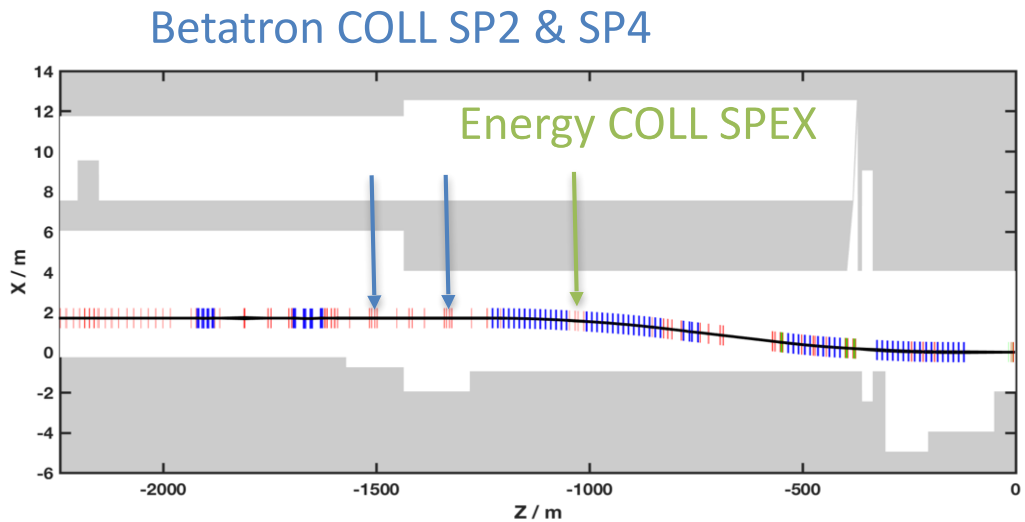
# Brief review of the muon background at the ILC-IP

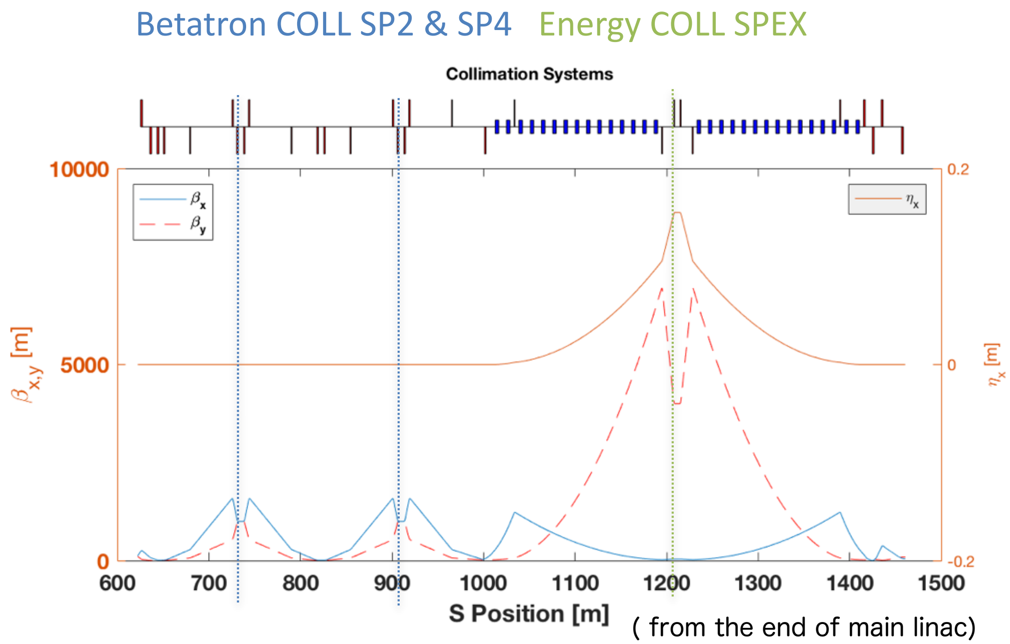
Thanks to Glen White and Lew Keller for comments on these muon suppression studies

T. Tauchi, KEK

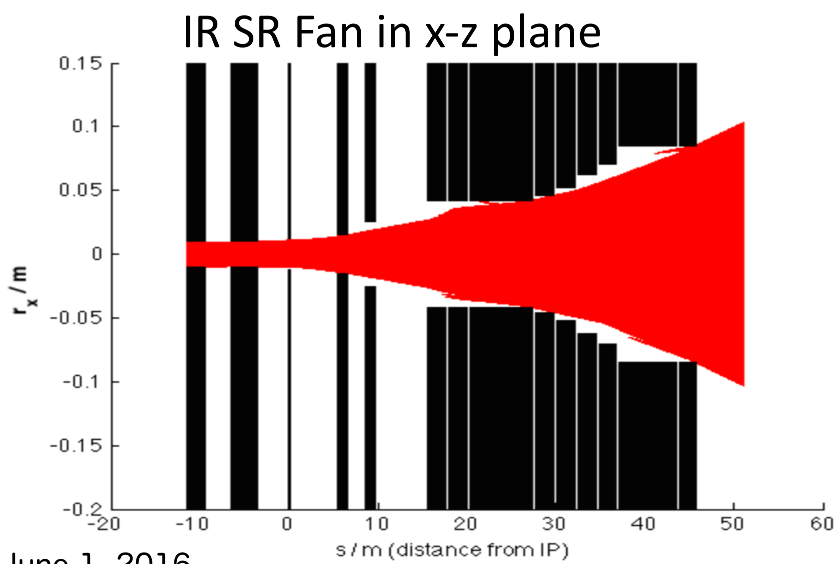
The Asian Linear Collider Workshop ALCW2018,
28 May to 1 July, 2018, Fukuoka, Japan

# Halo Collimation Systems




- Primary spoilers & absorbers source of muons in BDS
- Collimation apertures set to protect IR region from SR
  - Calculated from 6d particle tracking
  - Collimation types and settings recorded in BDS decks in ILC2015b



# Collimator

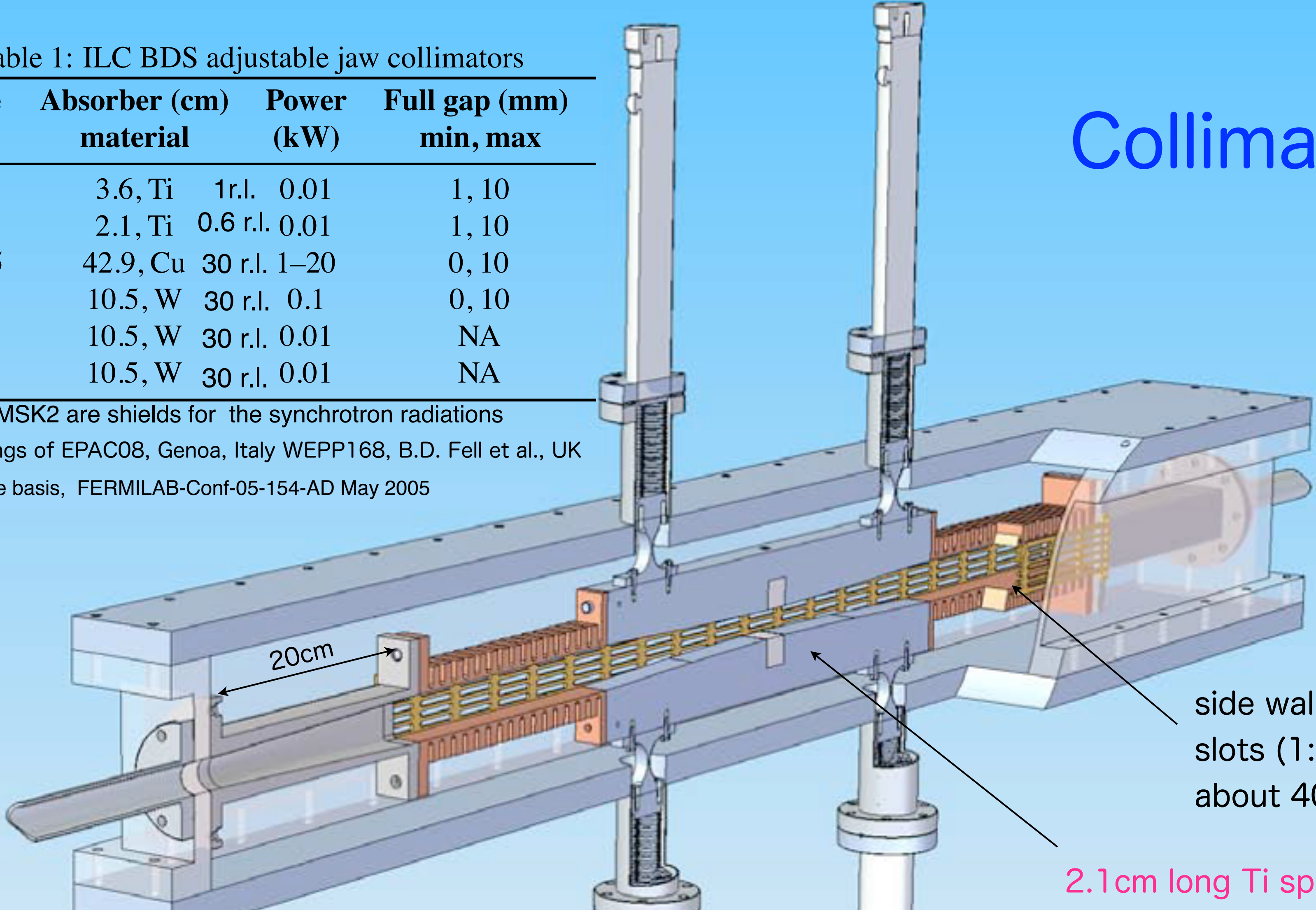
Table 1: ILC BDS adjustable jaw collimators

| Device | Absorber (cm) material | | Power (kW) | Full gap (mm) min, max |
|---|---|---|---|---|
| SPEX | 3.6, Ti | 1r.l. | 0.01 | 1, 10 |
| SP1–5 | 2.1, Ti | 0.6 r.l. | 0.01 | 1, 10 |
| AB2–5 | 42.9, Cu | 30 r.l. | 1–20 | 0, 10 |
| ABE | 10.5, W | 30 r.l. | 0.1 | 0, 10 |
| MSK1 | 10.5, W | 30 r.l. | 0.01 | NA |
| MSK2 | 10.5, W | 30 r.l. | 0.01 | NA |

MSK1, MSK2 are shields for the synchrotron radiations

Proceedings of EPAC08, Genoa, Italy WEPP168, B.D. Fell et al., UK

Also for the basis, FERMILAB-Conf-05-154-AD May 2005

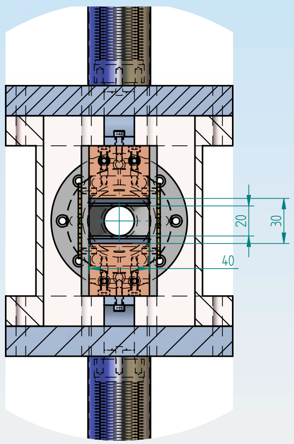



side walls with pumping slots (1:1 aspect ratio, about 40% transparency)

2.1cm long Ti spoiler block with Be tapers up- and downstream

passive survival of spoilers up to two full charge bunch impacts at 250 GeV beam energy

2cm $\phi$ beam pipe



# Collimator at the ATF2 final focus system, KEK, Japan

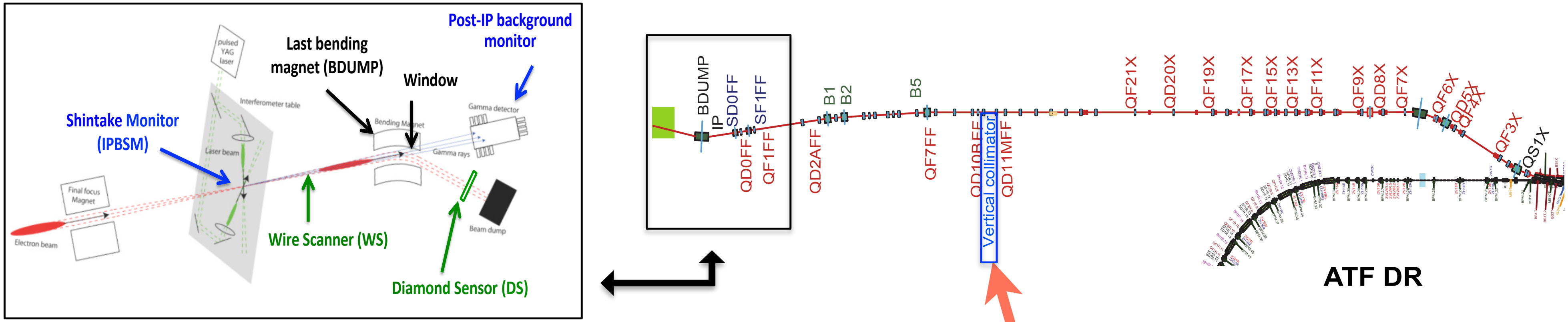



Figure 1: ATF and ATF2 layout with a zoom of the ATF2 post-IP beamline.

## Collimator as the ILC prototype

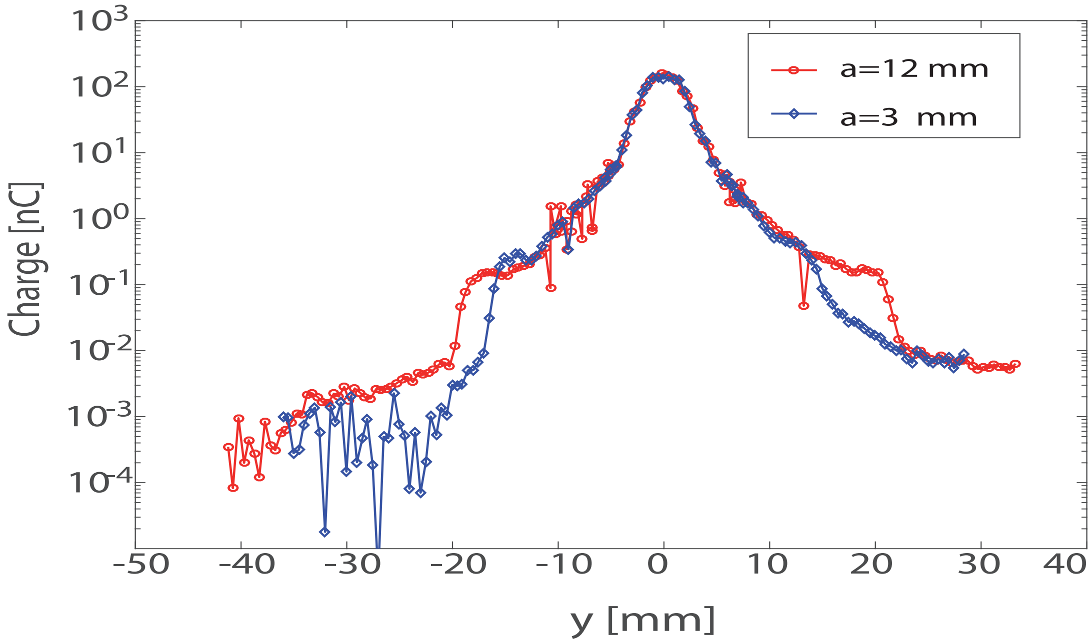



Figure 3: DS vertical beam halo distribution measurement.

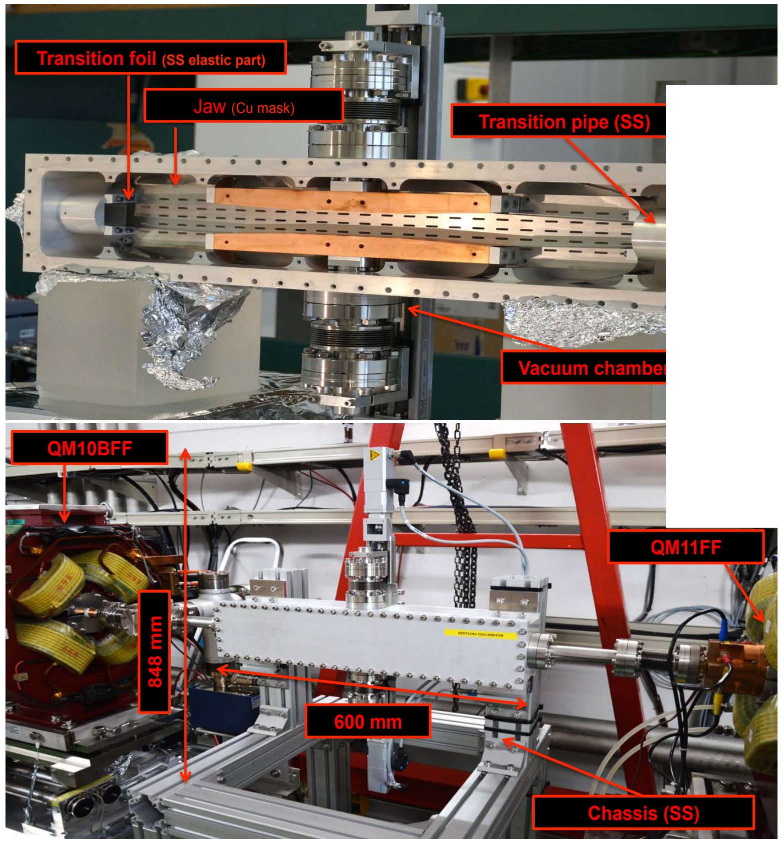



Figure 2: Vertical collimation system open at LAL (top) and installed at ATF2 (bottom)

N. Fuster-Martinez etal., MOPG40, proceedings of IBIC16, Barcelona, Spain

# Muons from the collimation section

The beam halo can be collimated by the collimators, where electromagnetic showers are generated in the absorbers. At the same time, muon pairs ($\mu^+, \mu^-$) are produced in the showers because the incident electron ( positron) energy is large compared with the muon mass.

The major production by the Bethe-Heitler process $e^{\pm} \to e^{\pm}\mu^{+}\mu^{-}N$

Roughly estimated production rate is

$$N_\mu = 3.9(2.3) \times 10^{-4} \left( \frac{E_{\mathrm{beam}}(\mathrm{GeV})}{250} \right) \text{ for } E_\mu > 2(5)\mathrm{GeV}$$

$$\frac{N_\mu(W)}{N_\mu(Cu)} \approx 0.55 \text{ for } N_\mu \propto Z^2 L(30X_0)/A$$

So the total number of muons are estimated to be produced for 0.1% beam halo as follows;

$$7.8(4.6) \times 10^3/\text{bunch crossing} \quad \text{for } E_\mu > 2(5)\mathrm{GeV}$$

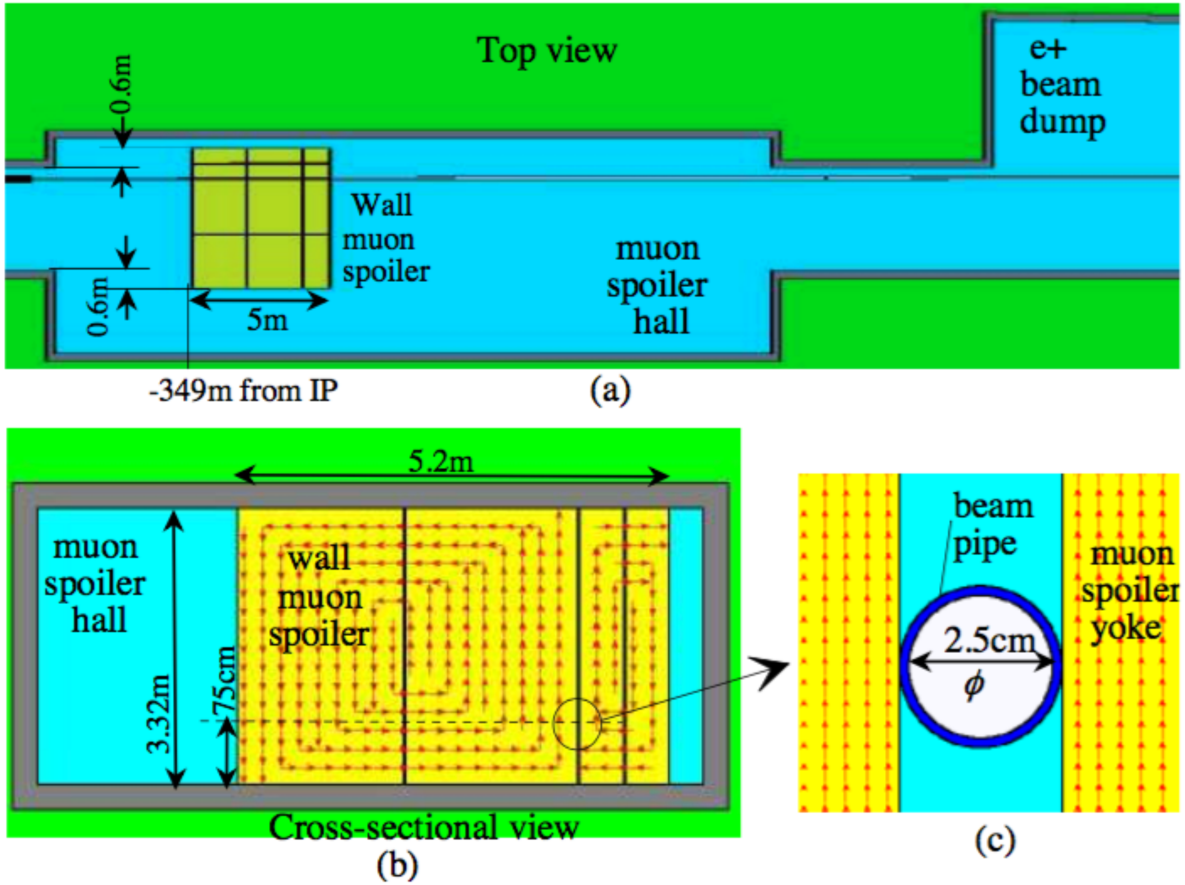
Muon production by the direct positron annihilation : For beam on the 0.6 rl spoilers the $\mu$/bunch is about 3% of BH but they still contribute significantly because the average muon energy is larger from direct annihilation of positrons on atomic electrons and also because 100% of the beam halo hits either SP2 or SP4. ( Lew Keller )

# Study just before the TDR

SLAC-PUB-12741
August 2007

## SUPPRESSION OF MUON BACKGROUNDS GENERATED IN THE ILC BEAM DELIVERY SYSTEM *

A.I. Drozhdin, N.V. Mokhov, N. Nakao†, S.I. Striganov, Fermilab, Bavia, IL 60510, USA
L. Keller, SLAC, Stanford, CA 94025, USA




Muon Shielding - Wall

MARS15 for muon generation, STRUCT for tracking in the ILC BDS , which agree with MUCARLO + TURTLE within a factor of 2

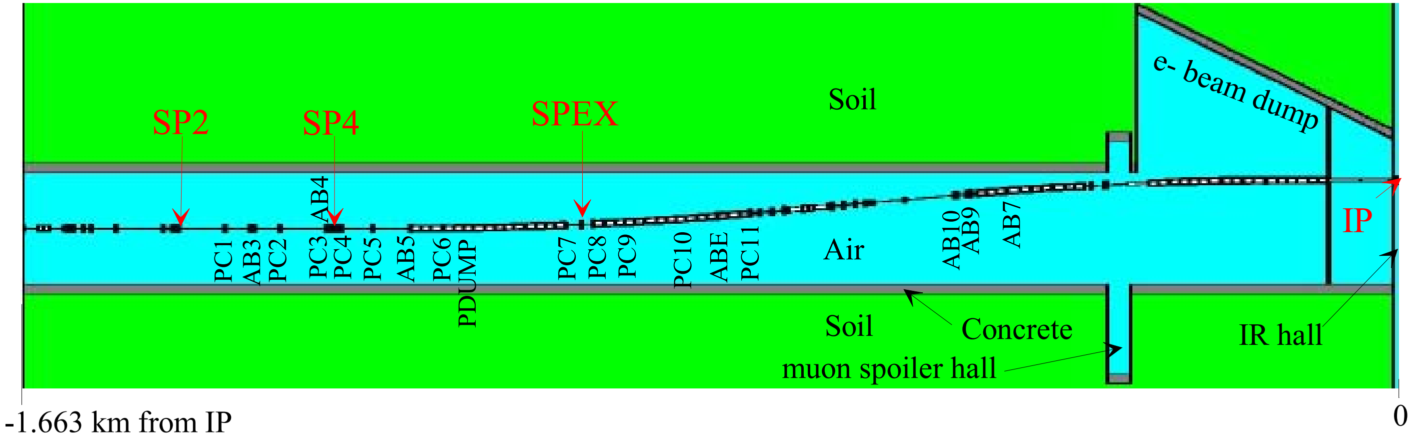



Figure 3: A top view of the BDS tunnel with the entire beam line described in MARS15 simulation. Three beam-loss locations at primary collimators(SP2, SP4, SPEX) are shown. The locations of protection collimators(PC) and absorbers(AB) are also shown.

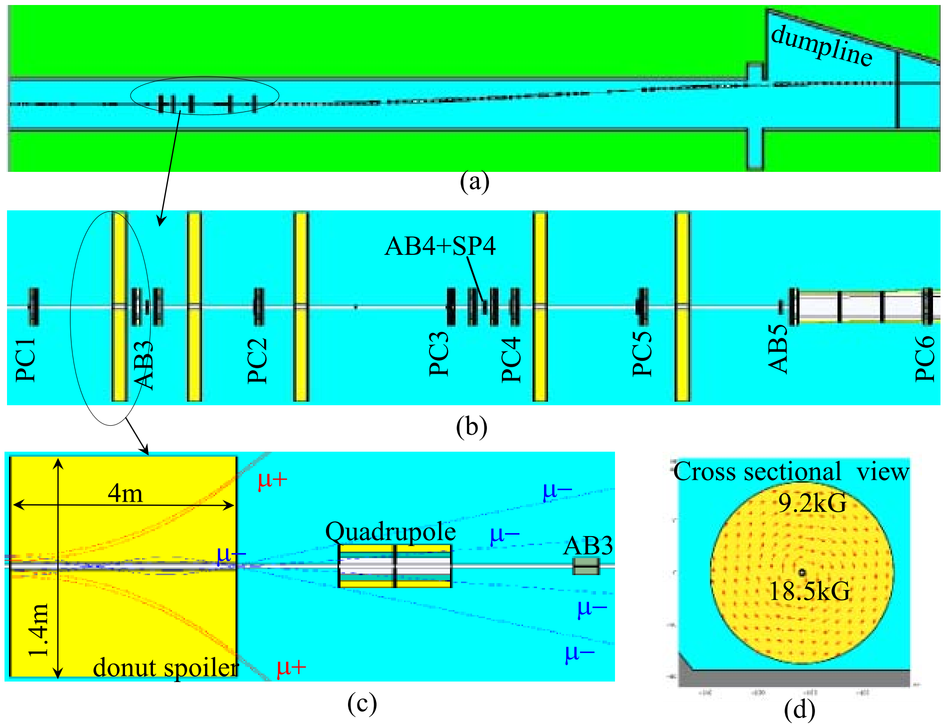



Figure 5: Top(a,b,c) and cross-sectional(d) views of five donut muon-spoilers and their locations on the beam line. Images of $\mu+$ and $\mu-$ trajectories are shown in (c).

Beam halo : 0.1% outside of ($8\sigma_x$ , $65\sigma_y$) and $\Delta p/p = 0.0067$

Table 1: Number of muons per bunch of $2 \times 10^{10}$ positrons by MARS15 in various radii at IR hall compared among the muon-spoiler types. Ratio to None (%) is in parenthesis.

| Type | R=6.5m | 2.5m | 2.0m | |
|---|---|---|---|---|
| None | 14.8 (100) | 9.10 (100) | 6.51 (100) | 1 |
| Donut | 2.54 (17) | 1.59 (17) | 1.09 (17) | 1/5 |
| Donut+Wall | 0.26 (1.8) | 0.18 (2.0) | 0.14 (2.2) | 1/50 |

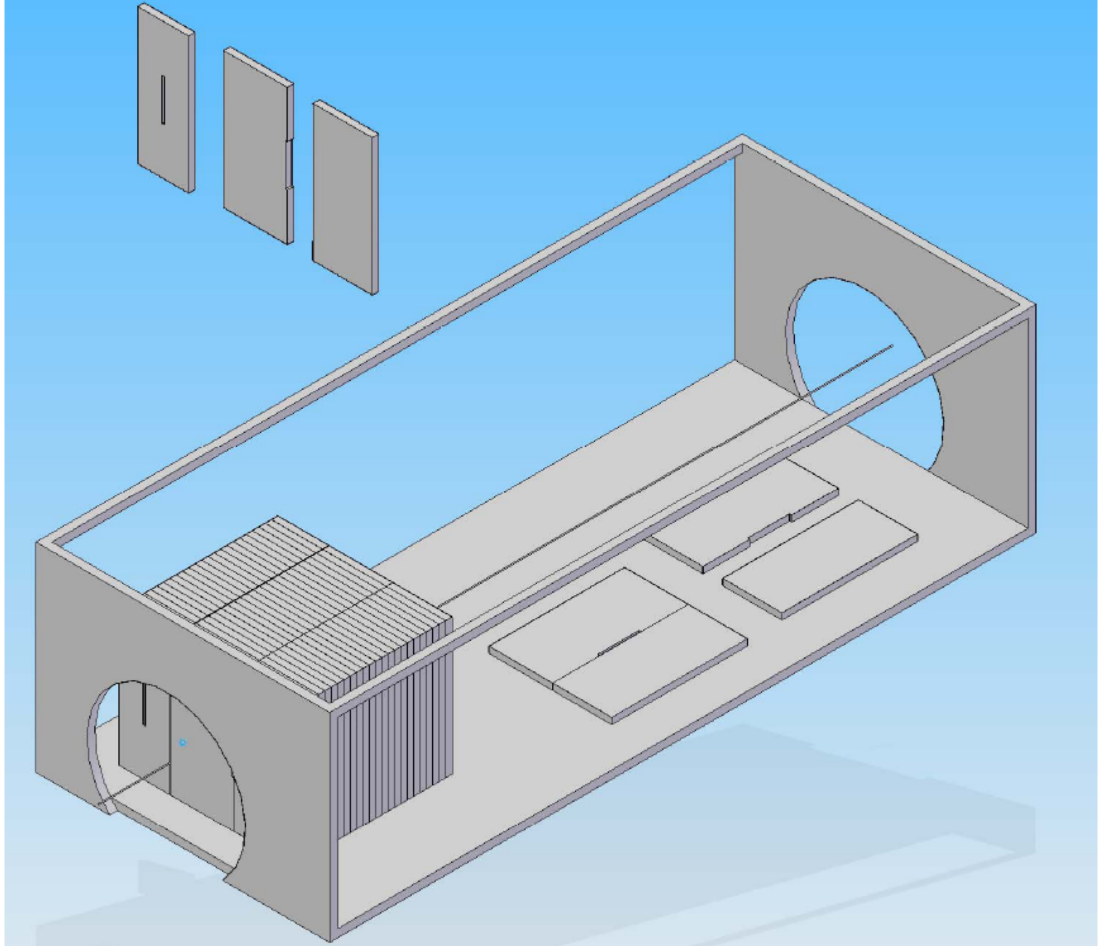
SLAC-PUB-12741, August 2007

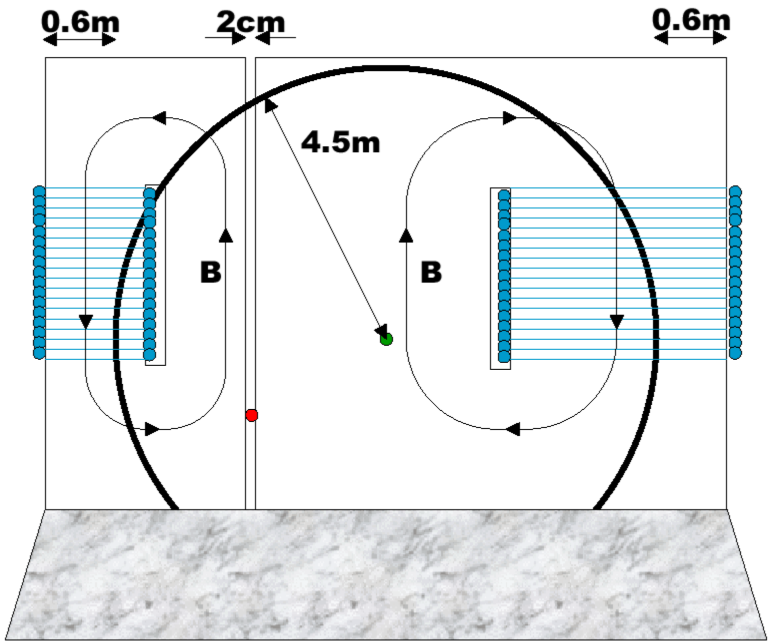
**TDR-3-2, 8.3.2.3 Halo-power handling :** The power-handling capacity of the collimation system is set by two factors: the ability of the collimators to absorb the incident beam power and the ability of the muon-suppression system to reduce the muon flux through the detector. In the baseline design, the muon-suppression system presents the more restrictive limitation, setting a tolerance of $1 \sim 2 \times 10^{-5}$ on the fraction of the beam collimated in the BDS. With these losses and the 5m wall, the number of muons reaching the collider hall would be a few muons per 150 bunches (a reduction by more than a factor of 100). Since the actual beam-halo conditions are somewhat uncertain, the BDS includes caverns large enough to increase the muon shield from 5m to 19m and to add an additional 9 m shield downstream. Filling all of these caverns with magnetized muon shields would increase the muon suppression capacity of the system to $1 \times 10^{-3}$ of the beam. The primary beam spoilers and absorbers are water cooled and capable of absorbing $1 \times 10^{-3}$ of the beam continuously.

TDR : ~ 0.01 muon / bunch for the 5m wall and a $10^{-5}$ beam halo

# Muon walls

- Purpose:
  - **Personnel Protection: Limit dose rates in IR when beam sent to the tune-up beam dump**
  - **Physics: Reduce the muon background in the detectors**






5m muon wall installed initially

If muon background measured too high, the 5m wall can be lengthened to 19m and additional 9m wall installed (Local toroids could be used also)

# An order of magnitude estimation of the beam halo by the Mott scattering in residual gas

For the Mott scattering, $\sigma_{Mott}(\theta > \theta_0) = \frac{2\pi Z^2 r_e^2}{\gamma^2} \frac{1}{1-\cos\theta_0} \approx \frac{4\pi Z^2 r_e^2}{\gamma^2} \frac{1}{\theta_0^2}(1 + \frac{2\theta_0^2}{4!} - \frac{2\theta_0^4}{6!} + \cdots)$

, where $\theta_{0,i} = n_i \sqrt{\frac{\varepsilon_i}{\beta_i}}$, $i = x, y$ and $\gamma = \frac{E_{beam}}{m_e}$, $r_e$ is the electron classical radius

$$\therefore \text{Probability of the halo generation}: P_{i,halo} = N_{res.gas} \frac{4\pi Z^2 r_e^2}{n_i^2} \frac{1}{\gamma\varepsilon_i} \int_{\text{beam line}} \frac{\beta_i}{\gamma} ds$$

For parameters, $N_{res.gas} = 5.2 \times 10^{24} P(torr)/\mathrm{m}^3$ at $\mathrm{T} = 2\mathrm{K}$ , $Z(He) = 2$, $r_e = 2.8 \times 10^{-15}\mathrm{m}$

$\gamma\varepsilon_x = 1.0 \times 10^{-5}, \gamma\varepsilon_y = 3.5 \times 10^{-8}$ $\mathrm{m \cdot rad}$ and $E_{beam} = 5 \sim 250\mathrm{GeV}, \gamma = \frac{E_{beam}}{m_e} = (0.098 \sim 4.9) \times 10^5$

$$\gamma(s) \approx \frac{245\mathrm{GeV}}{m_e \times \text{Length of the main Linac}(10\ \mathrm{km})} \approx 48 \cdot s$$

$$\therefore P_{i,halo} = \frac{4\pi Z^2 r_e^2}{n_i^2} \frac{N_{res.gas}}{(\gamma\varepsilon_i)} \int_{200}^{10,000} \frac{\beta_i(s)}{48} \frac{1}{s} ds \approx \frac{4\pi Z^2 r_e^2}{n_i^2} \frac{N_{res.gas}}{(\gamma\varepsilon_i)} \frac{\overline{\beta_i}}{48} \ln s|_{200}^{10,000}$$

$P_{x,halo} = 4.7 \times 10^{-8}$, $P_{y,halo} = 1.6 \times 10^{-7}$ for $\overline{\beta_i} = 100\mathrm{m}, n_x = 6.2, n_y = 55$ at $P = 1\mathrm{nTorr}$

An estimation of the beam halo generation at the ILC Main-LINAC, $10^{-5}$ for $> 30\sigma_y$ at 10nTorr, by H. Burkhardt et al., EUROTeV-Report-2007-064 CLIC-Note-714 .

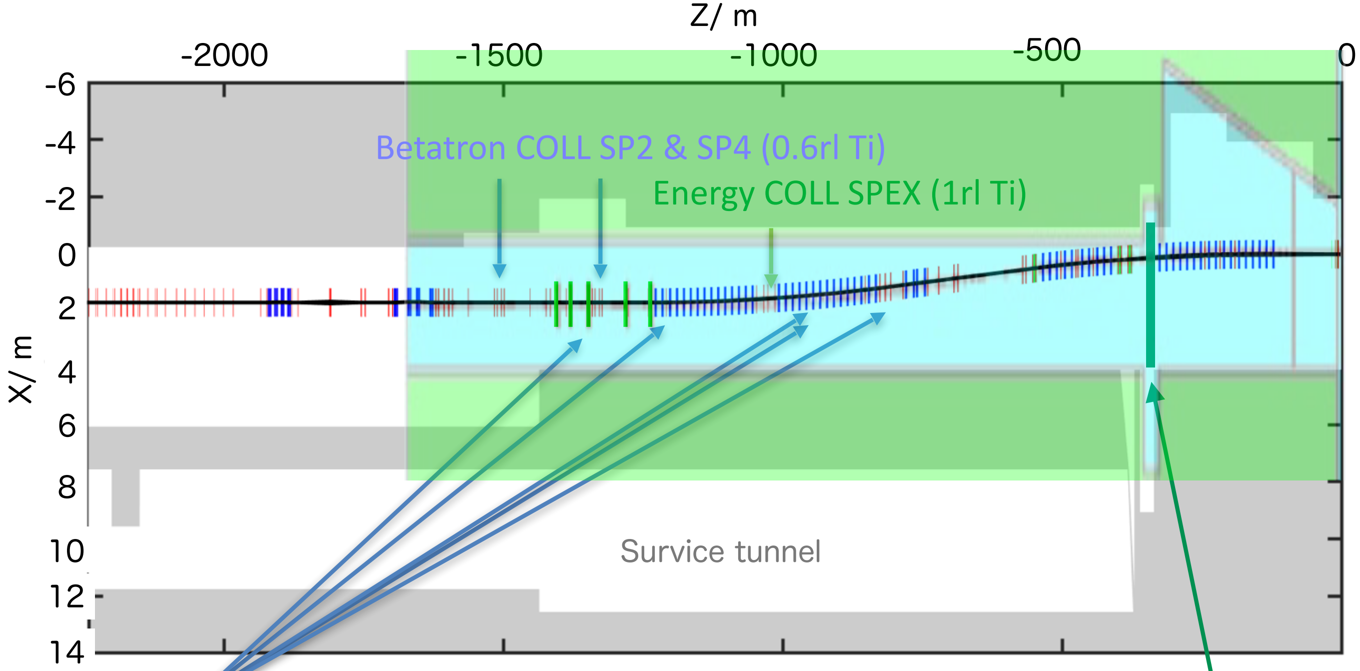
# Post-TDR : Muon Shielding – ( Donut ) Toroid Spoilers

for the “Kamaboko” tunnel and the optimization as 3 spoilers set in the bend section (ILC500)

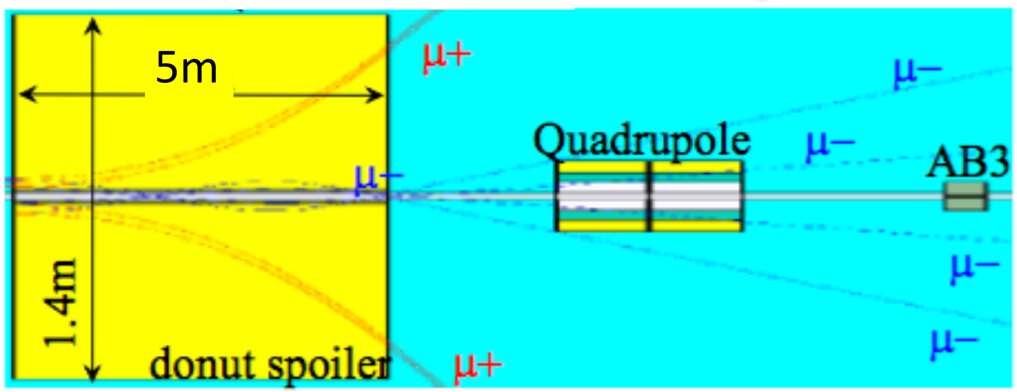
5 muon spoilers at z locations from IP:

Green positions to

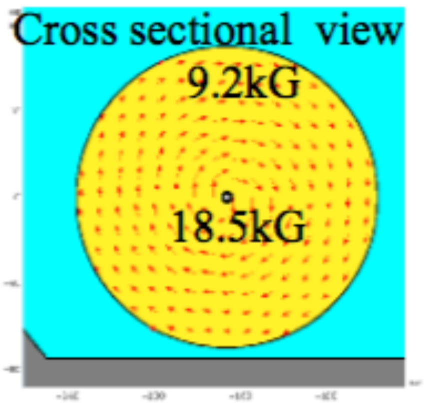
- 800 m
- 973 m
- 1143 m
- 1234 m
- 1358 m




Muon wall at ~ -349m




(c)




(d)

# Post-TDR : Calculated Muon Rates at Detector

| | ILC-500GeV | | | | ILC-250GeV |
|---|---|---|---|---|---|
| **Tunnel Condition** | **R < 6.5 m (rate/bunch crossing)** | | **R < 2.5 m (rate/bunch crossing)** | | |
| | ***GEANT4*** | ***MUCARLO*** | ***GEANT4*** | ***MUCARLO*** | MUCARLO |
| No Spoilers | 39.4 1 | 130* 1 | 20.5 1 | 40 1 | |
| 5 μ Spoilers (5x5m donuts) | 2.8 1/25 | 4.3 1/30 | 1.4 1/15 | 2.0 1/20 | 1.3 |
| 5 μ Spoilers + 5m Wall (5x5m donuts + 5m Wall) | -- —- | 0.68 1/191 | -- —- | 0.1 1/400 | 0.03 |

*: For "No Spoilers", 10 times more than the previous one(TDR)

- Total muon rates (from e- and e+ BDS sides) per bunch crossing
- Halo interception rate used = 0.1 % of main beam charge
- MUCARLO predicts more muons than GEANT4, mainly from d/s SPE source. MUCARLO uses more generic magnet model, but uses much higher statistics and semi-analytic model for muon production.
  - 60k MUCARLO IP hitting mu tracks for 5 spoiler case compared with ~150 (from 500k generated) for GEANT4
  - Increased stats for GEANT4 model requires more work on process biasing and parallelization of muon tracking code

# Torelable limits for the detectors

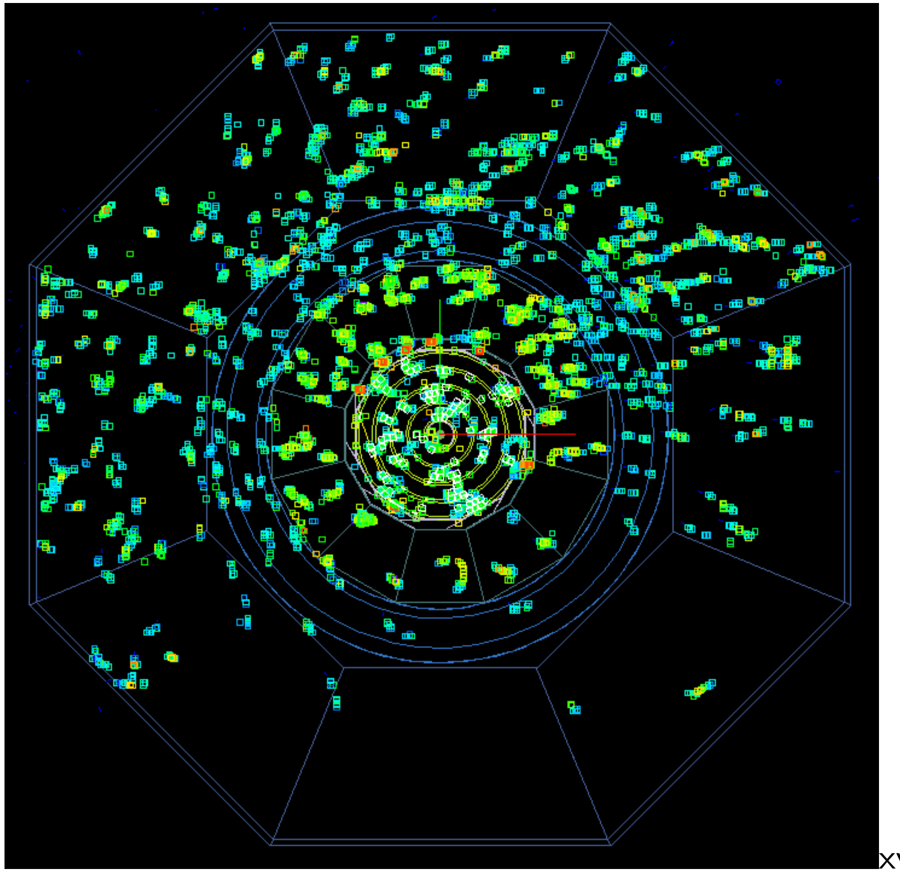
## In general, Occupancy < 0.1%* at the calorimeter, tracker and vertex detector

The occupancy depends on the cell size, the integration time, depth of data buffer and the readout time for each detectors, keeping the resolutions (position especially secondary/tertiary verteces, angle, energy, momentum etc. ) , tracking efficiency and the pattern recognition for the Particle-Flow reconstruction, so that the same physics performances are obtained.

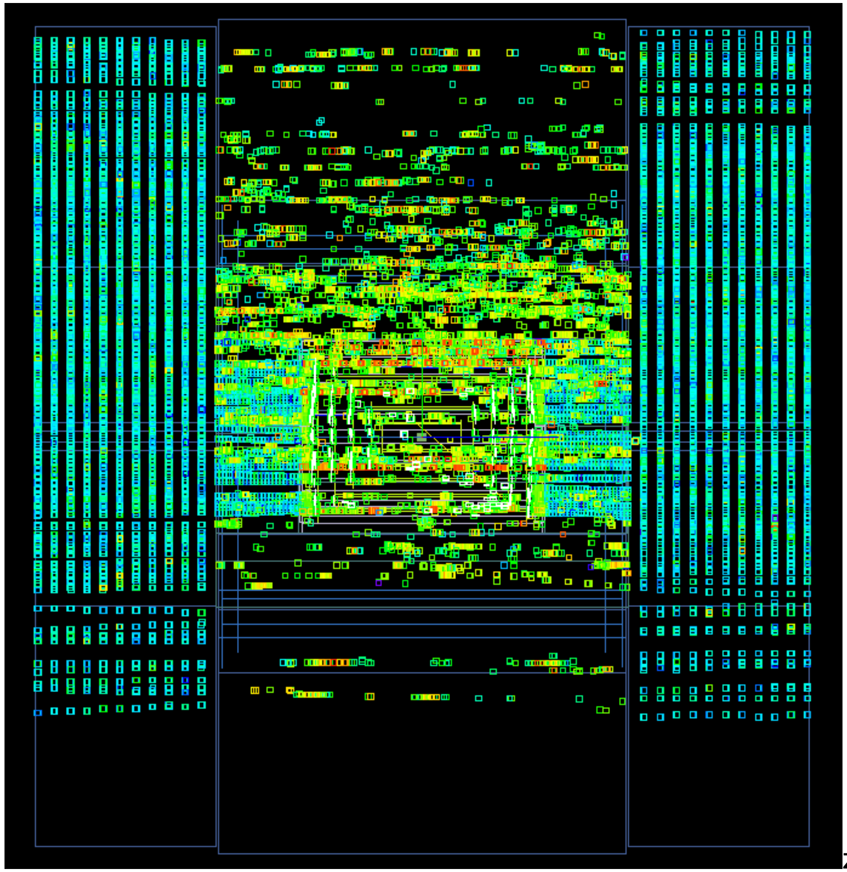
* to be verified by the experimental groups

# *WIRED4 event display - 5 Spoilers + Wall*

1 train's worth of muons ($\sim$ 515 muons) **from the positron line only**:

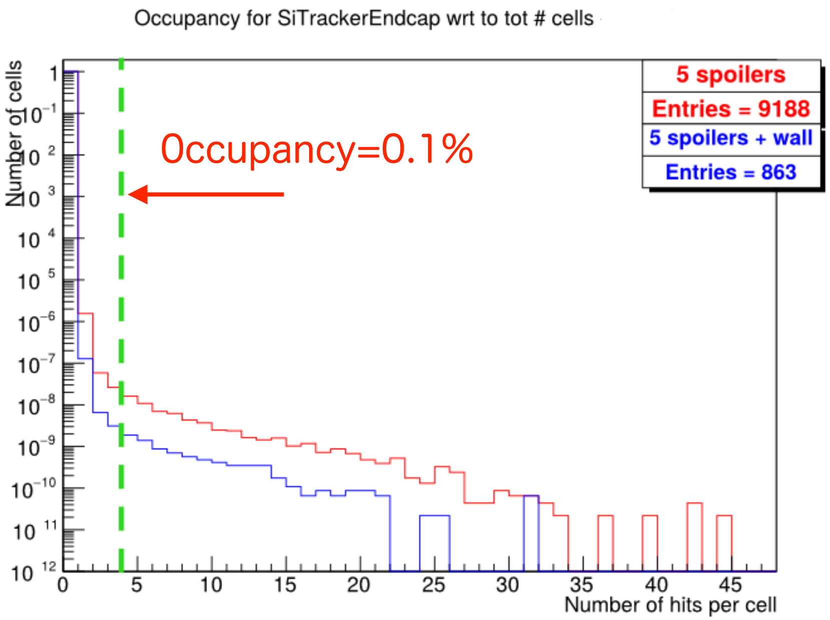


xy-view

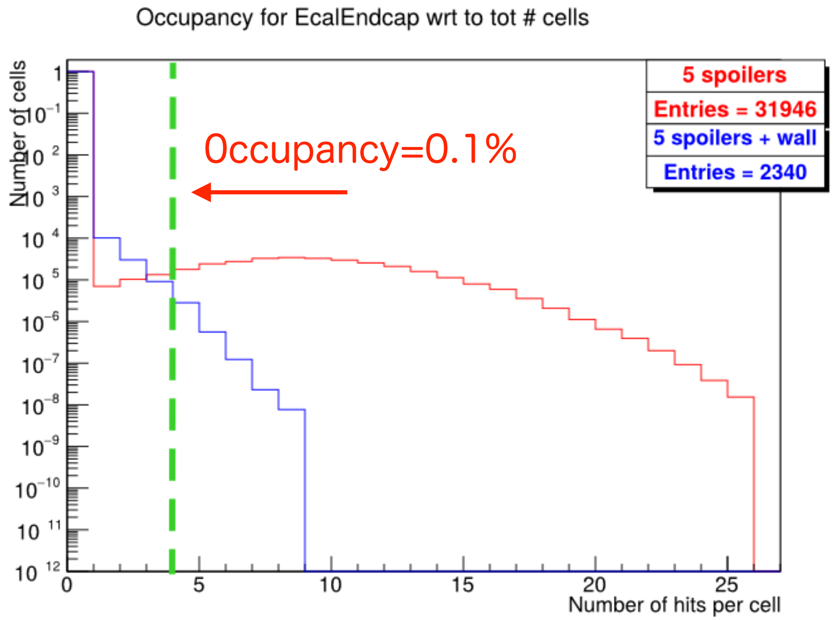


zy-view

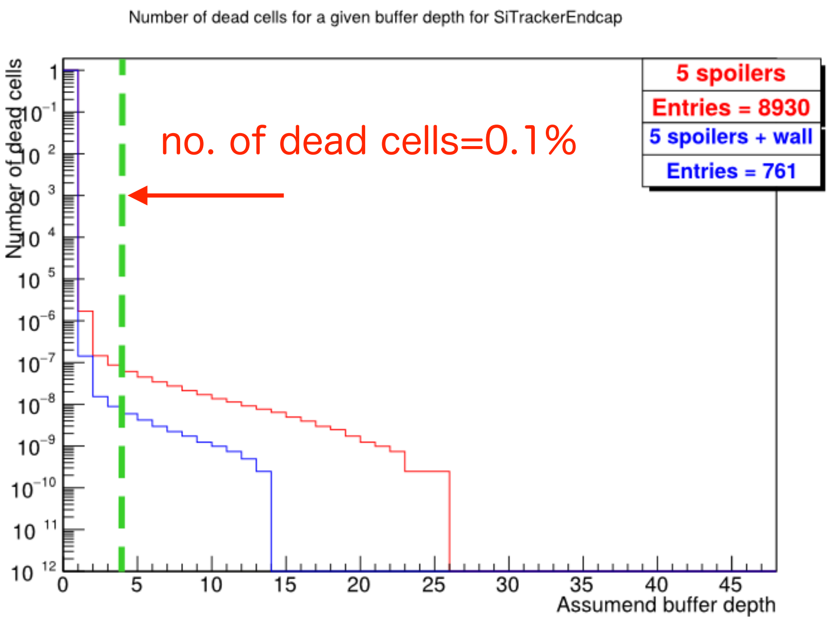
Together with the muons from the e⁻ line, there will be $\sim$ **900 muons per train in the '5 Spoilers + Wall' scenario**.



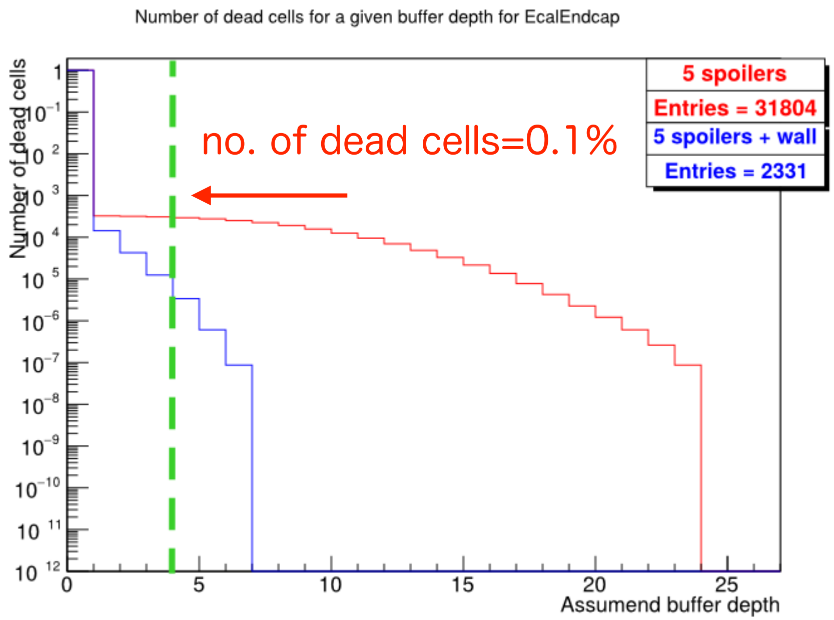

(a) Tracker endcap occupancy




(b) ECAL endcap occupancy




(c) Dead cells in the tracker endcaps




(d) Dead cells in the ECAL endcaps

Anne Schütz, Lewis Keller, Glen White, proceedings of LCWS2016, airXiv:1703.05738v1,16 Mar 2017

*Updated analysis framework and new numbers for ILC250 have shown:*

- Muons penetrate the whole detector horizontally.
- At 500 GeV, the 5 spoilers can reduce the number of muons to ∼4/bunch crossing, which results in occupancies of around $\sim 10^{-4}$ (limit of acceptance).
- The 5 spoilers + wall scenario reduces this significantly.
- In the ILC250 stage, the number of muons/bunch crossing is reduced by about a factor of 2.
- The occupancies are for both shielding scenarios well below $\sim 10^{-4}$.

*Conclusion:*

- High energy muons could be used for tracker alignment.
- Spatial distributions quite different in scenarios w/ & w/o the wall.
- With the shown evaluation of the muons from the current MUCARLO simulations, the magnetized wall is not required for limiting the detector occupancy in the ILC250 stage. However, the wall serves as a tertiary containment device, and might be mandatory anyway.

# The other radiations

## Neutron and photon flux estimates from SHIELD11

@ Detector

$E_{cm}$ = 500GeV

| Photons | | | | Neutron Total | |
|---|---|---|---|---|---|
| Rem/KWH | Rem/hr | #/cm**2.sec | | Rem/hr | #/cm**2.sec |
| 7.20E-17 | 3.74E-16 | 8.24E-10 | | 5.82E-15 | 4.24E-10 |
| 3.80E-05 | 1.98E-04 | 4.35E+02 | | 1.82E-05 | 9.26E-01 |
| 2.7 | 1.40E+01 | 3.09E+07 | | 6.40E-03 | 4.87E+02 |

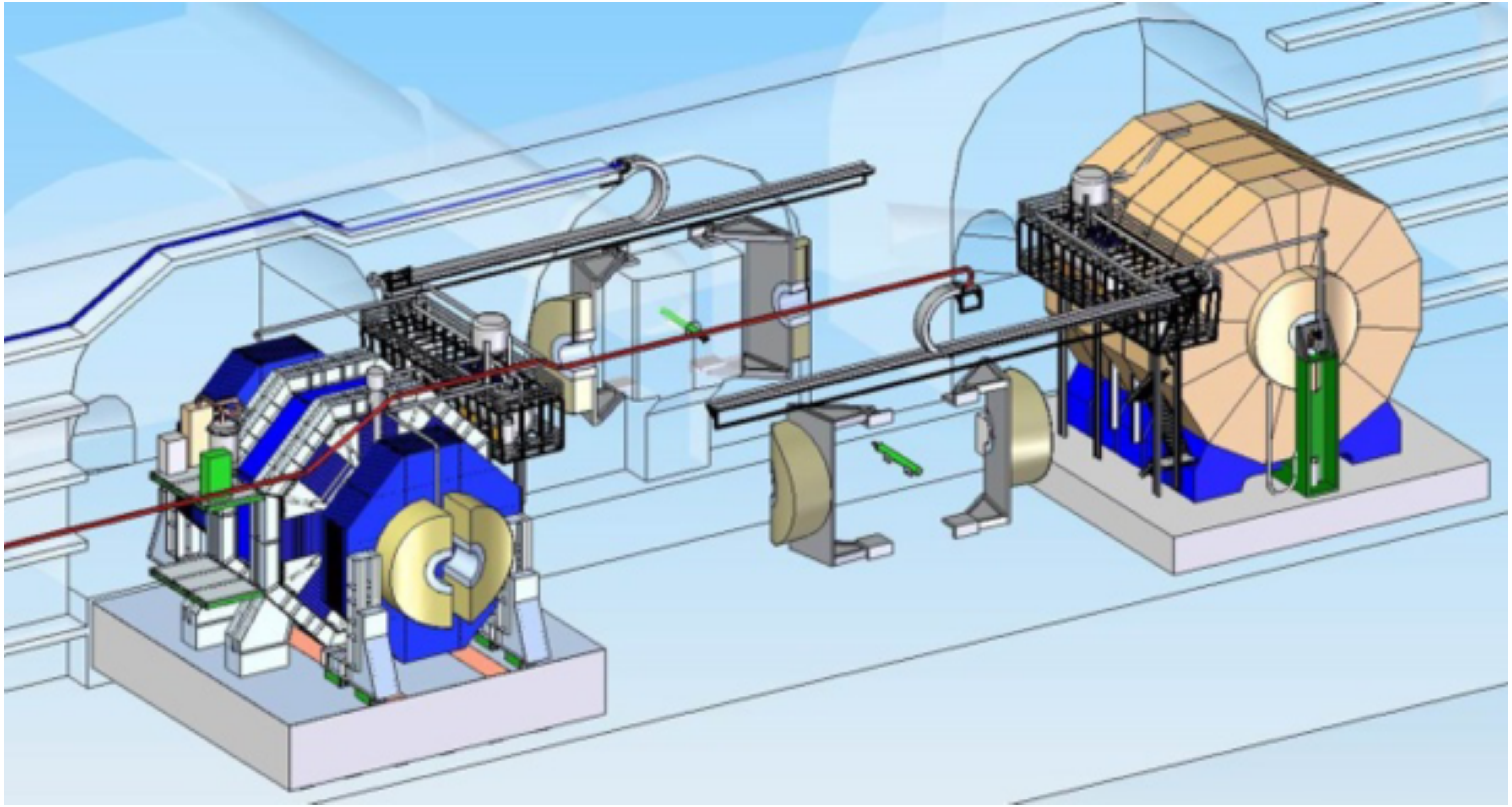
| Wall Condition | Photons | Neutrons |
|---|---|---|
| • 5m iron | <<0.2μSv/h | <<0.2μSv/h |
| • 2m concrete | 2μSv/h | 0.02μSv/h |
| • No wall | 0.14Sv/h | 64μSv/h |

which is smaller than that expected from the beamstrahlung bakground, $\sim 5.4 \times 10^{12}\mathrm{hit/cm^2}$ for 3 years at the innermost vertex detector (NIMA568(2006)233)

- Analytical estimate from SLAC SHIELD11 program for photon and neutron flux order-of-magnitude estimate.
- NOT ACCURATE (especially for photons) -> need detailed (e.g. FLUKA or GEANT) simulation including material interactions
- Need some shielding for neutrons. Maybe pacman enough for this?

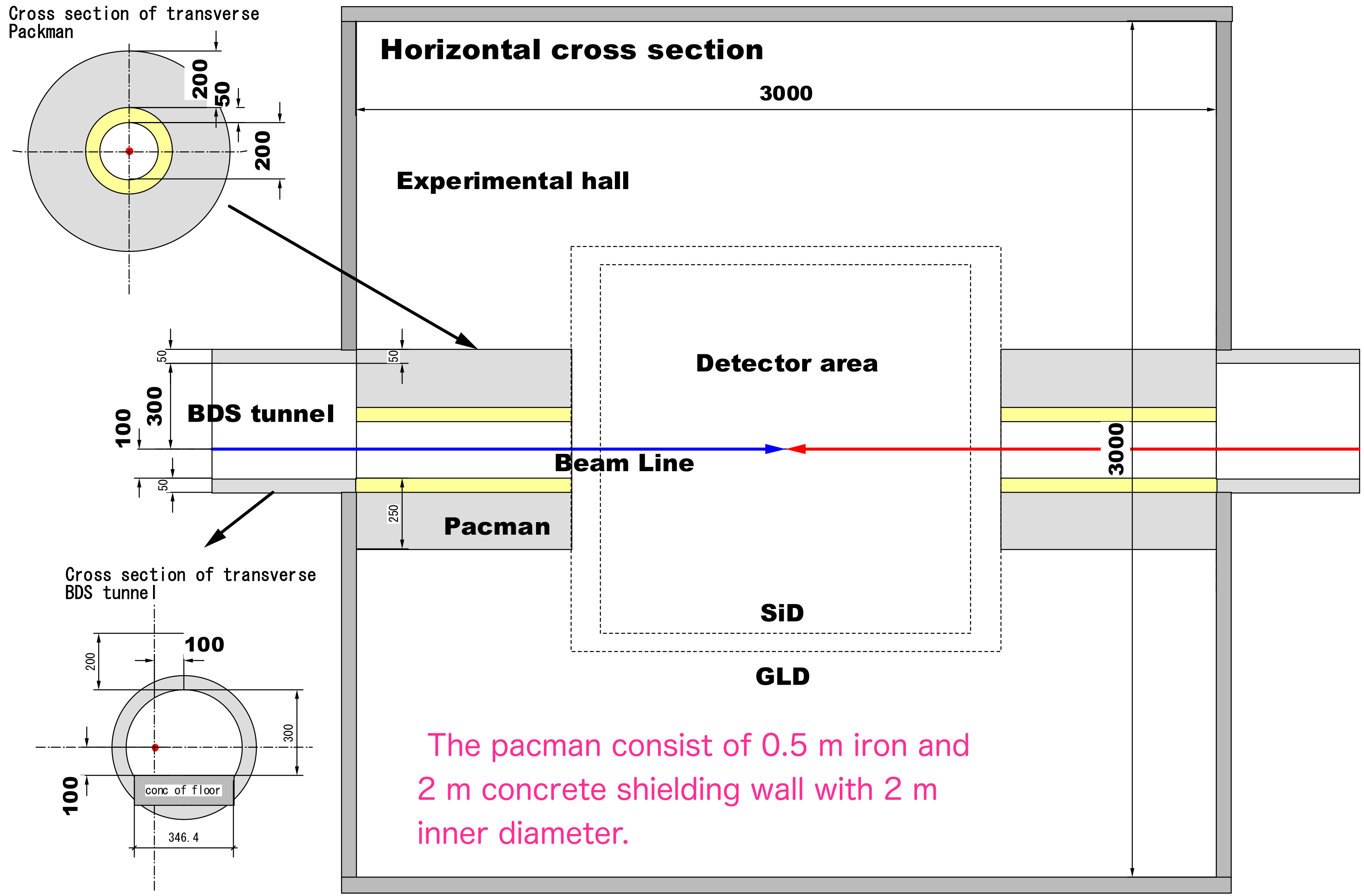
KEK radiation rules (1 Sv = 100 Rem)
0.2 μSv/h for Non-designated area (K1)
1.5 μSv/h for Supervised area (K2) , e.g. experimental hall

# Self-shielding and the Pacman



M. Oriunno / Nuclear and Particle Physics Proceedings 273–275 (2016) 1196–1201

# Pacman for radiation shield

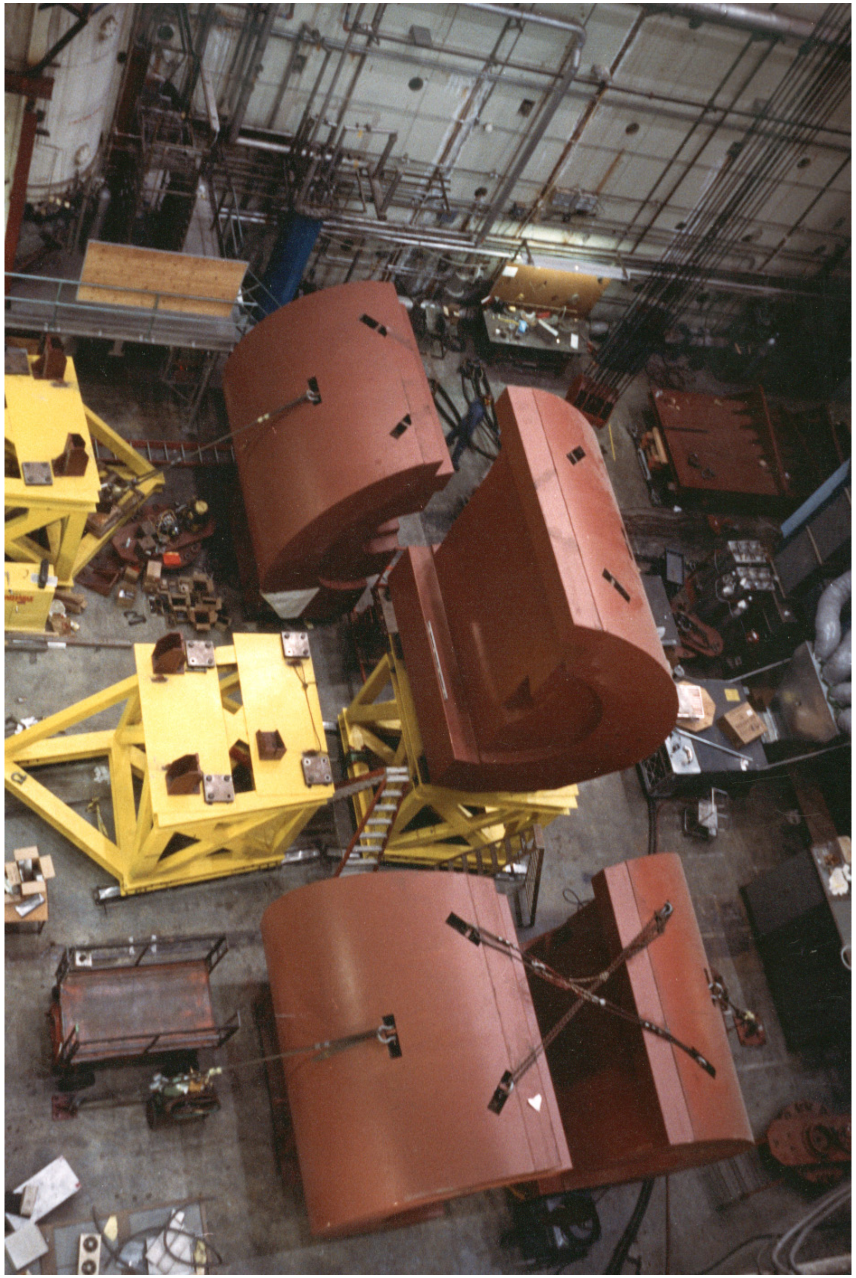



The pacman consist of 0.5 m iron and
2 m concrete shielding wall with 2 m
inner diameter.

Fig 3-2-1 Layout of IR hall used in this calculation

T.Sanami, A.Fasso, M.Santana, L.Keller, A.Seryi, S.Rokni, S.Ban, SLAC RADIATION PHYSICS NOTE RP-09-08, March 30, 2009

# Pacmen for SLD at SLAC



Retractable shielding for the triplets.

Only serious injury during construction – contract welder falls from ladder into web of rebar.

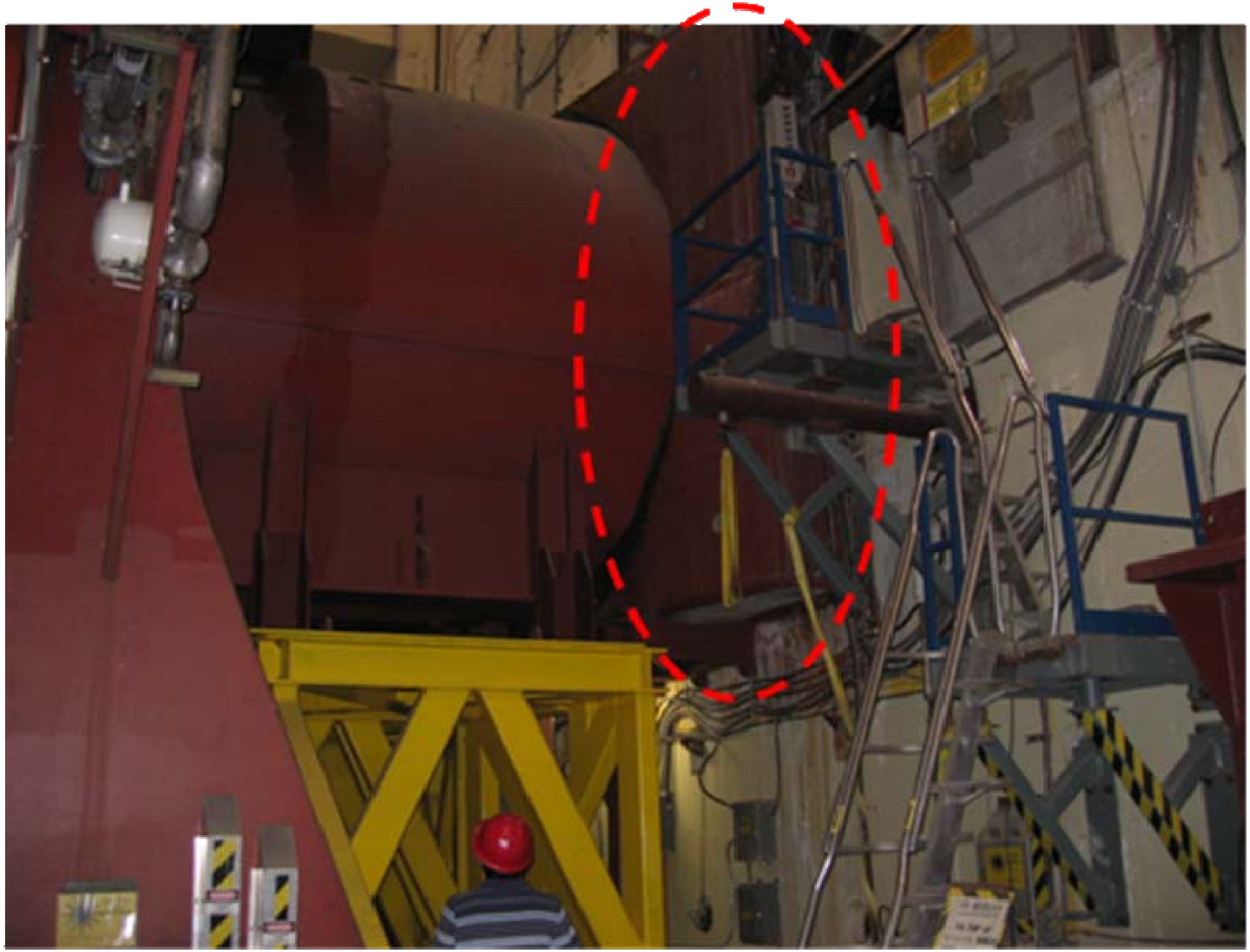


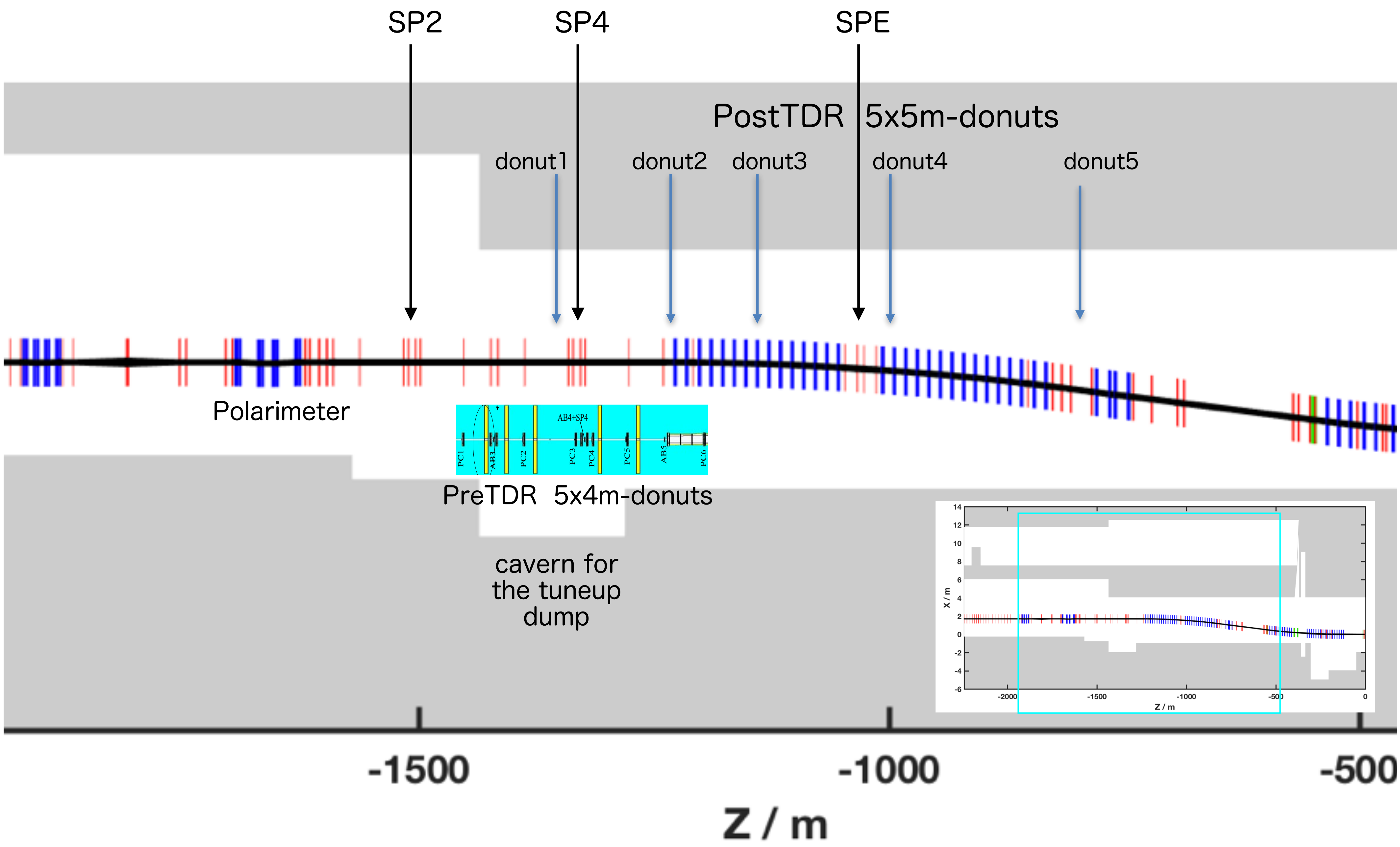
Fig. 3-2-5 Additional shielding of the connection between pacman and tunnel for the case of SLD.

# Summary of muons/bunch estimations for ILC (R<6.5m) and CLIC (suppression)

| | PreTDR | TDR | PostTDR | | CLIC |
|---|---|---|---|---|---|
| Beam energy (GeV) | 250 | 250 | 250 | 125 | 1500 |
| Beam intensity | $2\times10^{10}$ | $2\times10^{10}$ | $2\times10^{10}$ | $2\times10^{10}$ | $3.7\times10^{9}$ |
| Program | MARS15/STRUCT (MUCARLO/TURTLE) | MARS15 (?) | MUCARLO (GEANT4) | | HTGEN/PLACET BDSIM |
| tunnel | 4m$\phi$ round | 4m$\phi$round | 5m x 5m square | | 4.5m$\phi$round(?) |
| Vacuum(nTorr) | - | 10* | - | - | 1 |
| Beam Halo | $10^{-3}$ | $1\sim2\times10^{-5}$* | $10^{-3}$ | $10^{-3}$ | $1.5\times10^{-5}$ |
| no. of muons ($E_\mu$>2GeV) | 7,800x2 for both beams | 78~156 x2 | 7,800x2 | 3,900x2 | 87x2 (134.6**) |
| No spoiler | 14.8x2 | - | 130 | - | 39.5 |
| Donuts | 2.54x2(1/5.8) (5 x 4m-donuts) | - | 4.3(1/30) (5 x 5m-donuts) | 1.3 | - |
| Wall | (1/5) | ~0.01 5m-Wall | 25†(1/5.5) 5m-Wall | - | - |
| Donuts + Wall | 0.26x2(1/57) 5x4m-donuts+5m-Wall | - | 0.68 (1/191) 5x5m-donuts+5m-Wall | 0.03 | - |
| 4x10m-donuts | - | - | - | - | 3.1(1.2T)(1/13) 11.4(0.7T)(1/3.5) |
| 8x10m-donuts | - | - | - | - | 2.3(1.2T)(1/17) 6.1(0.7T)(1/6.5) |

*) $1\times10^{-5}$ at 10nTorr by HTGEN †)"No spoiler" = 138 **) one by CLIC group

# Positions of the 5 donuts for PreTDR and PostTDR



# Summary

## (1) Beam Halo

$10^{-3}$ from the measured value at the SLD, SLC
$10^{-5}$ estimated with 10nTorr in the main LINAC by the HTGEN (Halo and Tail generator)

## (2) Muon suppression

Post-TDR 5x5m-donuts whose locations are opimized have a suppression of 1/30 and a 5m-Wall addition has a suppresion of 1/191. A 5m-Wall has a suppression of 1/5.5 .

Pre-TDR 5x4m-donuts have a suppression of 1/5.8 and a 5m-Wall addition has a suppresion of 1/57. A 5m-Wall has a suppression of 1/5. TDR 5m-Wall may have a suppression of ~1/10. There is also difference in “No spoiler” between Pre- and Post-TDR.

These numbers vary, since the tunnel geometries and the spoiler positions are different.

## (3) Tolerable limit for the detectors

SiD : Even with 0.1% beam halo, the occupancy is well below $10^{-4}$ for both the 5x5m-donuts and the 5x5m-donuts+5m-Wall configulations. Regarding the experimentation by the SiD, the 5m-Wall is not needed, i.e. 5x5m-donuts configuration is enough at the ILC250.
ILD : Under study

# Summary (continued)

## (4) 5m-Wall as the tunnel filler

It is very efficient to shield any radiations from the upstream beam line during the machine operation/tuning as well as the supppression of muons.

It is not essential for following solutions when necessary and for additional radiations to be shielded by the pacman for the personnel protection.

## (5) Further suppression

Vacuum pressure at the main LINAC : 10nTorr to 1nTorr by 1/10
Material of the absorbers AB2 - 5 : Copper to Tungsten by 1/2
,while the ABE is already tungsten

However, the above improvements may be helpless for the 0.1% halo.

Additional donuts : The suppression shall be investigated by optimizing the locations as well as the number, which should be <1/6 to be comparable to the 5x5m-donuts + a 5m-Wall.

These donuts are not trivial. They weigh about 60 tons each(Lew Keller).

In addition, the 5-19m Wall can be installed in the muon spoiler hall if it is kept.