Muon Collider Machine-Detector Interface Summary

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Muon Collider Physics Workshop
Fermilab
November 10-12, 2009

Introduction

Muon collider detector performance is strongly dependent on background particle rates in various sub-detectors. The deleterious effects of background and radiation environment produced by muon decay products have been identified in mid-90s as a potential showstopper. After all studies done on the subject, background mitigation remains to be the critical issue in the IR lattice, detector and magnet designs.

There have been impressive presentations, productive discussions and constructive dialogue of Machine-Detector Interface issues at this Workshop.

MDI Presentations

- Muon collider, CLIC and ILC overviews (M. Zisman, R. Palmer, D. Schulte, A. Seryi), MDI overview (N. Mokhov), related detector issues (M. Demarteau: “backgrounds, backgrounds, backgrounds”)
- Lattice design (Y. Alexahin, C. Johnstone)
- MDI approaches at CLIC and ILC (D. Schulte and A. Seryi)
- Background simulations (V. Alexahin, S. Striganov, C. Gatto)
- Calibrating energy at IP and polarization issues (T. Raja)
- IR magnets (A. Zlobin, R. Gupta, F. O’Shea, R. Palmer, Meinke)

Sources of Background at Muon Colliders

1. **IP $\mu^+\mu^-$ collisions:** Production x-section 1.34 pb at $\sqrt{S}$ = 1.5 TeV.

2. **IP incoherent e^+e^- pair production:** x-section 10 mb which gives rise to background of 3×10^4 electron pairs per bunch crossing.

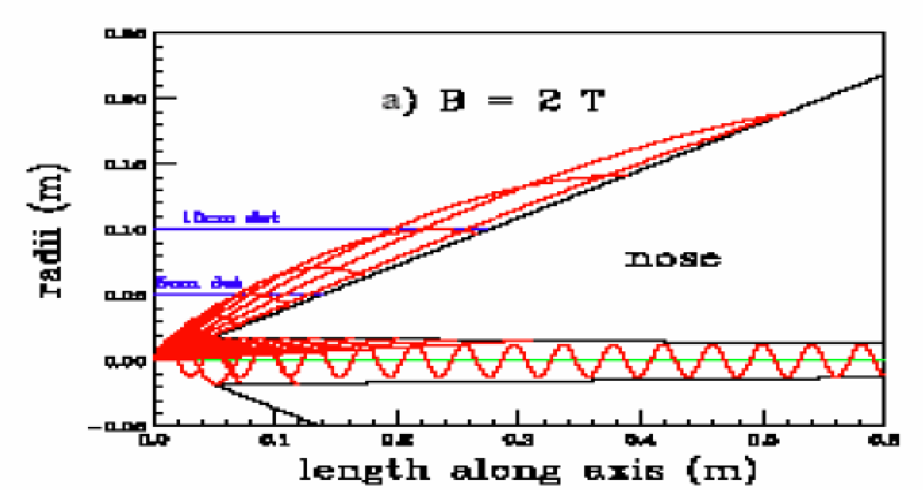
3. **Muon beam decay backgrounds:** Unavoidable bilateral detector irradiation by particle fluxes from beamline components and accelerator tunnel – ***major source at MC***.

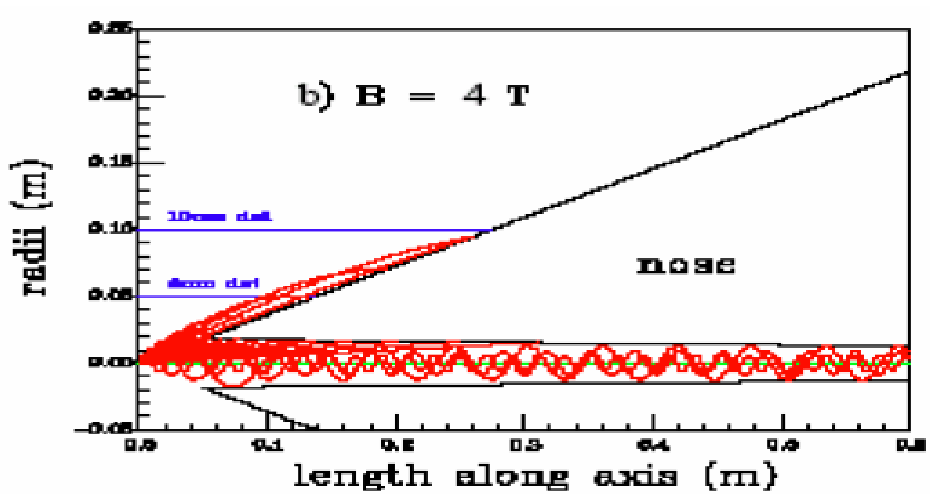
4. **Beam halo:** Beam loss at limiting apertures; unavoidable, but is taken care with an appropriate collimation system far upstream of IP.

Incoherent Pair Production

Incoherent pair production from $\mu^+\mu^- \rightarrow \mu^+\mu^- e^+e^-$ can be significant for high energy muon colliders.

- Estimated cross section of 10 mb giving 3×10^4 electron pairs per bunch crossing.
- The electron pairs have small transverse momentum, but the on-coming beam can deflect them towards the detector.
- Figures show examples of electron pairs tracked near the detector in the presence of the detector solenoid field.
- With a 2 Tesla field, only 10% of electrons make it 10 cm into the detector. With 4 Tesla field no electrons reach 10 cm.





SCRAPING MUON BEAM HALO

- For TeV domain, extraction of beam halo with electrostatic deflector reduces loss rate in IR by three orders of magnitude; efficiency of an absorber-based system is much-much lower.

- For 50-GeV muon beam, a five meter long steel absorber does an excellent job, eliminating halo-induced backgrounds in detectors.

Muon Beam Decays: Major Source of Backgrounds

Contrary to hadron colliders, almost 100% of background and radiation problems at MC arise in the lattice. **Muon decays is the major source**. The decay length for 0.75-TeV muons is $\lambda_D = 4.7 \times 10^6$ m. With 2e12 muons in a bunch, one has 4.28×10^5 decays per meter of the lattice in a single pass, and 1.28×10^{10} decays per meter per second for two beams.

Electrons from muon decay have mean energy of approximately 1/3 of that of the muons. At 0.75 TeV, these 250-GeV electrons, generated at the above rate, travel to the inside of the ring magnets, and radiate a lot of energetic synchrotron photons towards the outside of the ring.

Electromagnetic showers induced by these electrons and photons in the collider components generate intense fluxes of muons, hadrons and daughter electrons and photons, which create high background and radiation levels both in a detector and in the storage ring at the rate of about **0.5 kW/m**.

2009 Muon Collider Tentative Parameters

√s (TeV)	1.5	3
Av. Luminosity / IP (10^{34}/cm^2/s)	0.8	3.4
Max. bending field (T)	10	14
Av. bending field in arcs (T)	6	8.4
Circumference (km)	3	4.5
No. of IPs	2	2
Repetition Rate (Hz)	15	12
Beam-beam parameter/IP	0.1	0.1
β* (cm)	1	0.5
Beam size @ IP (μm)	6	3
Bunch length (cm)	1	0.5
No. bunches / beam	1	1
No. muons/bunch (10^{12})	2	2
Norm. Trans. Emit. (μm)	25	25
Energy spread (%)	0.1	0.1
Norm. long. Emit. (m)	0.07	0.07
Total RF voltage (MV) at 800MHz	80	900
μ+ in collision / 8GeV proton	0.008	0.007
8 GeV proton beam power (MW)	4.8	4.3

$$\langle \mathcal{L} \rangle = f_0 \frac{n_b N_\mu^2}{4\pi\varepsilon_\perp \beta^*} h \times \frac{1}{2}\tau f_{rep} \sim \frac{P_\mu \xi}{C\beta^*} h \tau$$

Pμ – average muon beam power (~ γ)

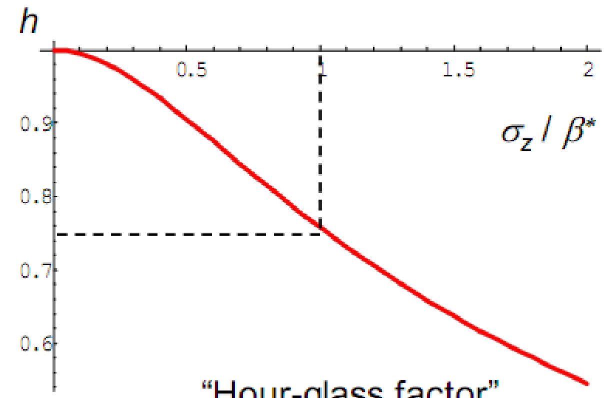
$$\xi = \frac{r_\mu N_\mu}{4\pi\gamma\varepsilon_\perp}$$ – beam-beam parameter

$\gamma\varepsilon_\perp$ – normalized emittance

C – collider circumference (~ γ if B=const)

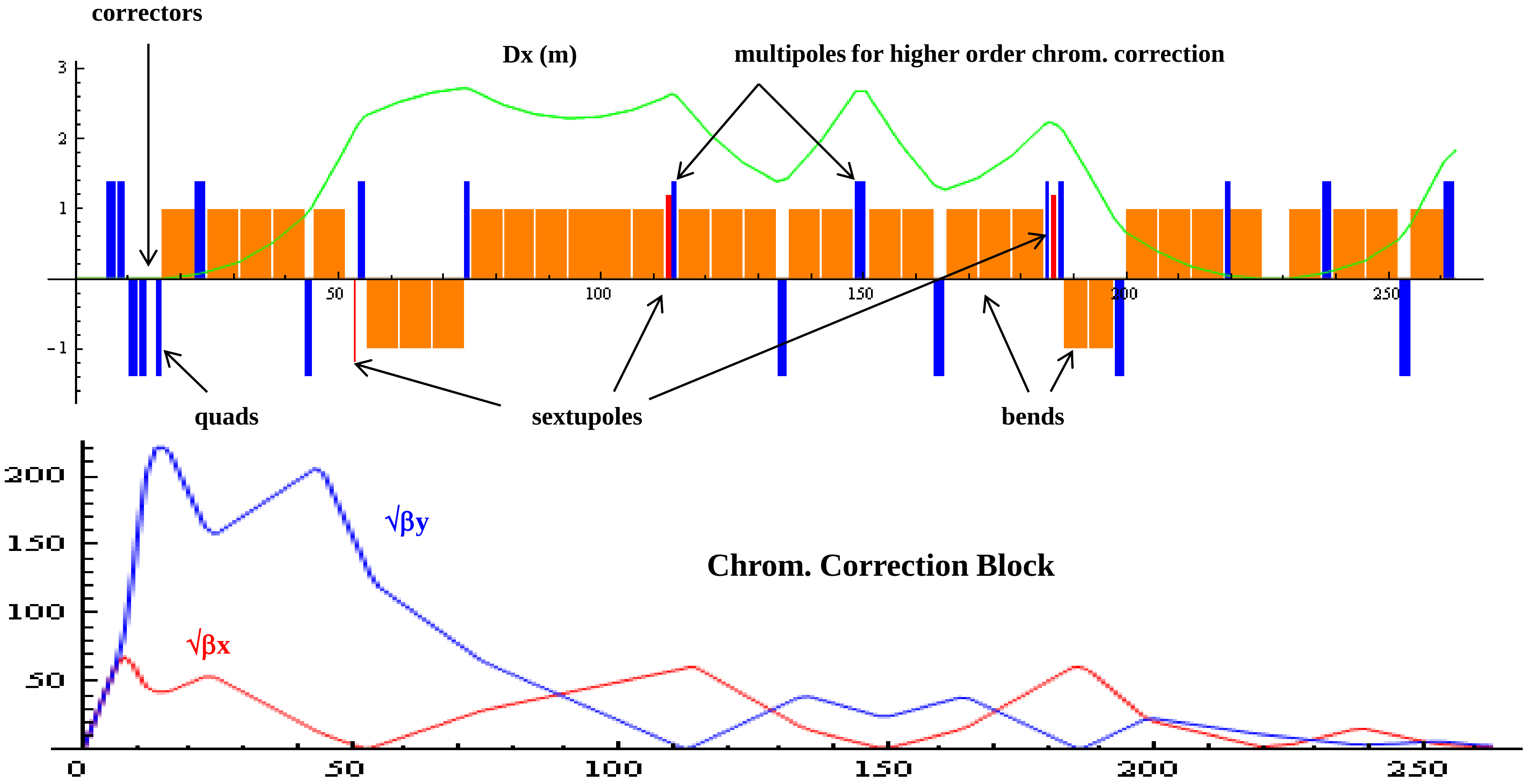
τ – muon lifetime (~ γ)

β* – beta-function at IP

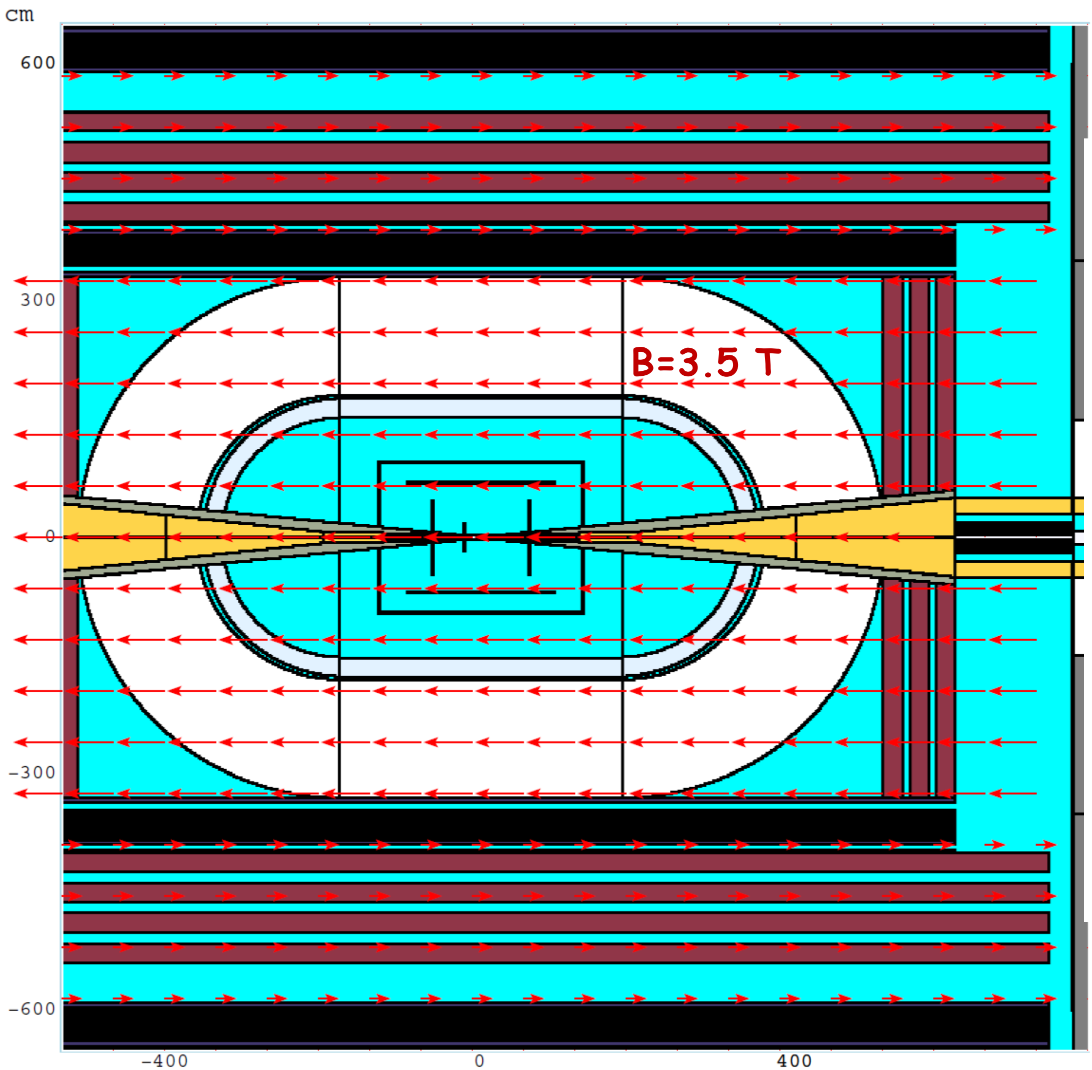


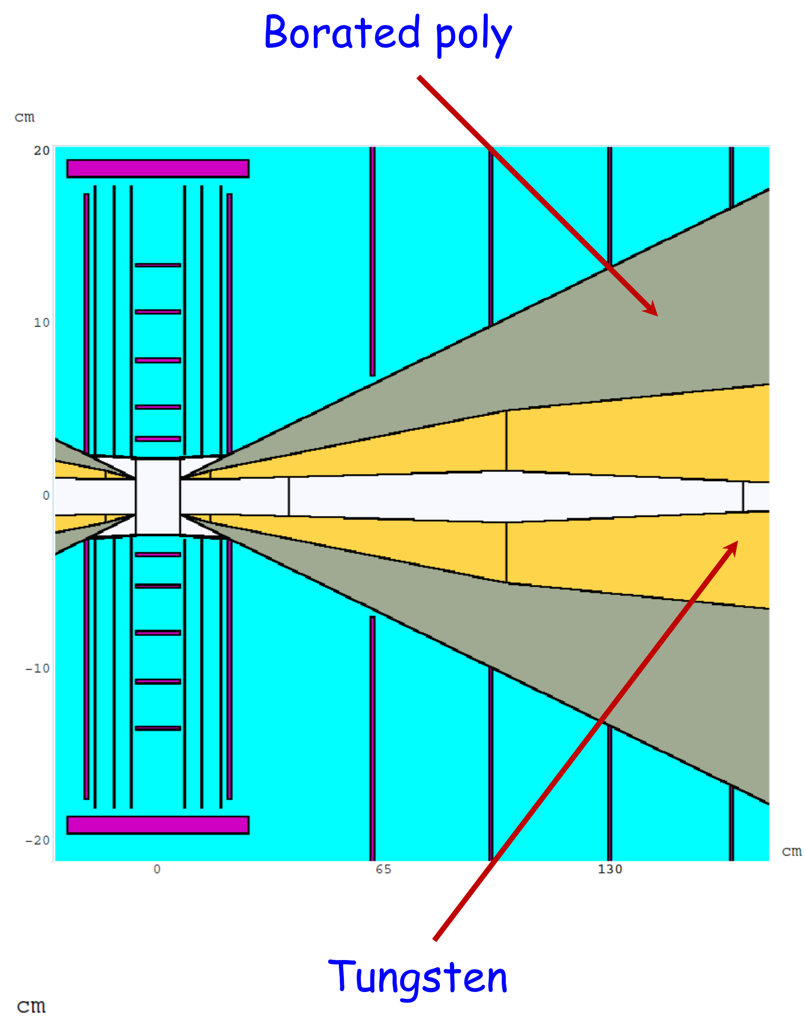
"Hour-glass factor"

IR Design by E.Gianfelice-Wendt & Y.Alexahin (2009)

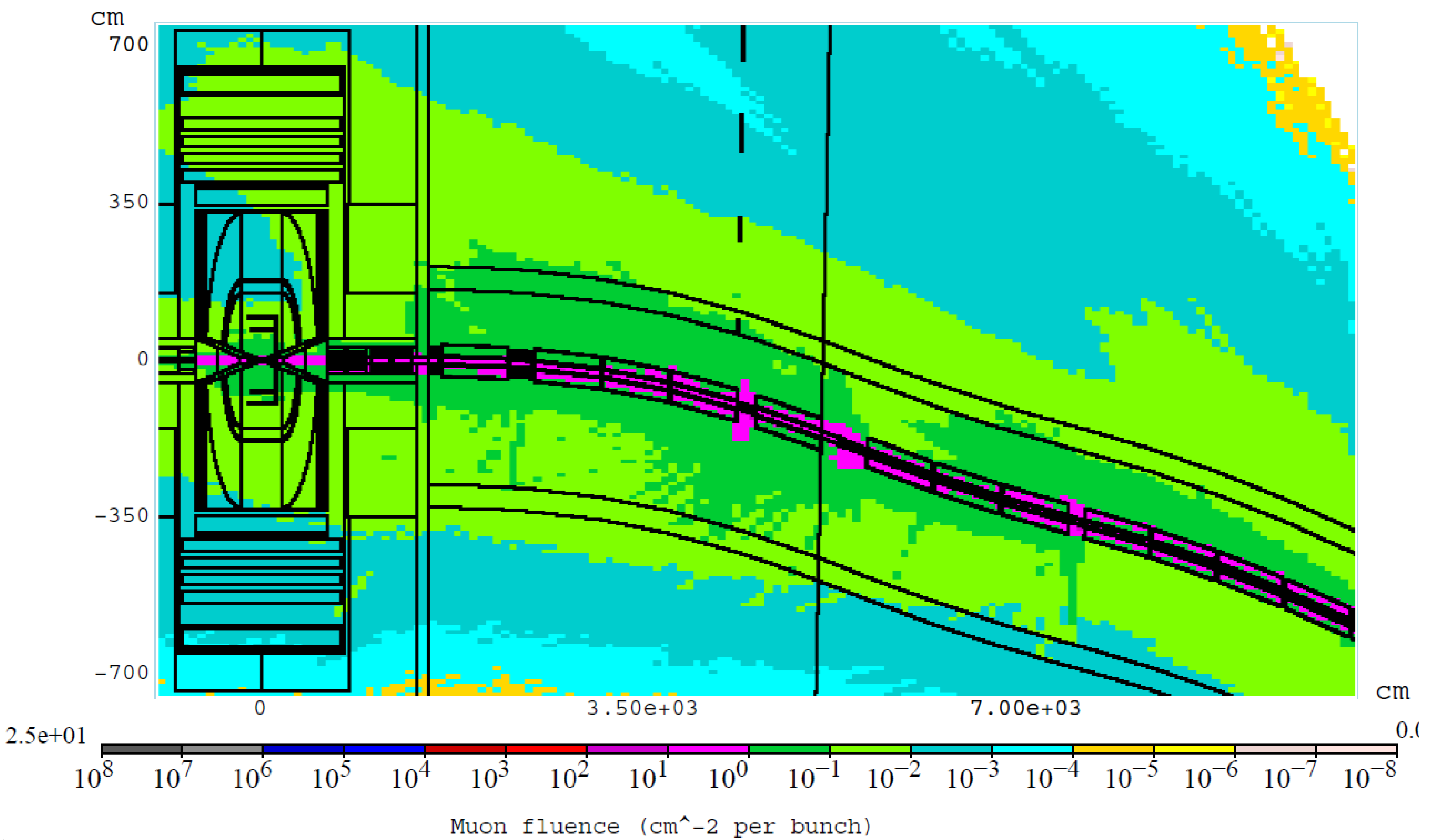


4th Concept Detector at MC: MARS15 Model

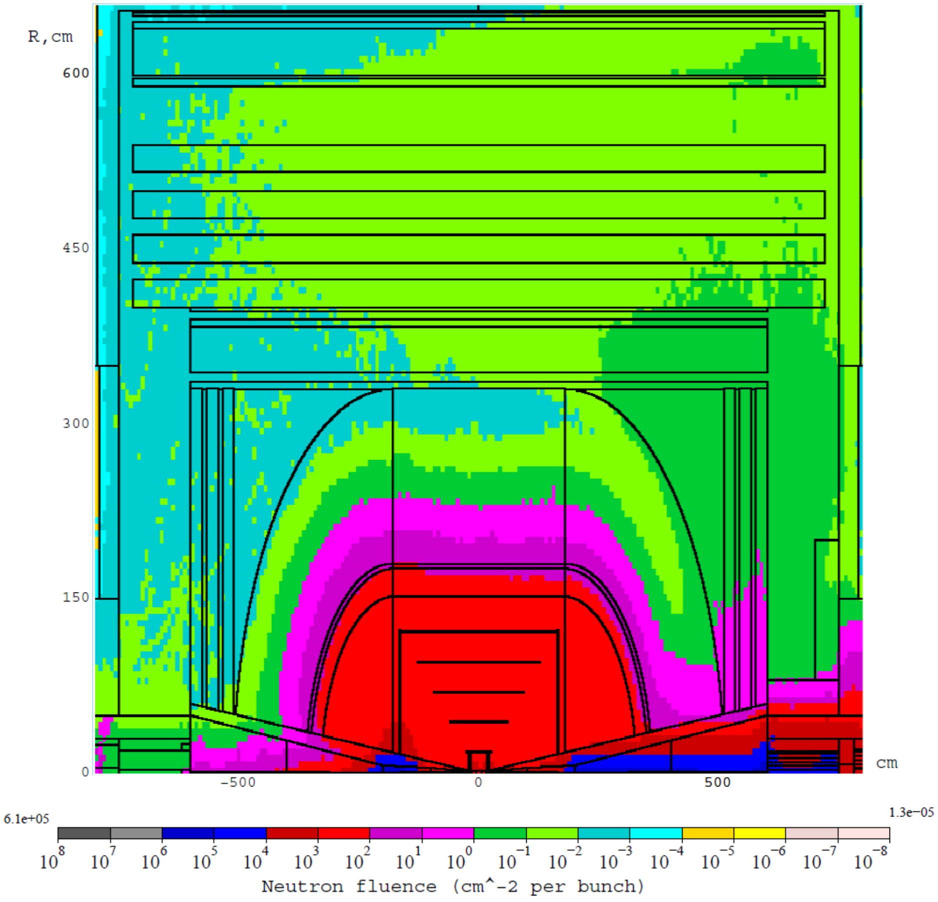


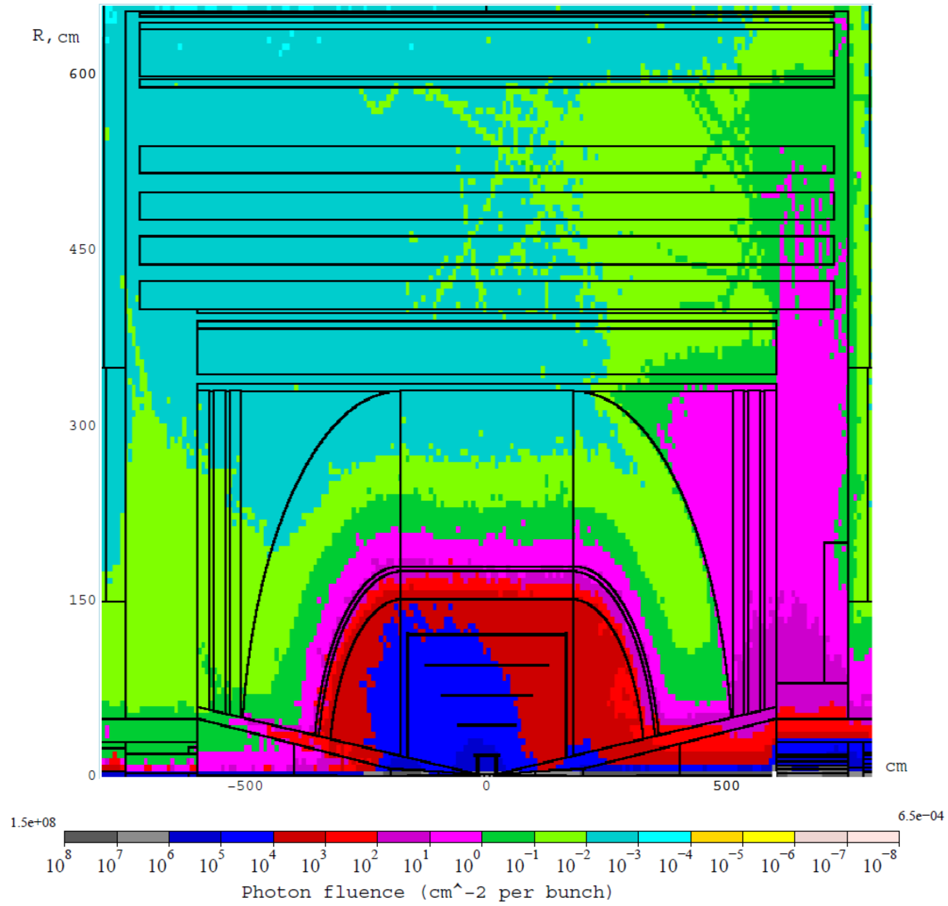


Muon Fluence in Orbit Plane

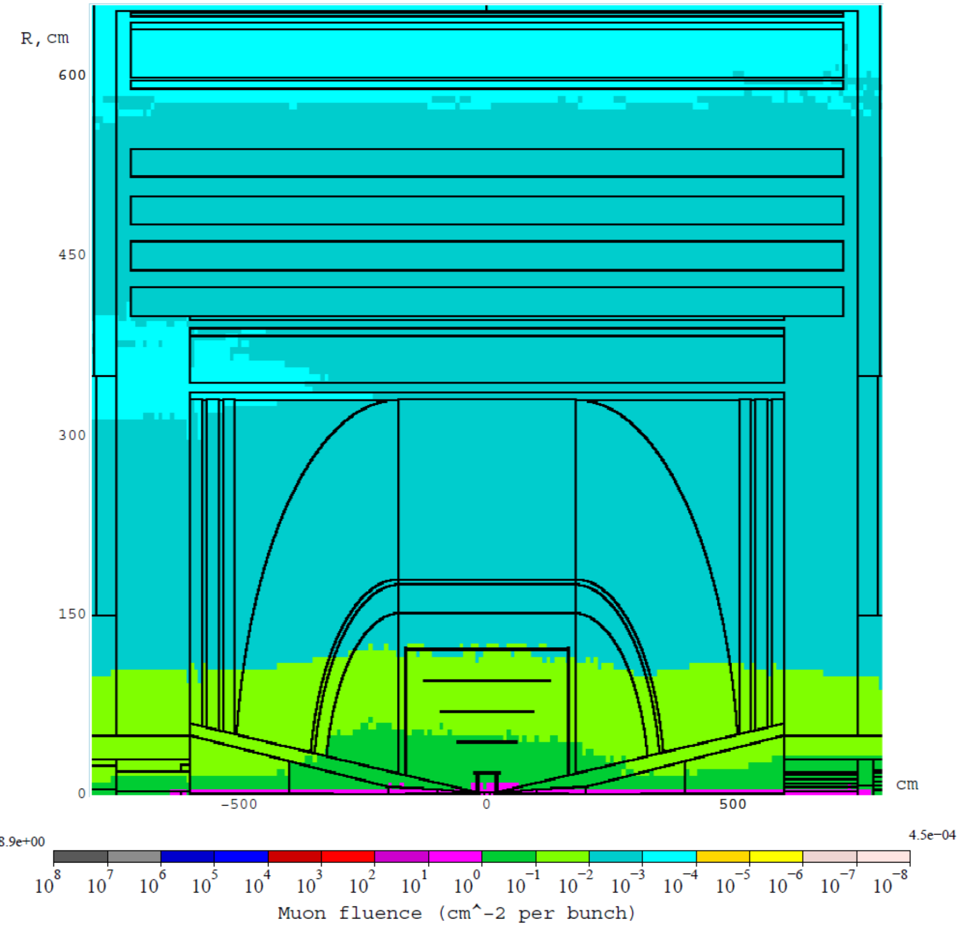


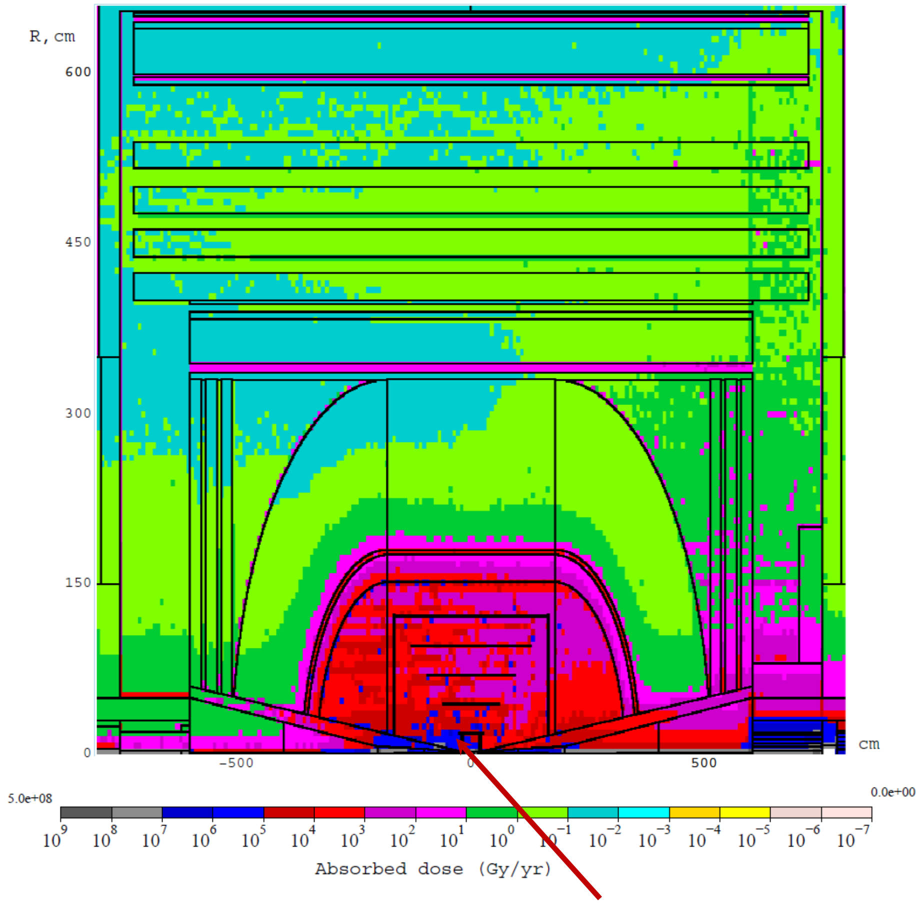
Neutron and Photon Fluence





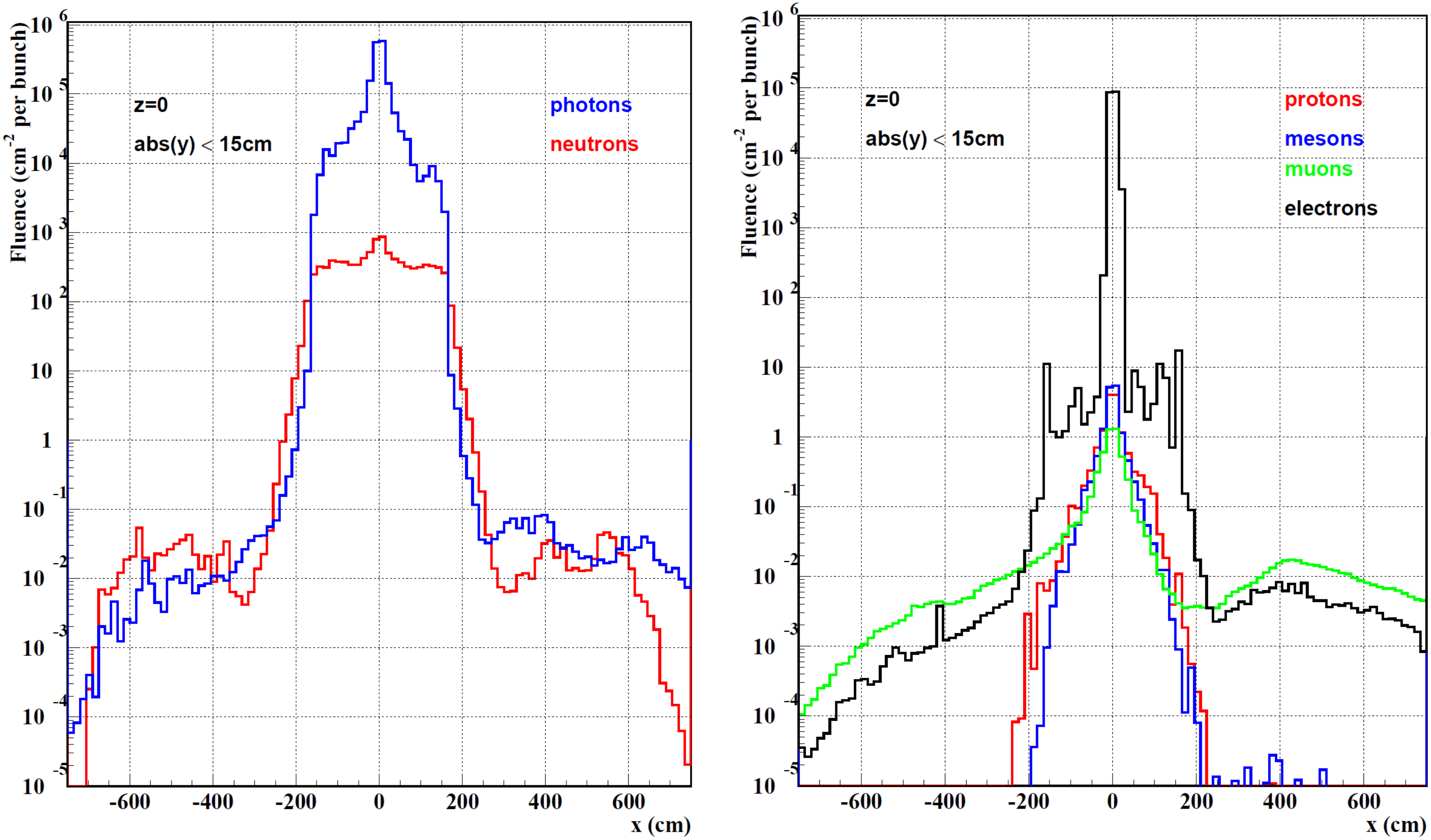
Muon Fluence and Total Dose per Year





~1 MGy/yr for 2 beams, Comparable to LHC

Particle Fluence in Horizontal Plane at z=0



Compare to '96 Studies w/Optimized 20-deg Nozzle

Longitudinal fluence

Detector	Radius(cm)	γ's	neutrons	$e^{\pm}$	$\pi^{\pm}$	protons	$\mu^{\pm}$
Vertex	5-10	7900	1100	69	14.4	0.8	1.5
	10-15	3100	1200		3.7	0.05	0.5
	15-20	1600	1000		4.6	4.0	2.3
Tracker	20-50	450	870		0.8	3.9	0.3
	50-100	120	520		0.1	2.2	0.06
	100-150	130	330		0.003	0.4	0.01
Calorimeter	160-310						0.002
Muon	310-10000						0.0002

Radial fluence

Detector	Radius(cm)	γ's	neutrons	$e^{\pm}$	$\pi^{\pm}$	protons	$\mu^{\pm}$
Vertex	5	16900	1600	84.0	9.5	1.7	.35
	10	4800	1400	9.4	4.5	1.4	0.43
	15	2200	1400	2.1	2.1	1.1	0.33
	20	1250	1400		1.3	1.9	0.20
Tracker	50	440	1500		0.22	4.2	0.032
	100	160	360		0.04	0.8	0.008

Neutrons (with same Eth) are 2-3x lower. Muons are the same. Pions 2x lower; protons 5x higher, photons 100x higher, electrons (?) 1000x higher (smaller cone, neutron Eth~0 now, and rather different detector).

'96 Studies w/Optimized 20-deg Nozzle

Vertex Detector Hit Density (a layer of Silicon at a radius of 10 cm):

750 photons/cm^2	$\rightarrow$	2.3 hits/cm^2
110 neutrons/cm^2	$\rightarrow$	0.1 hits/cm^2
1.3 charged tracks/cm^2	$\rightarrow$	1.3 hits/cm^2
TOTAL		**3.7 hits/cm^2**

$\rightarrow$ 0.4% occupancy in 300x300 μm^2 pixels

- ***MARS predictions for radiation dose at 10 cm for a 2x2 TeV Collider comparable to at LHC with L=10^{34} cm^{-2}s^{-1}***

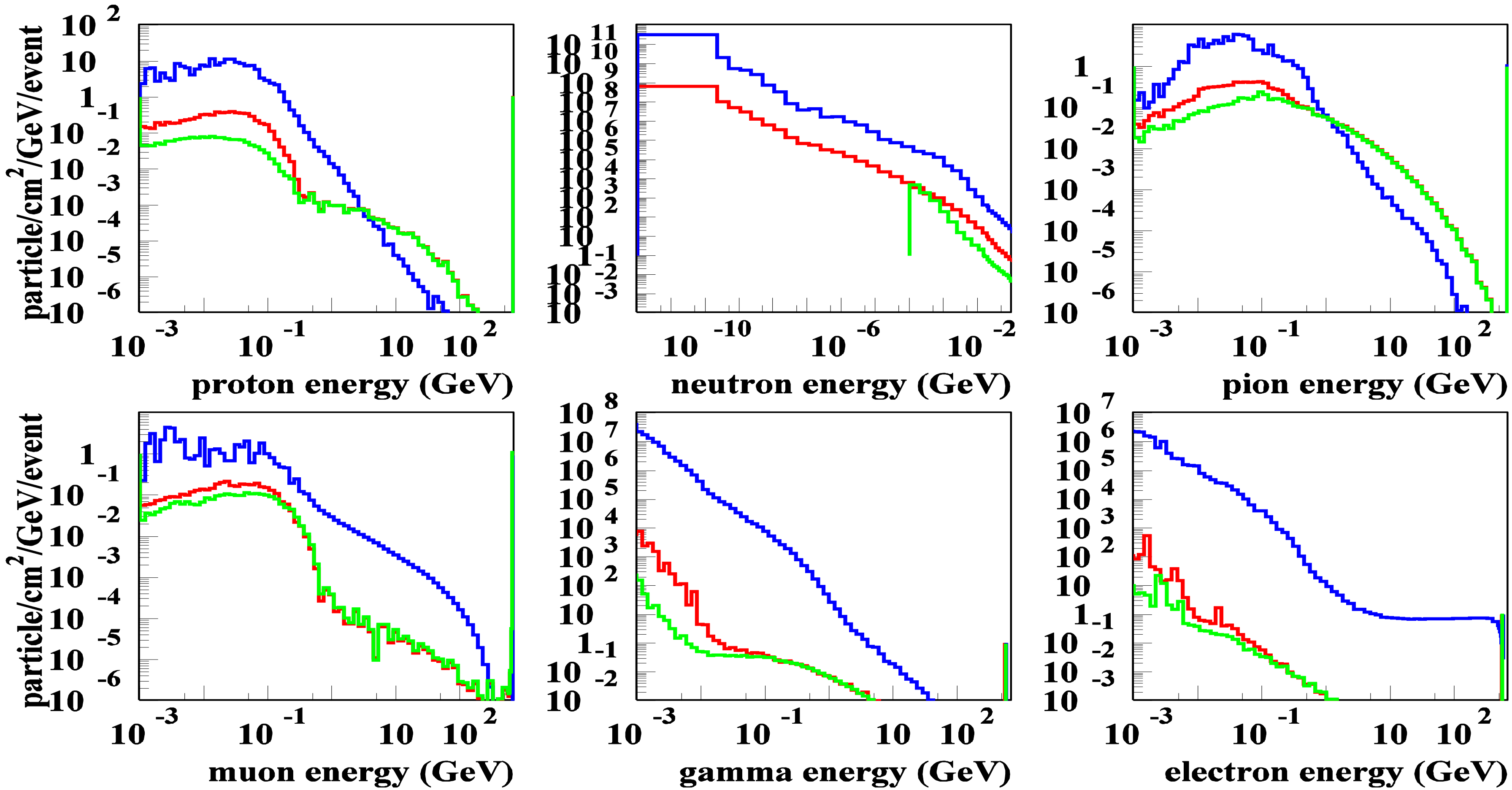
- At 5cm radius: 13.2 hits/cm^2 $\rightarrow$ 1.3% occupancy

- For comparison with CLIC (later) … at r = 3cm hit density about ×2 higher than at 5cm $\rightarrow$ ~20 hits/cm^2 $\rightarrow$ 0.2 hits/mm^2

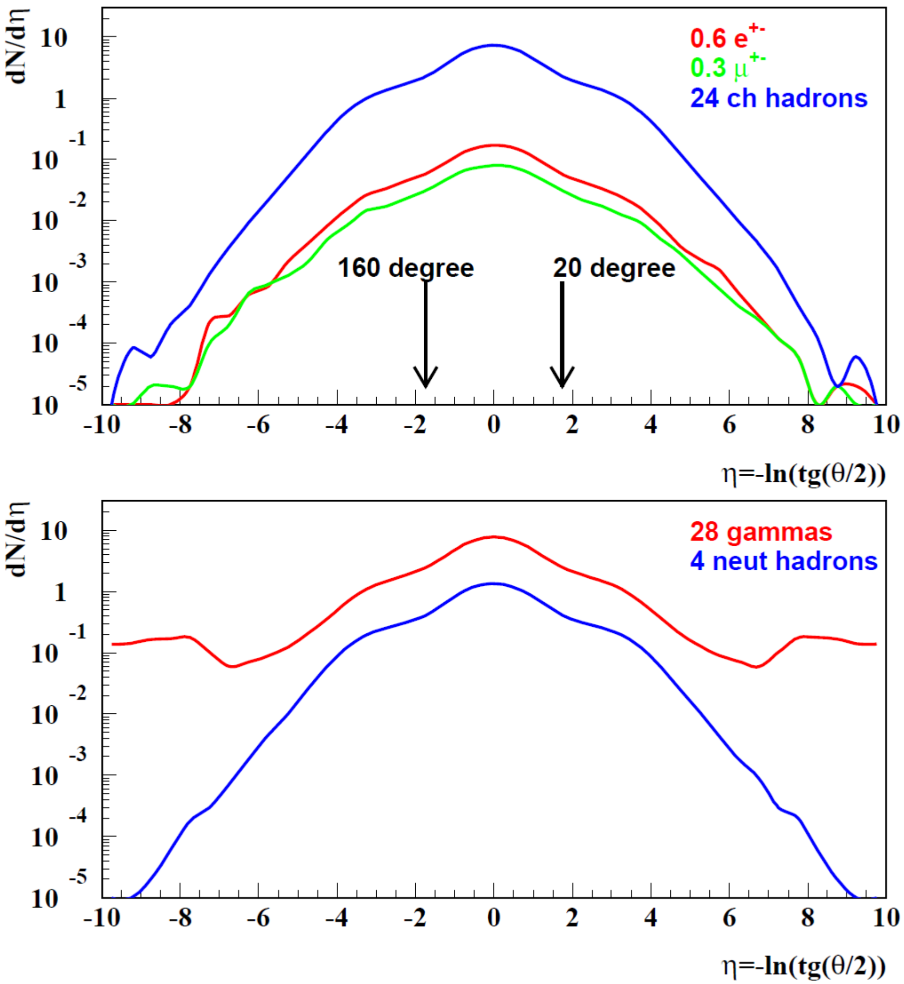
Machine vs Vetrex Backgrounds in Tracker

Energy spectra in tracker (+-46x46x5cm)

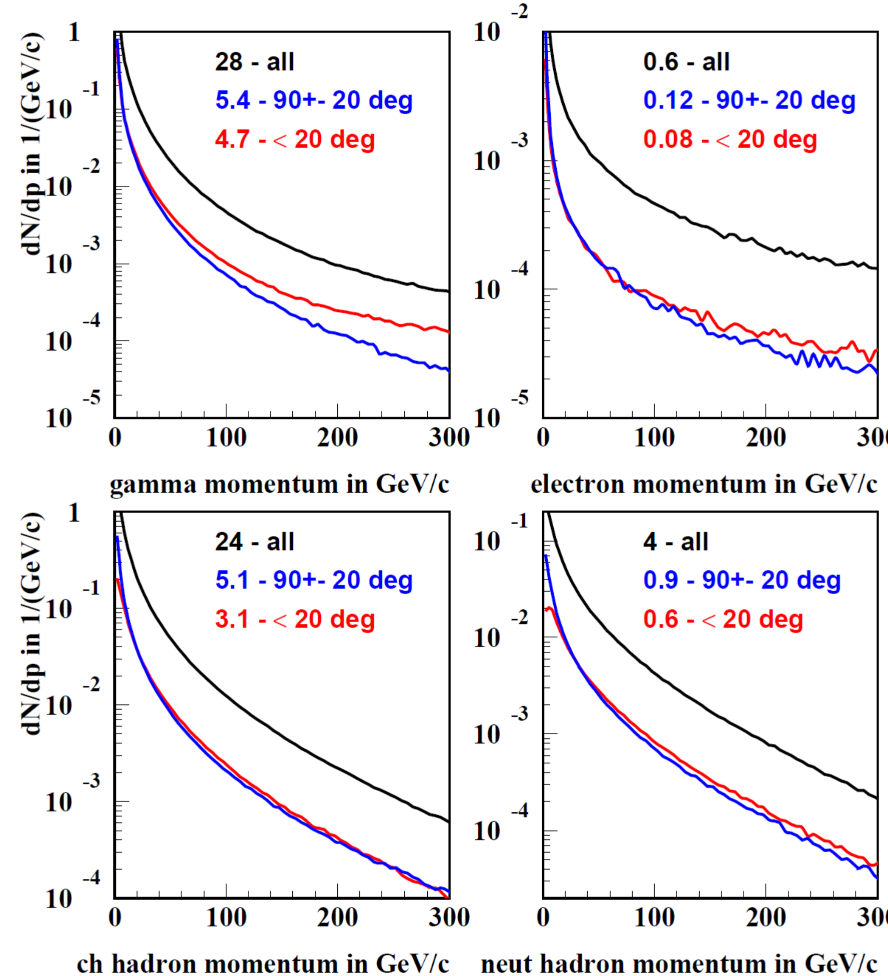
Blue lines - from machine, red lines - Z0 events, green lines - Higgs events



Rapidity and Momentum Spectra from $\mu^+\mu^-$ Collision



$\mu^+ \mu^- \rightarrow \gamma^*/Z^0$ at 1500 GeV (1.34 pb)



$\mu^+ \mu^- \rightarrow \gamma^*/Z^0$ at 1500 GeV (1.34 pb)

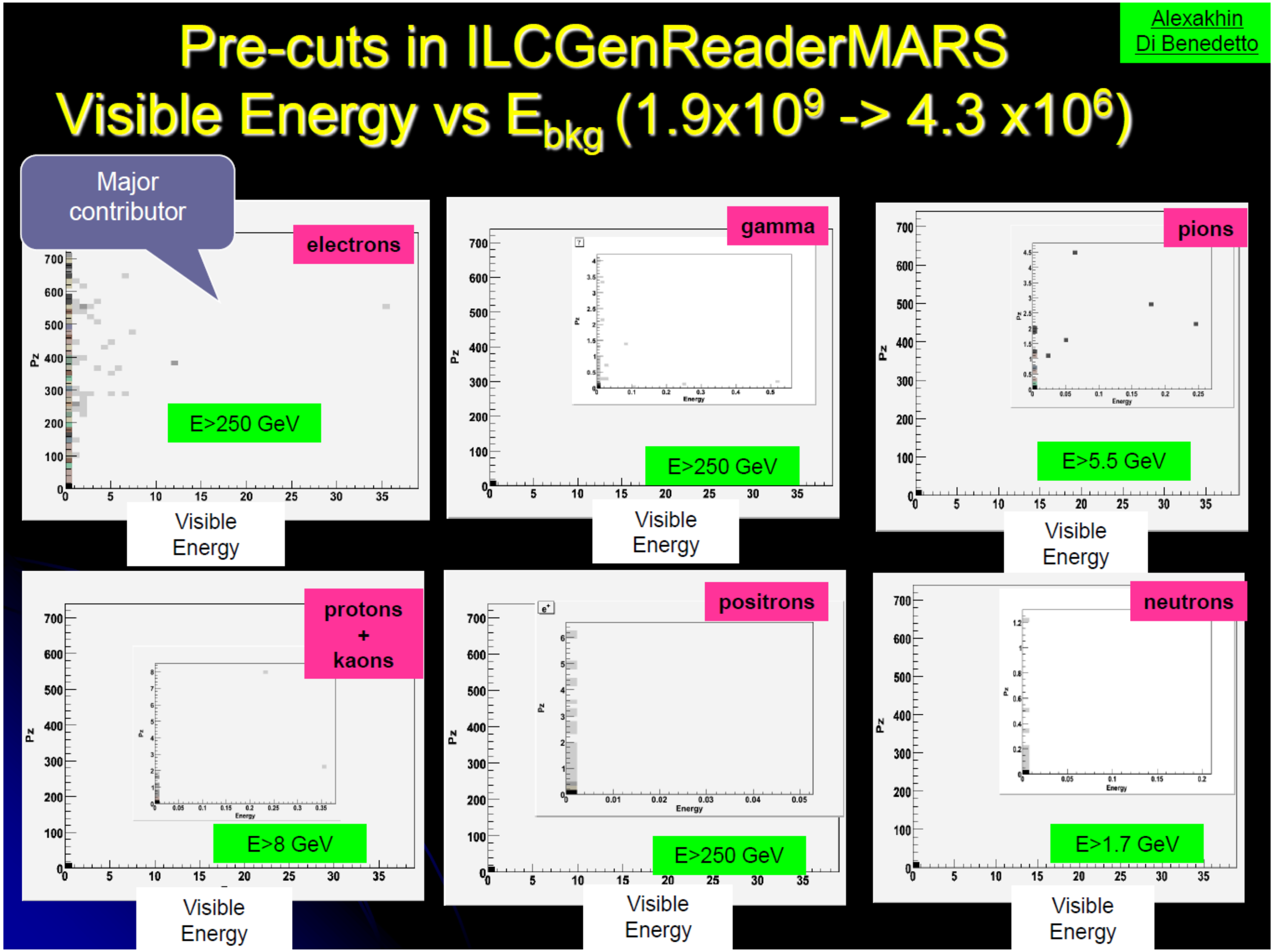
Simulation and Performance of Detectors Corrado Gatto)

ILCroot: root Infrastructure for Large Colliders

- **Software architecture based on root, VMC & Aliroot**
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
  - Extremely large community of users/developers
- **Re-allignement with latest Aliroot version every 1-2 years (v4.17 release)**
- **It is a simulation framework and an Offline Systems:**
  - **Single framework, from generation to reconstruction through simulation. Don't forget analysis!!!**
  - It is immediatly usable for test beams
  - Six MDC have proven robustness, reliability and portability
- **Main add-ons Aliroot:**
  1. Interface to external files in various format (STDHEP, text, etc.)
  2. Standalone VTX track fitter
  3. Pattern recognition from VTX (for si central trackers)
  4. Parametric beam background (# integrated bunch crossing chosen at run time
- Growing number of experiments have adopted it: Alice (LHC), Opera (LNGS), (Meg), CMB (GSI), Panda(GSI), 4th Concept, (SiLC ?) and LHeC
- ***It is Publicly available at FNAL on ILCSIM since 2006***

November 11th, 2009 MuonCollide Workshop - C. Gatto 7

Simulation and Performance of Detectors Corrado Gatto)



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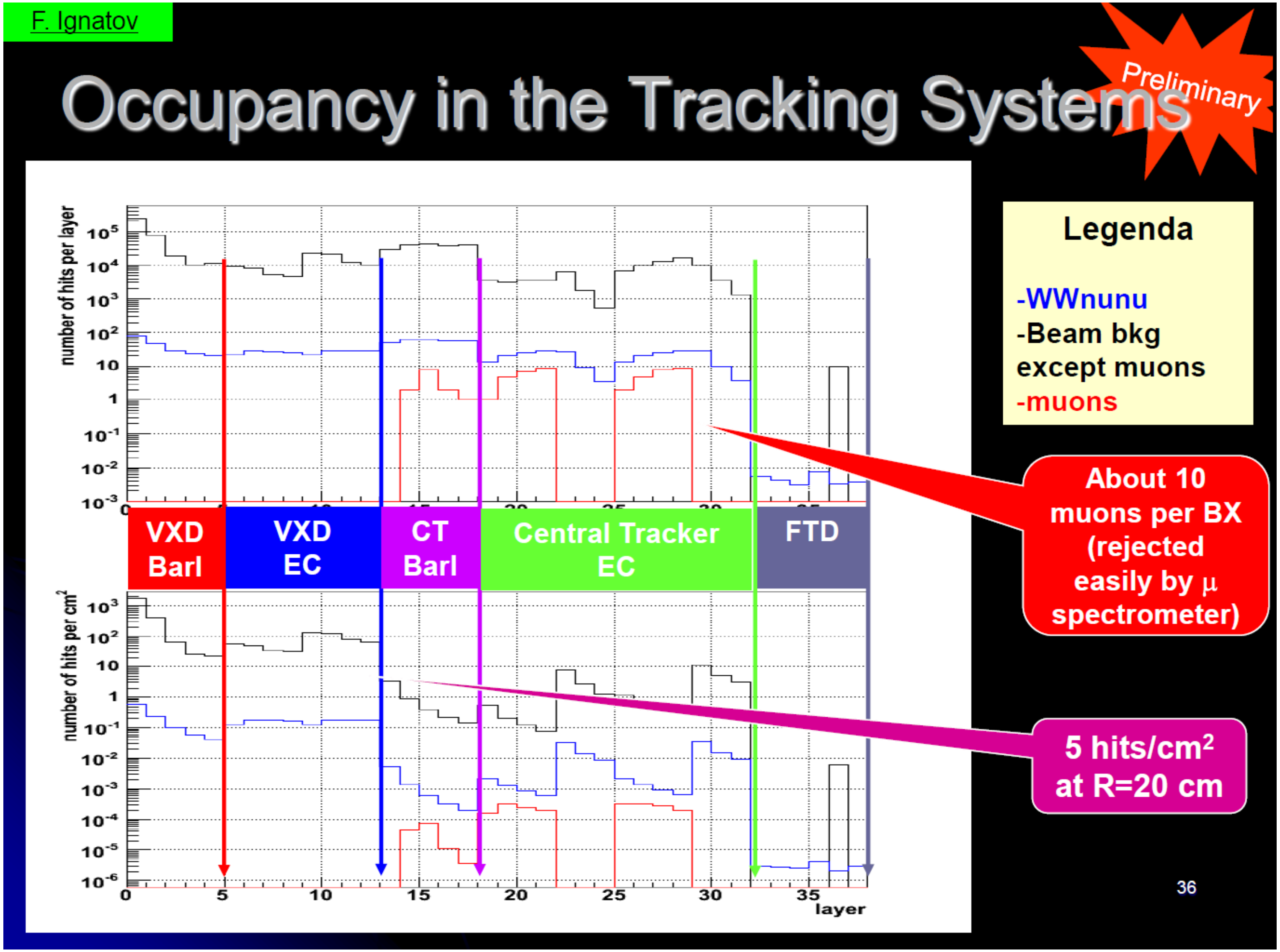
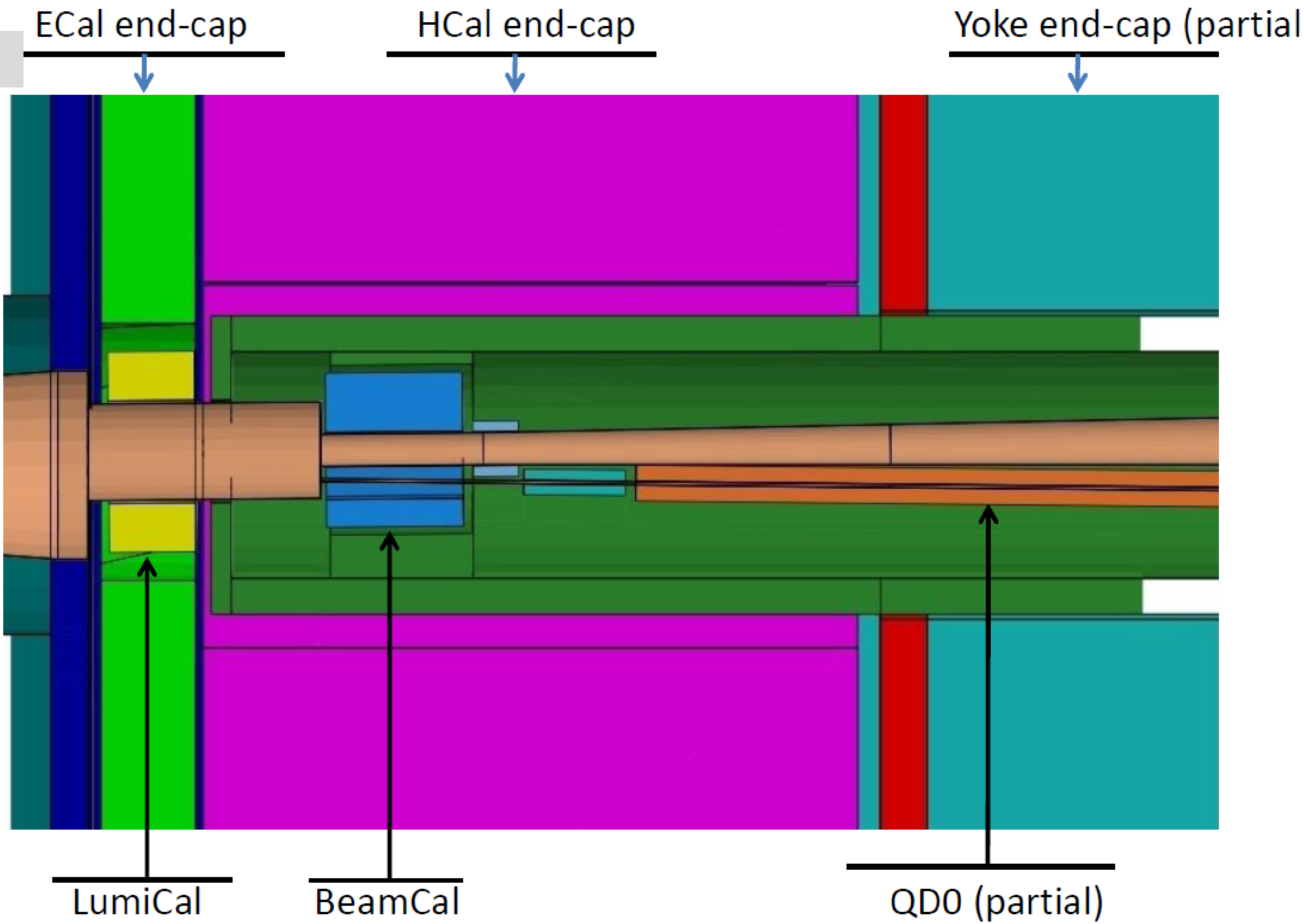


CLIC_ILD Detector Concept: Forward Region

Version 3 Nov. 2009

Andre Sailer



MDI Working Group Priorities

Highest priority for the work until end 2010 are those subjects linked to the “CLIC critical feasibility items”, nota bene:

- Choice of the **magnet technology for the FF magnets**
- **Integration of these magnets** into the detectors, and their alignment
- Feasibility study of sub-nm active **stabilization** of these magnets
- **Luminosity instrumentation**
- **Spent beam disposal**
- **Beam background backsplash** from the post-collision collimators and dumps into the detector
- **Intrapulse-Beam feedback systems** in the interface region

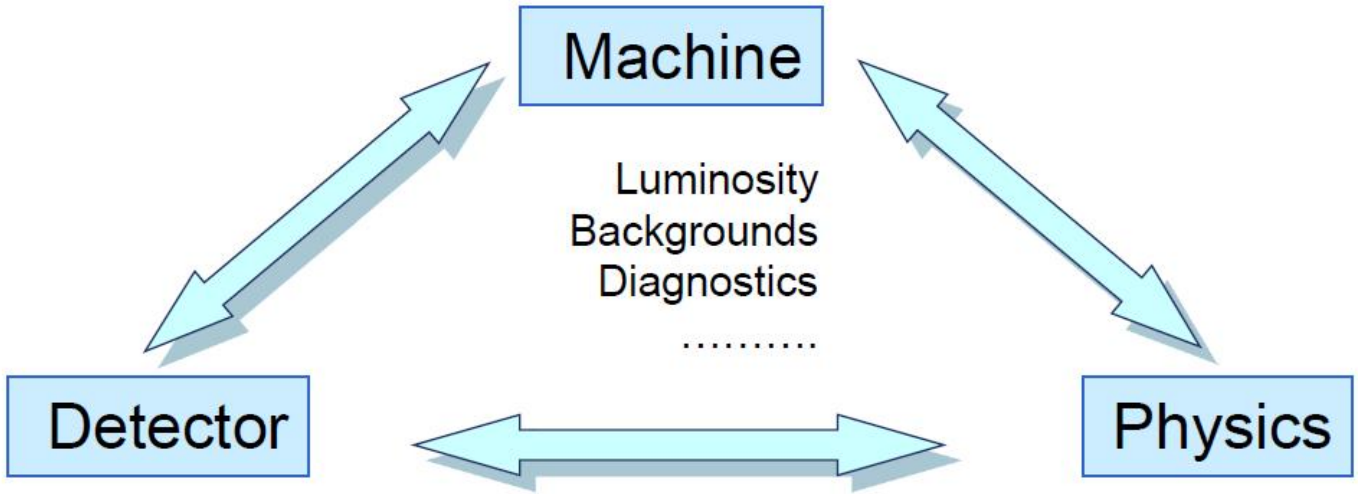
L. Gatignon et al.

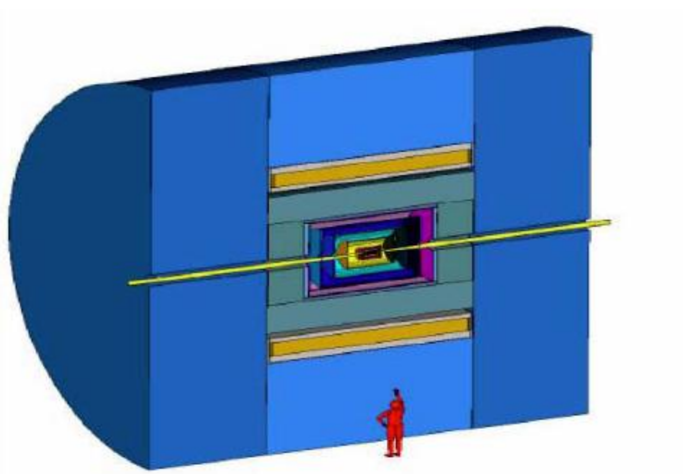
Other Items to be Addressed in MDI:

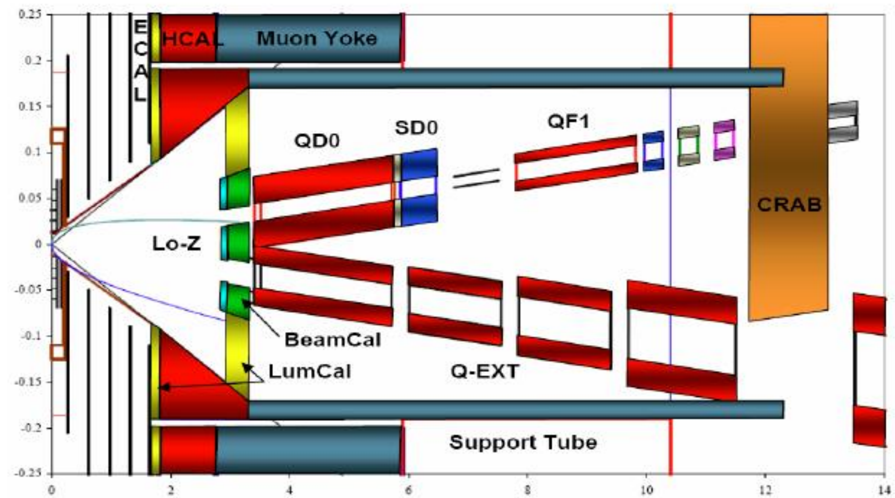
- Issues where the beam delivery system (BDS) influences the beam/**background** conditions for the detector
- Issues where the BDS physically impacts on the detector
- Beam **background** and its impact on the forward (det.+accel.) elements, including backsplash of **background** particles from one hardware element to the surrounding elements
- Beam pipe, beam vacuum and vacuum infrastructure in the interface region
- Radiation environment and radiation shielding in the interface region
- Cryogenic operational safety issues in the interface region
- Magnetic environment in the interface region (shielding of FF quadrupole, correction coils, anti(-DID), stray fields from the detector, etc.)
- Overall mechanical integration (including the routing of services) in the interface region
- Pull-push elements and scenarios (detector-to-detector interface)
- Cavern layout and services (handled principally under CES WG)

From the CLIC MDI working group mandate

Machine Detector Interface

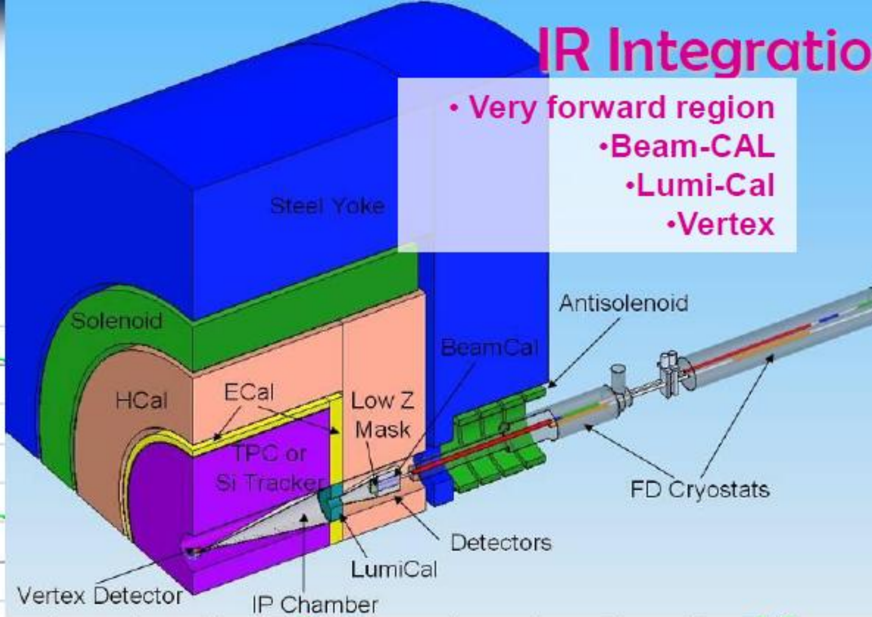


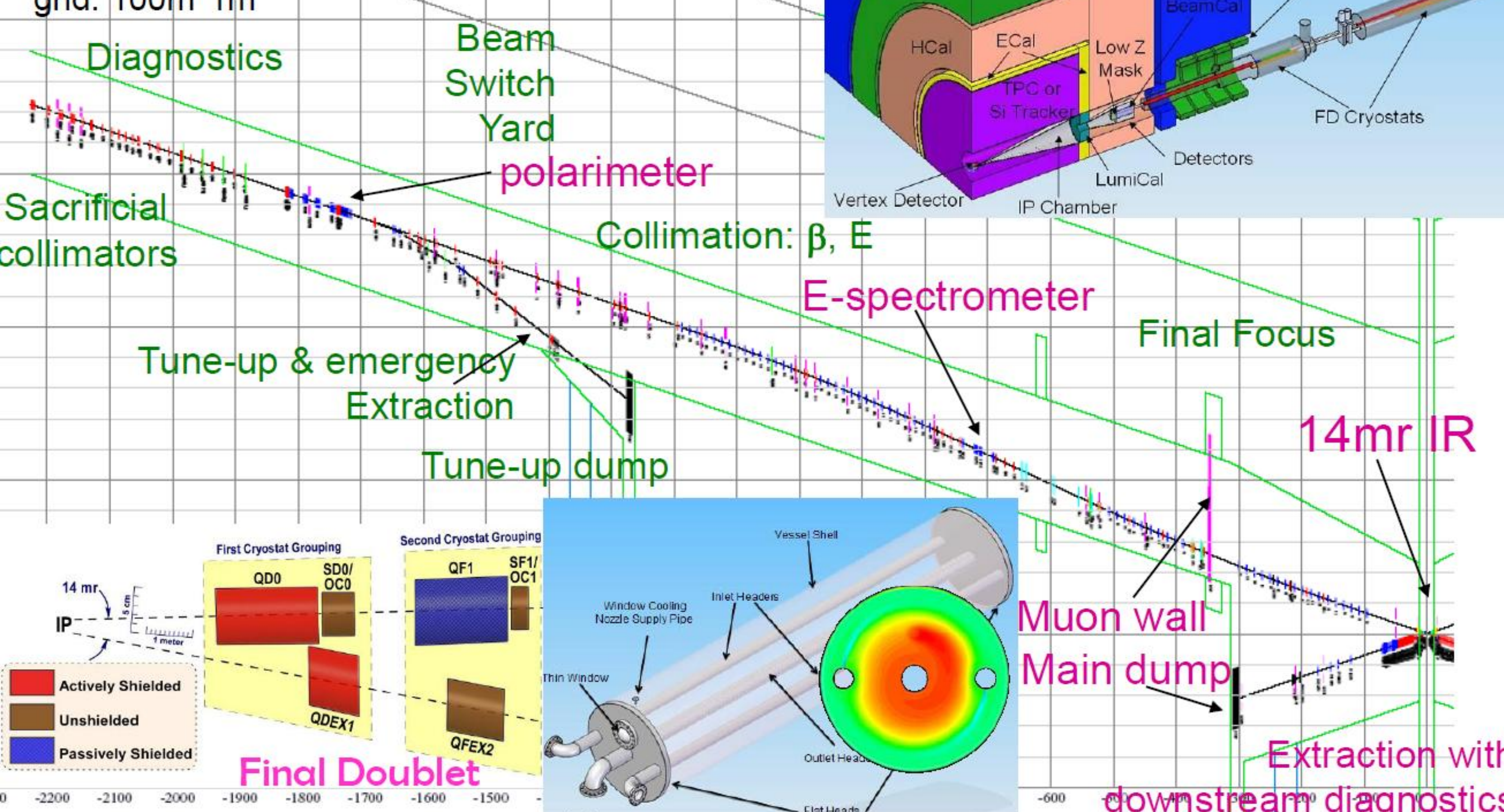




Beam Delivery & MDI elements

1TeV CM, single IR, two detectors, push-pull





IR Magnets: Requirements/Issues

- Dipoles in IR do an excellent job in spreading decay electrons thus reducing backgrounds in detector; split them in 2-3 m modules with a thin liner inside and tungsten masks in interconnect regions.
- Full aperture $A = 10\ \sigma_{max} + 2$cm
- Maximum tip field in quads = 10T (G=200T/m for A=10cm)
- B = 8T in large-aperture dipoles, = 10T in the arcs
- IR quad length < 2m (split in parts if necessary) with minimal or no shielding inside
- Serious quadrupole, dipole and interconnect technology and design constraints.

IR Quadrupole Issues (A. Zlobin)

- Bmax(1.9K/4.5 K)~15T/13 T
  - LARP TQ best results ~12T/13 T at 4.5K/1.9K
- Bnom~11-12 T
- Operation margins ~20% @ 1.9K and only ~10% @ 4.5 K
  - Operation at 4.5K more preferable
  - Usually 20% for IRQ but 10% maybe OK for Nb_3Sn magnets
- Good field quality aperture (<1 unit) ~2/3 coil ID
- Quench protection looks OK (short magnets)
- Max stress in Q2, Q3 >150 MPa => Nb_3Sn conductor degradation
  - use Nb_3Al
  - stress management
- Open questions:
- Is margin sufficient? Do we need internal absorbers (larger aperture)?
- Can the IRQ maximum/nominal gradient be increased?

Dipole Issues (A. Zlobin)

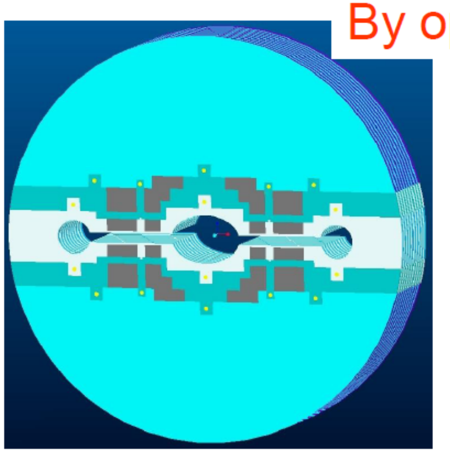
- Traditional 2-layer design
  - Bmax(1.9K/4.5 K)~13.5T/12.5 T
  - Operation margins ~70% @ 1.9K and ~55% @ 4.5 K
  - Good field quality inside R<55 mm
  - **Coil shielding in midplane**
    - **use low-Z material in midplane**
    - **Split magnet and insert absorber**
- Open midplane
  - New complicate design
  - Bmax(1.9K/4.5 K)~10T/9 T
  - Operation margins ~20% @ 1.9K and ~10% @ 4.5 K
  - **Poor field quality**
- Large stored energy => factor of 5-8 larger than in present LHC IRQ
- Coil stress management needs more studies
- Questions: margin, design, field quality, quench protection,…
- Can we make such complicate magnets!?

High-Field HTS Open-Midplane Dipoles

BROOKHAVEN
NATIONAL LABORATORY

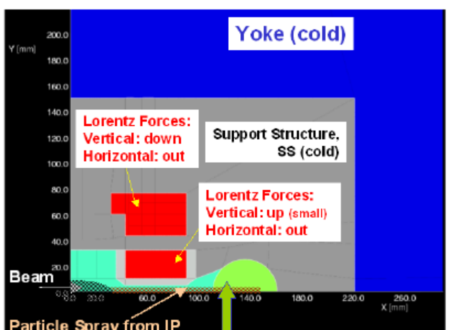
Superconducting
Magnet Division

Why a True Open Midplane Design?



By open midplane, we mean truly open midplane:

- Particle spray from detector deposit energy in a warm (~80 K) absorber sufficiently away from the superconducting coils and support structure .
- In some earlier "open midplane designs", although there was "no conductor" at the midplane, there was some "other structure" between the upper and lower halves of the coil.
- Those designs, though avoided a direct hit from primary shower, created secondary showers in that other structure. The secondary shower then deposited a significant amount of energy in the superconducting coils.
- Earlier designs, therefore, did not work as well in protecting coils against large energy deposition.



A large amount of particles coming from high luminosity IP deposit energy in a warm (or 80 K) absorber, that is inside the cryostat. Heat is removed efficiently at higher temperature.

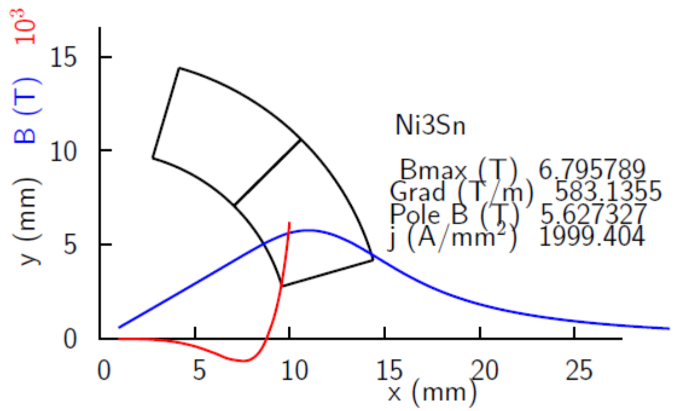
High-Field HTS Open-Midplane Dipoles

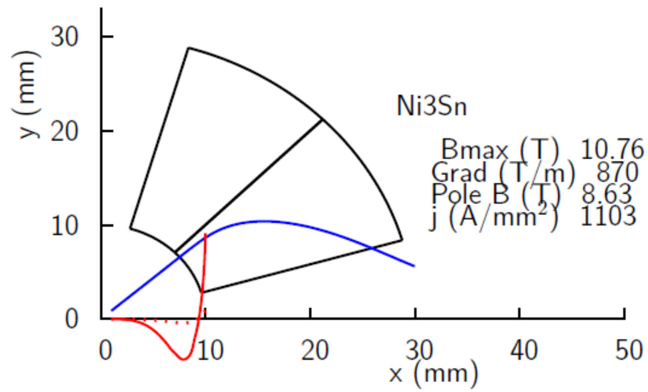
- The development of open midplane design is important to $\mu^+\mu^-$ colliders, as large number of decay particles at the midplane may limit the performance of superconducting coils and/or increase the operating cost of the machine.
- The design concept has been significantly developed under LARP funding. Now, we can have a truly "Open Midplane" design with a way to deal with Lorentz forces and obtain a good field quality, as well.
- HTS plays an important role in high field open midplane design. HTS can generate very high fields and can tolerate and remove large heat loads.
- It has been shown that HTS magnets can be designed, built and operated in presence of a large radiation and heat load environment.
- Combined function magnet design with skew quadrupole offers an interesting possibility. Such magnets and lattice has been designed.

Of course, all of above still require a significant amount of work before magnets based on such a design could be inducted in an operating machine.

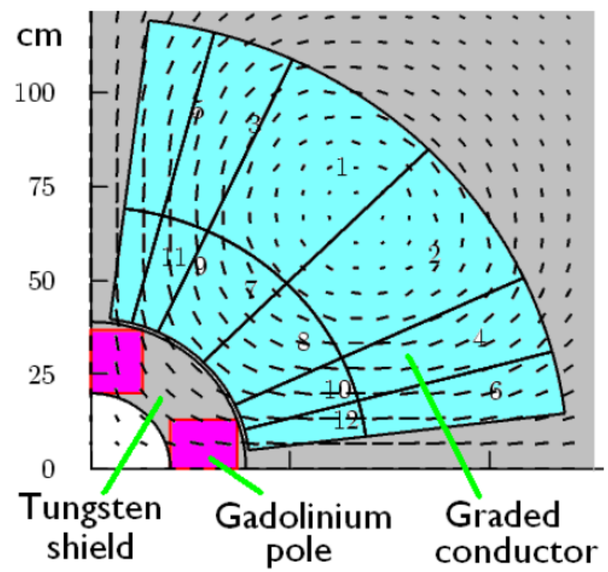
High-Gradient Quads w/Exotic Materials (R. Palmer)

Optimize radial thickness



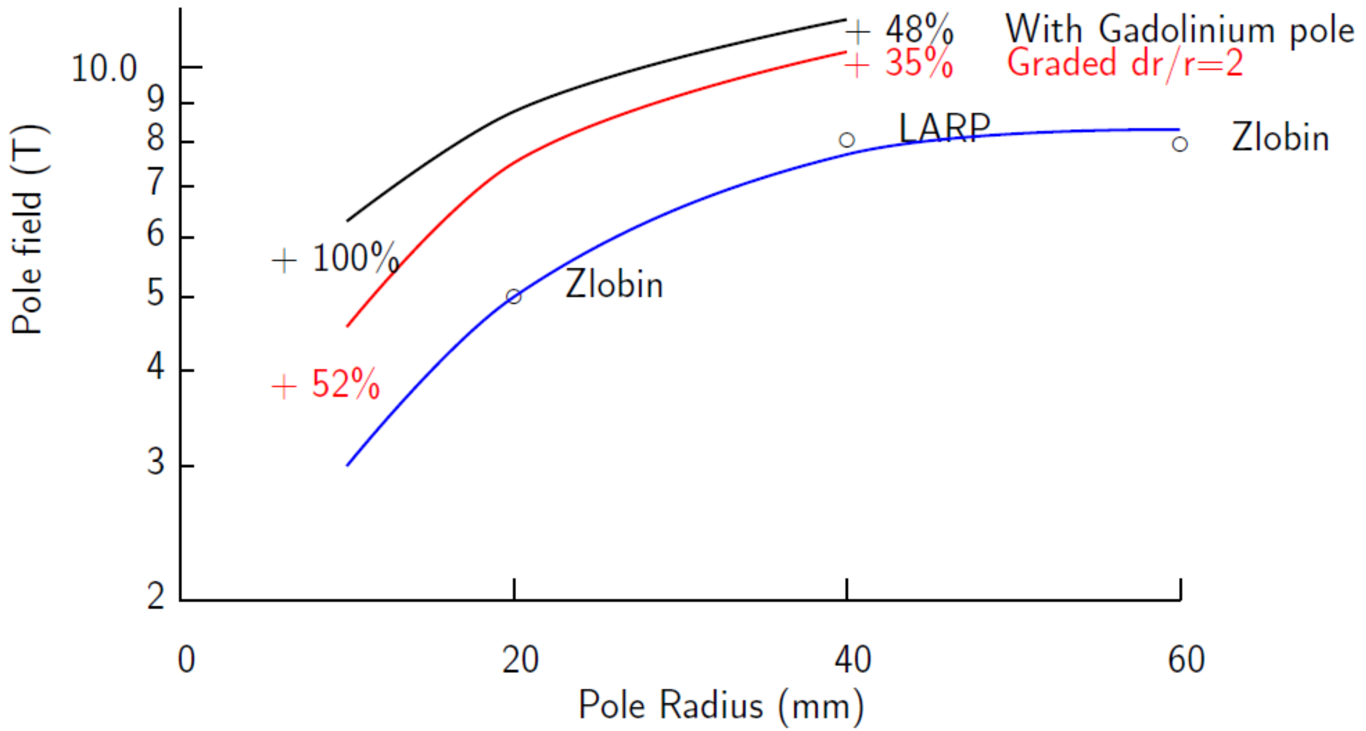


Grade conductor and add Gadolinium in shield



High-Gradient Quads w/Exotic Materials (R. Palmer)

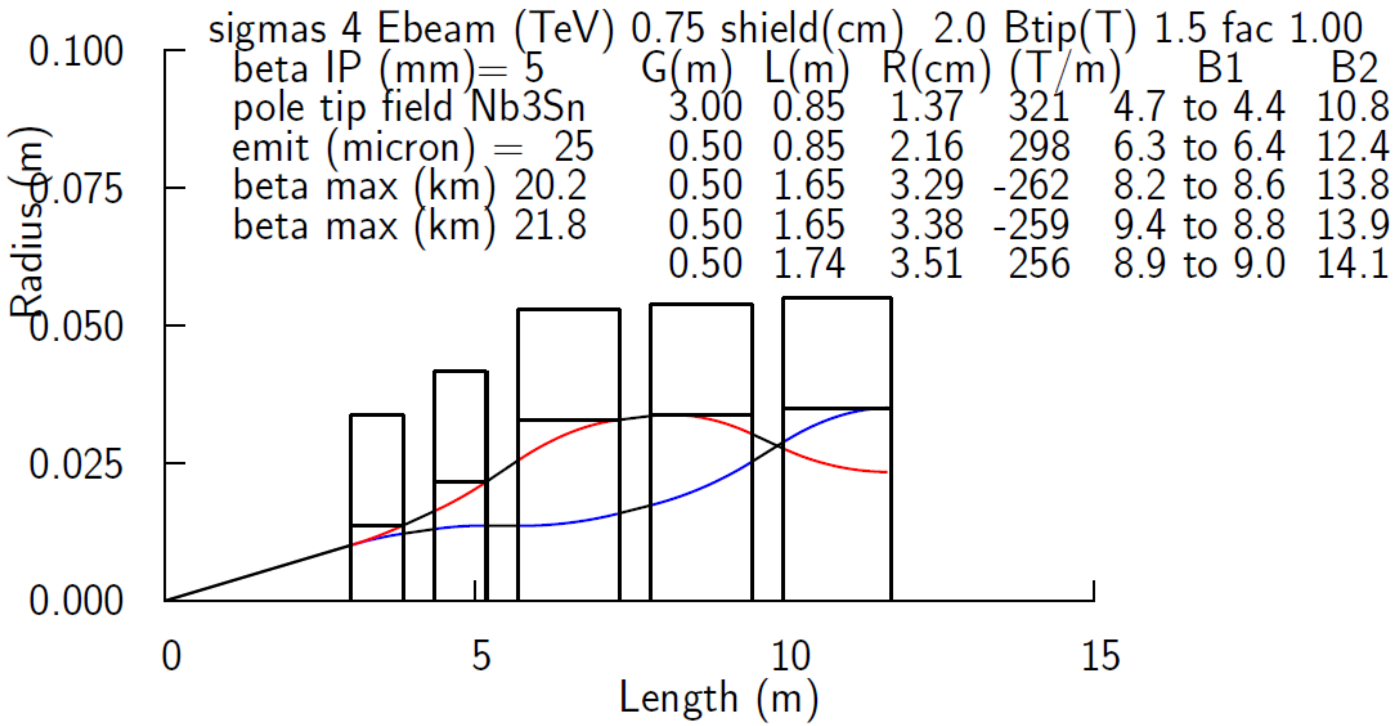
Pole Fields vs radius with 2 cm shield



- Gain now a factor of 2 for 10 mm
- Gain a factor of 1.5 for 30 mm

High-Gradient Quads w/Exotic Materials (R. Palmer)

Example with 3 m to first quad including gadolinium



- Betamax=22 km is less than baseline
- But 5 mm beta star gives twice the luminosity,
- or half the background and driver requirements

MDI Issues and Work to Do (1)

1. Dealing with 0.5-1 kW/m loss rate in magnets (dynamic heat load and quench stability).

2. ~10 T dipoles: open midplane versus conventional cosθ (splitted in ~3m long pieces with masks in between and modest high-Z liners). Put significant effort into open mid-plane dipole designs to get field quality, handle the forces and enclose the beam dumps so that radiation is controlled in the tunnel.

3. Alternative technologies for short IR quads: permanent high-gradient quads very close to IP, holmium/gadolinium liners in quads, novel adhesive-free approach. Explore higher gradient quadrupoles and determine if a lower beta star is feasible. If this is possible, evaluate whether to use the gain to raise the luminosity or reduce N raise f and thus reduce the detector background.

4. Add more realistic geometry and magnetic field maps to MARS model.

MDI Issues and Work to Do (2)

5. Interconnect regions: 40-50 cm needed, seems OK for optics, backgrounds and neutrino radiation for 750-GeV muon beams; need to keep them as short as possible with energy going up.
6. Design a ring for 3 TeV and compare the background problems with 1.5 TeV.
7. Explore if short 20-30 T solenoid(s) from the last bend to the IP (with gaps for the quadrupoles) would help backgrounds.
8. For each design, determine how much shielding is needed inside the final quadrupoles.

MDI Issues and Work to Do (3)

9. Continue the optimization of detector background, balancing advantages of smaller nozzle angle vs effects of the greater background if it has a smaller angle, not sacrificing physics; consider its instrumentation (Lumical and other ILC experience).

10. Investigate if such an optimal cone confines incoherent pairs with the detector 3.5-T field.

11. Establish an MDI Task Force with a very tight connection between accelerator, magnet and detector groups.

12. Model detector response to physics signal in presence of IP and machine backgrounds. To first order, the backgrounds will drive critical parameters of the μC detector design, not the physics.

13. Revisit beam scraping schemes for 0.75 and 1.5-TeV muon beams.