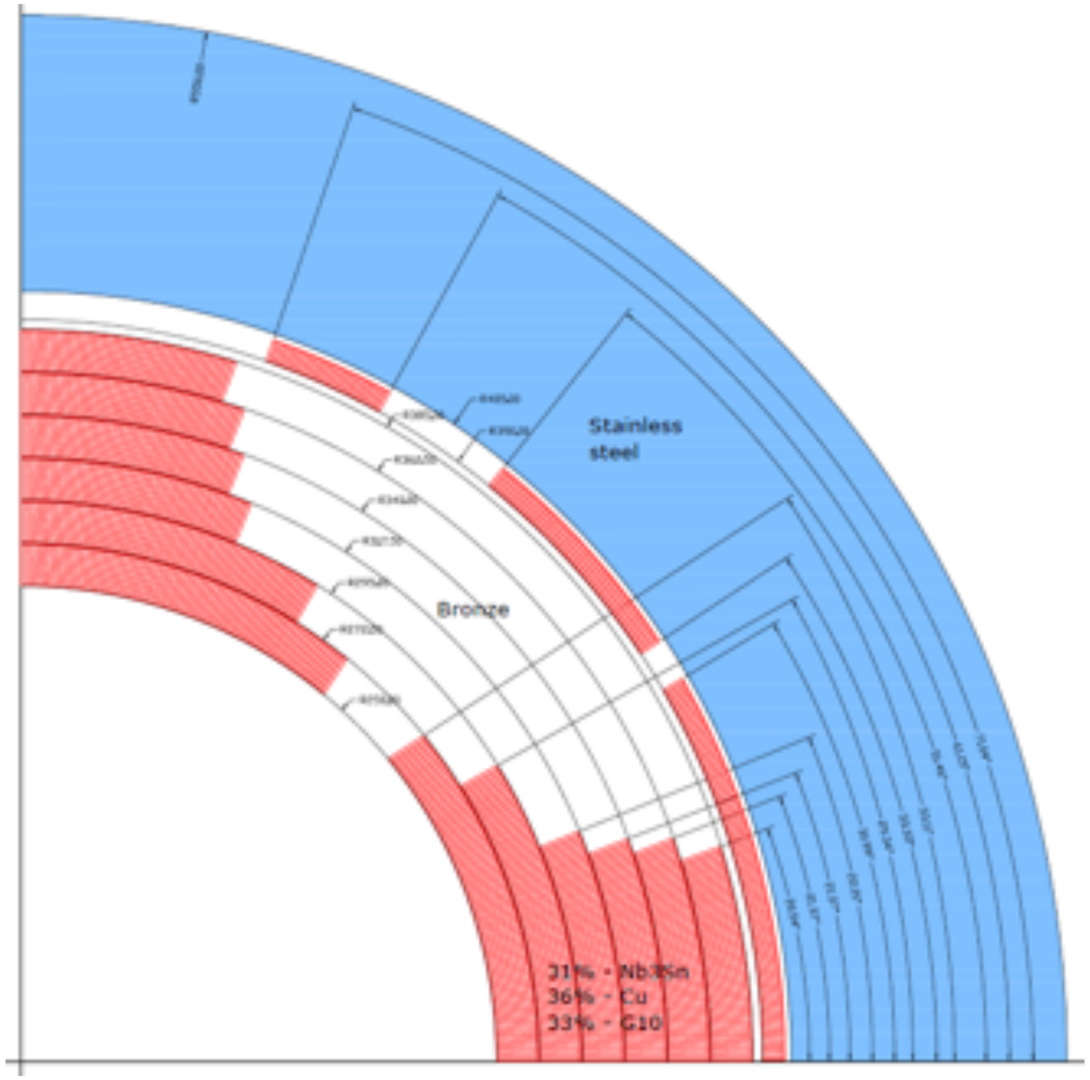
- IR:



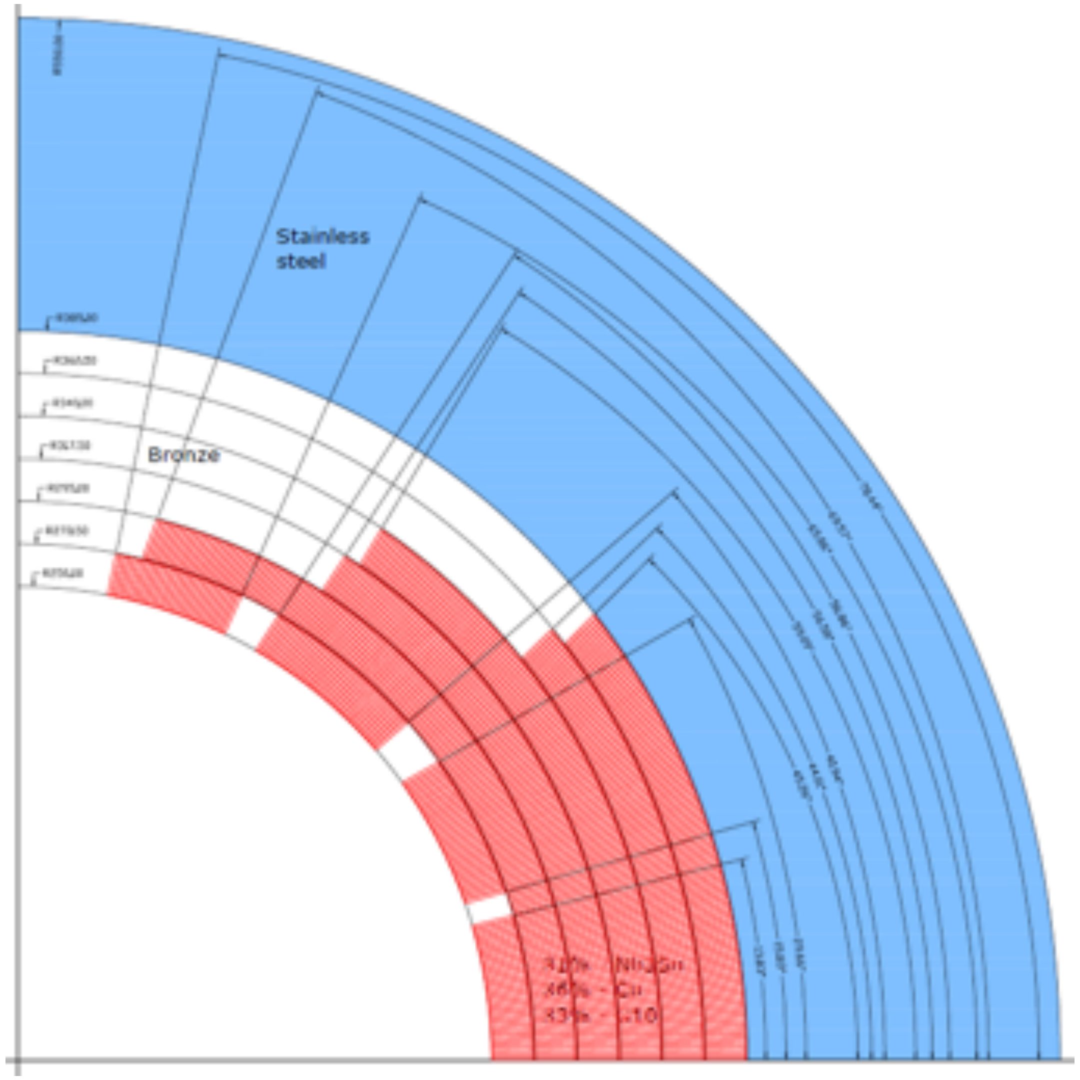
Q1, 320 mm Q3, 500 mm Q2,4, 500 mm B1, 500 mm

HF Storage Ring magnet cross-sections

- Example of IR magnets:



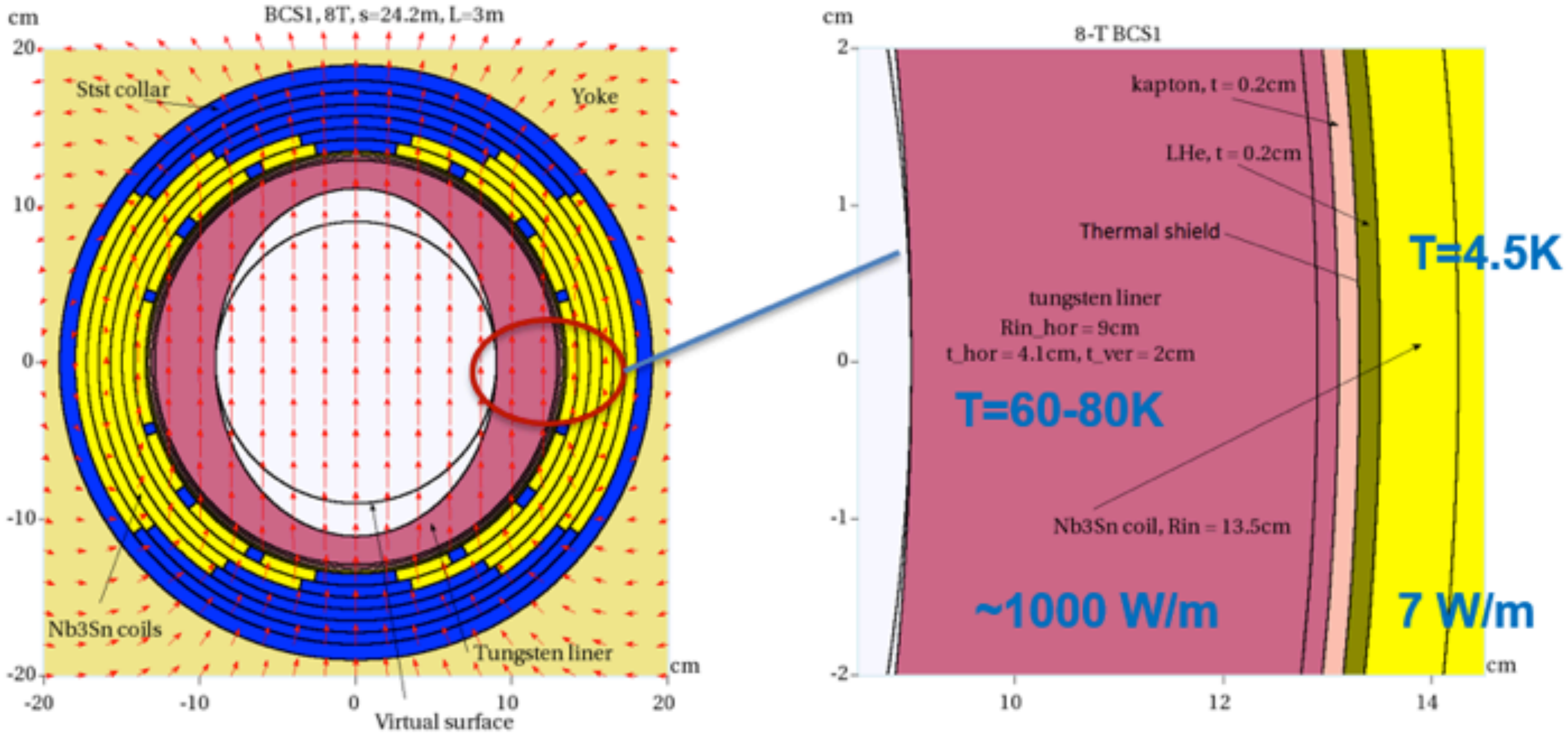
50-cm ID IR quadrupoles Q2 and Q4 as designed



50-cm ID IR 8 Tesla dipoles B1 and B2 as designed

HF Storage Ring magnet cross-sections

- Example of IR magnets:



Elliptical tungsten liner inside BCS1 8 T dipole — reduces power deposition > 100x.

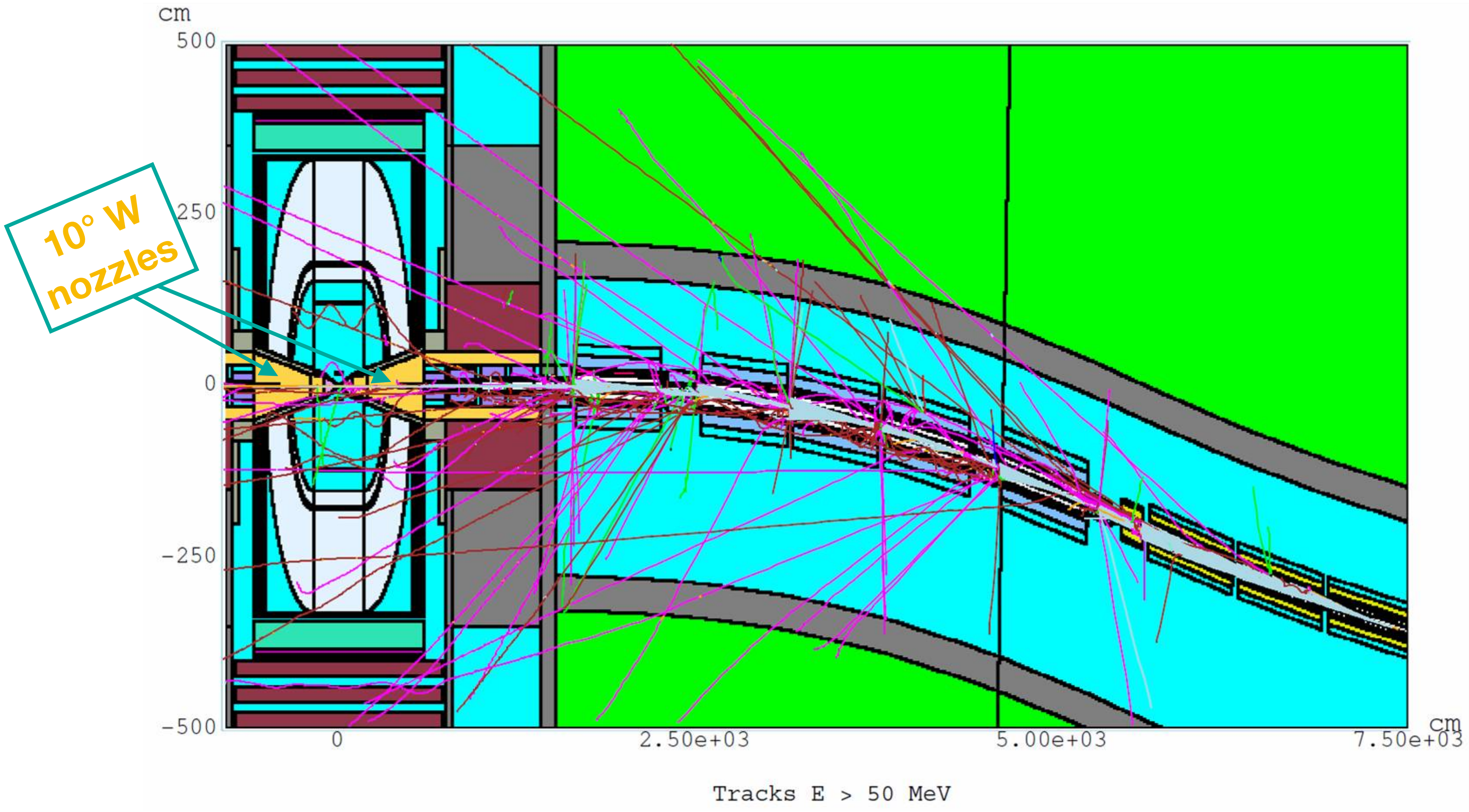
The Issues

2. Suppression of muon-decay backgrounds in detectors
   - muon decay electrons are out of time with particles from IP
     - typically by ≫ 1 ns
     - Higgs Factory is example, applies to higher-E muon colliders as well
   - potentially make events difficult/impossible to analyze
   - solved by MDI tungsten cone & ultrafast detectors

1.5 TeV MC Machine-Detector Interface

[**A Study of Muon Collider Background Rejection Criteria in Silicon Vertex and Tracker Detectors,** V. Di Benedetto, et al., arXiv:1806.08883; JINST, to appear]

- Machine–Detector Interface:



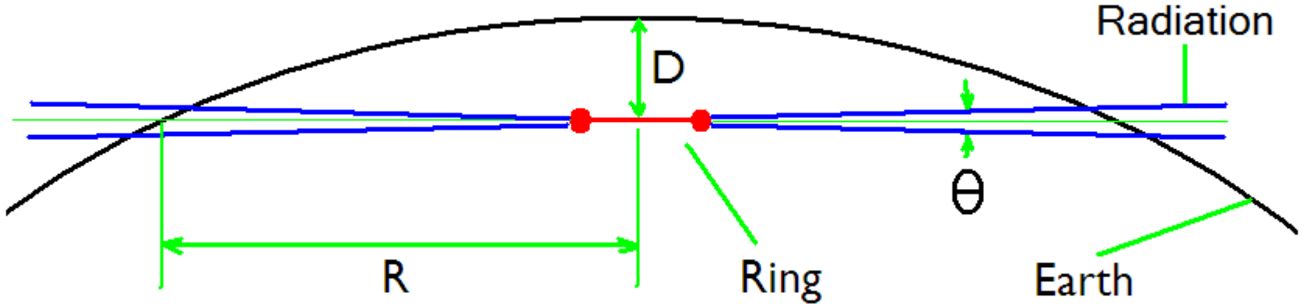
- Obtain >10^3 rejection of detector hits
  - from both shielding & timing (e.g., pixel coinc.)
- Resulting detector bkg comparable to LHC

The Issues

3. Protection of people from off-site neutrino-induced radiation

- neutrinos are "benign": weak cross section ≪≪ hadronic
  - by ~ 30(?) orders of magnitude
- however –
  - $\sigma_\nu \propto E$
  - Lorentz boost $\propto E \Rightarrow$ neutrino-cone intensity $\propto E^2$

    ⇒ people living where "neutrino pancake" intersects Earth's surface irradiated by DIS in rock, want dose ($\propto E^3$) $\lesssim$ 1 mR/y (statute/policy)



- imposes E-dependent limit on $\mathscr{L}$
- to alleviate: avoid straight sections (e.g. combined-function magnets & $B \neq 0$ between magnets), helical beam orbits, fewer μ,…

Off-site neutrino-induced radiation

- Radiation dose:

[**Muon Colliders**, R.B. Palmer, RAST **7** (2014) 137–159]

$$R_B = 4.4 \times 10^{-24} \frac{N_\mu f E^3 t \langle B \rangle}{DB} \mathrm{Sv},$$

$$R_L = 6.7 \times 10^{-24} \frac{N_\mu f E^3 t \langle B \rangle L}{D} \mathrm{Sv},$$

- Actually goes asymptotically as E^2, since $f \propto 1/E$

where E is the beam energy, f the repetition rate, t the time, D the depth (assumed to be 135 m at 1.5 and 3 TeV, and 540 m at 6 TeV), L the "straight-section" length, B the magnetic field strength

Table 4. Constraints on lattice designs to limit neutrino radiation.

One concept

E	B(min)	L(max)	$\mathscr{L}$
TeV	T	m	10^{34} cm^{-2} s^{-1}
1.5	0.25	2.4	0.008
3.0	1.5	0.28	0.6
6.0	1.5	0.28	12*

* constrained by ν radiation

- Solution beyond 10 TeV unclear at present†
- I would love to have that problem!

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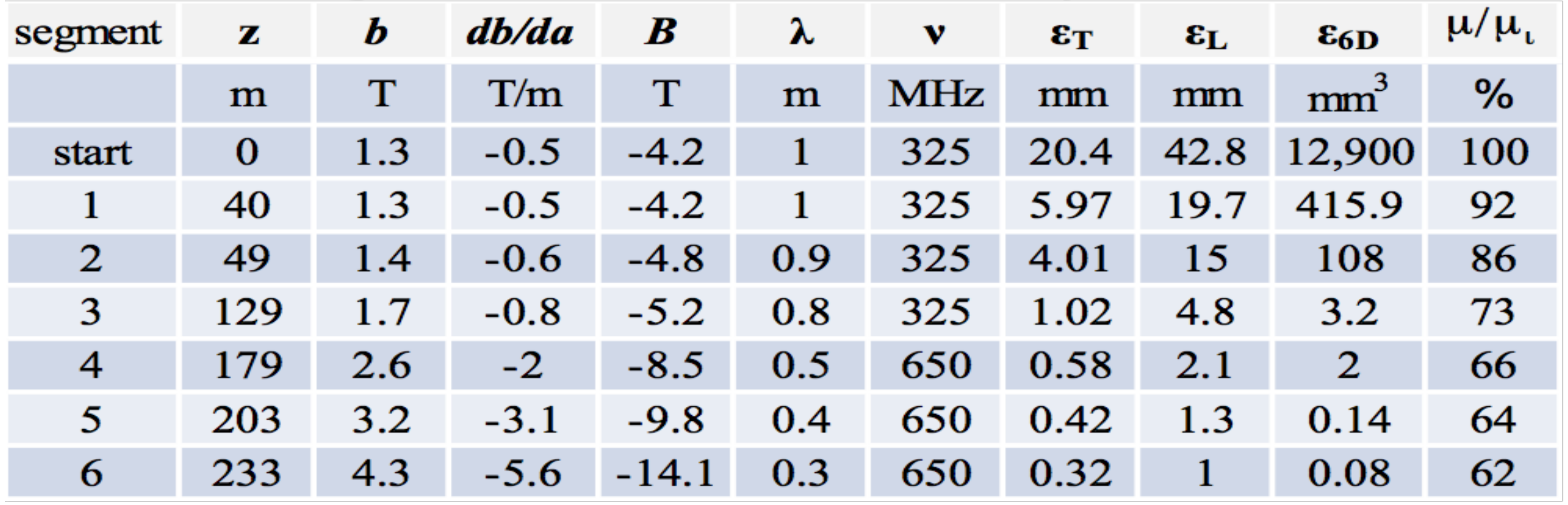
† although cf. AIP Conf. Proc. 1507 (2012) 860

Possible ν-Rad. Mitigations

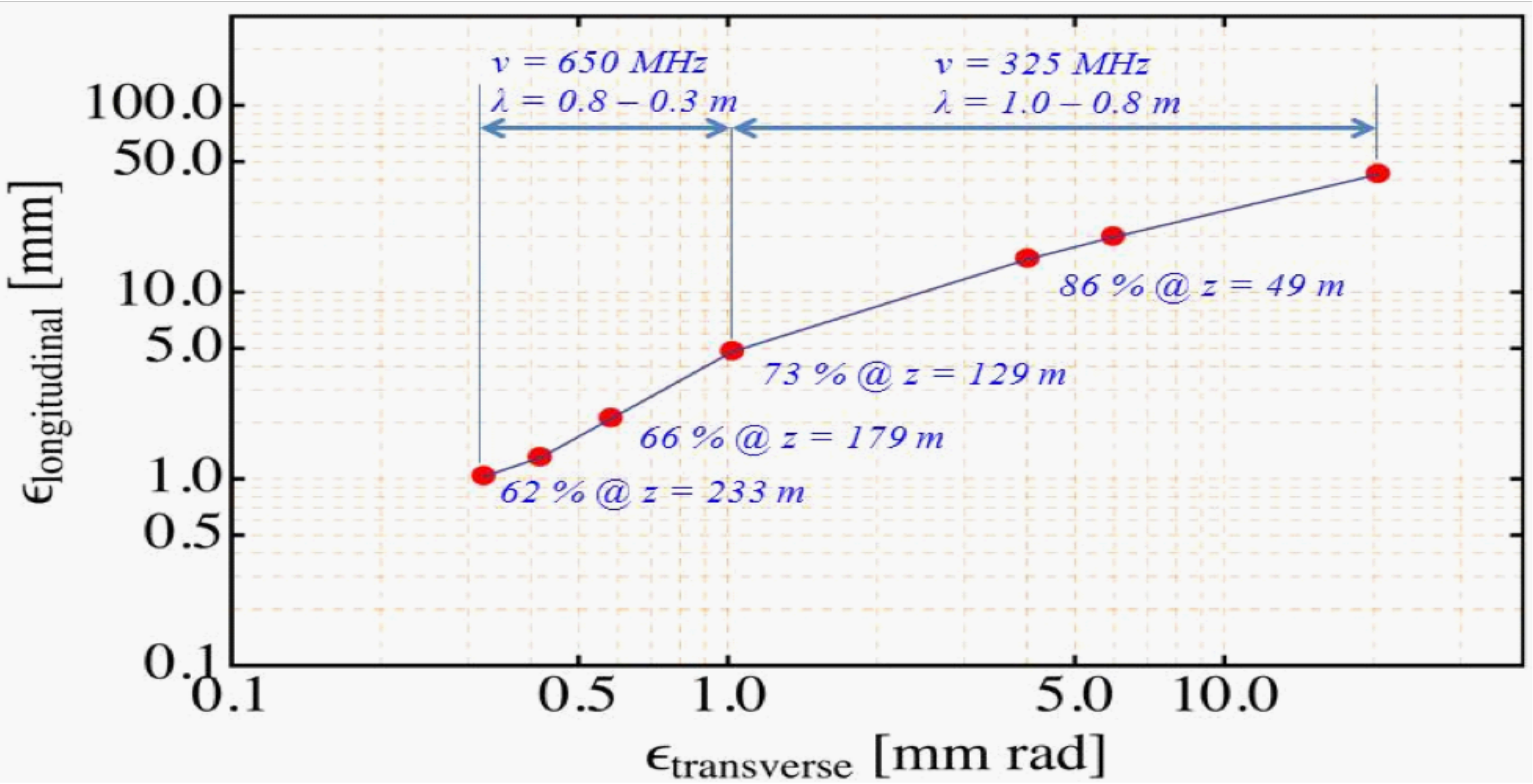
- Combined-function magnets & magnetic collars between magnets } (R. Palmer assumptions)
- Variable Pretzl orbits
- More cooling and lower muon intensities
  - ideas:
    - Better 6D cooling (e.g., using HTS magnets)
    - Parametric-resonance Ionization Cooling (PIC)
    - Optical Stochastic Cooling (testable at IOTA, https://fast.fnal.gov/projects.osc.shtml)
    - Coherent Electron Cooling

6-D HCC gets to ΔE~4 MeV~Γ_H

Table I: 6-segment HCC as simulated by G4beamline

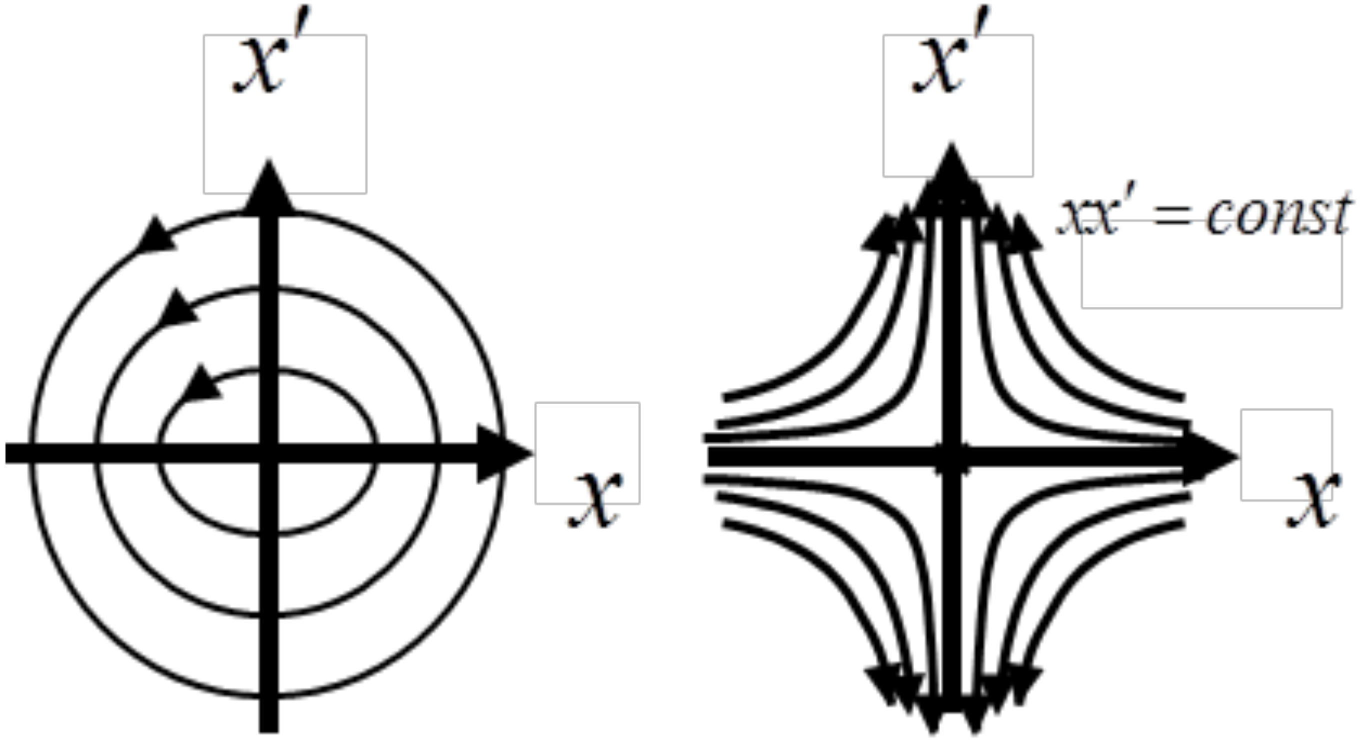


segment	z	b	db/da	B	λ	ν	ε_T	ε_L	ε_{6D}	μ/μ_ι
	m	T	T/m	T	m	MHz	mm	mm	mm^3	%
start	0	1.3	-0.5	-4.2	1	325	20.4	42.8	12,900	100
1	40	1.3	-0.5	-4.2	1	325	5.97	19.7	415.9	92
2	49	1.4	-0.6	-4.8	0.9	325	4.01	15	108	86
3	129	1.7	-0.8	-5.2	0.8	325	1.02	4.8	3.2	73
4	179	2.6	-2	-8.5	0.5	650	0.58	2.1	2	66
5	203	3.2	-3.1	-9.8	0.4	650	0.42	1.3	0.14	64
6	233	4.3	-5.6	-14.1	0.3	650	0.32	1	0.08	62



Muons, Inc.

Status of Skew PIC



- Increasing L by X 10 -> MC Higgs factory compelling
- Δx reduced, Δx’ limited by Ionization Cooling
- ½ integer resonance difficult to control
- Derbenev adds skew quads, simplifies optics, x,y->r
- Be absorber -> need ~200 mrad acceptance
- Using Chebyshev expansions ->
  - have solution with ~ 90 mrad acceptance

Status of Skew PIC

REFERENCES

[1] A. Afanasev *et al.*, "Skew-Quad Parametric- Resonance Ionization Cooling: Theory and Modeling," IPAC15, TUPHA013 (2015).
[2] A. Sy *et al.*, "Muon Tracking Studies in a Skew Parametric Resonance Ionization Cooling Channel," IPAC15, WEPJE015 (2015).
[3] A. Sy *et al.*, "Progress on Skew Parametric Resonance Ionization Cooling Channel Design and Simulation," NAPAC2016, TUPOB35 (2016).
[4] V.S. Morozov *et al.*, "Parametric -Resonance Ionization Cooling of Muon Beams," AIP Conf. Proc. 1507, 843-848 (2012).

Summary

- Magnet-coil shielding scheme from muon-decay radiation designed & practical
- Detector shielding scheme from muon-decay radiation designed & practical
    - in conjunction with ultrafast detectors
- Neutrino-induced radiation may be significant constraint on ultrahigh-energy muon colliders
    - won’t know until detailed design work @ $\sqrt{s}$ > 10 TeV
        - not an urgent problem
    - more μ cooling would help