Beam Collimation and Machine-Detector Interface

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ILC R&D Meeting
Fermilab
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OUTLINE

- ILC BDIR Critical Design Choices.
- IP Backgrounds.
- Crossing Angle and Machine-Detector Interface.
- Machine Backgrounds.
- BDS Tracking and Interaction Simulations.
- Energy Deposition Issues in BDIR.
- Collimation System Design and Performance.
- Radiation in BDIR and Backgrounds at Detectors.
- Work Tasks.

ILC BDIR CRITICAL DESIGN CHOICES

- Crossing Angle
  - Head on
  - Very small vertical crossing angle
  - Small horizontal or crossing angle (~2mrad)
  - Large horizontal crossing angle (7-20mrad, ~35 mrad)
- Final Doublet Technology
  - Compact SC or PM quad, or large bore SC
- L*
  - e.g. 3,4,5m
- Detector VXD inner radius
- Instrumentation Choices
- MPS Questions
- Detector Questions
- Collimation Choices
- Beam Stabilization choices
- Risk Mitigation

OPTIONS

- Gamma-gamma
  - In, particular, consequence of ~35 mrad crossing angle on e+e- luminosity
- e- e-
- e+ polarized
- Above 1 TeV running
- Consequence of simultaneous running of both IRs

IP BACKGROUNDS

Source: Beam-beam interactions (e^+e^- pairs, disrupted primary beam and beamstrahlung photons), hadrons from $\gamma\gamma$ interactions and radiative Bhabhas.

From the standpoint of integrated background, e^+e^- linear colliders are relatively 'clean' machines. Average integrated hadronic fluxes produced at the IP are about six orders of magnitude lower compared to LHC.

However, the instantaneous rates are not so drastically different. Say, for the $\gamma\gamma$ option, a peak radiation field is about 10% of that at LHC. The e^+e^- option is 10 times better.

In general, this source is well understood and under control.

These backgrounds depend on crossing angle, detector and masking scheme designs, solenoid field, and beampipe.

CROSSING ANGLE

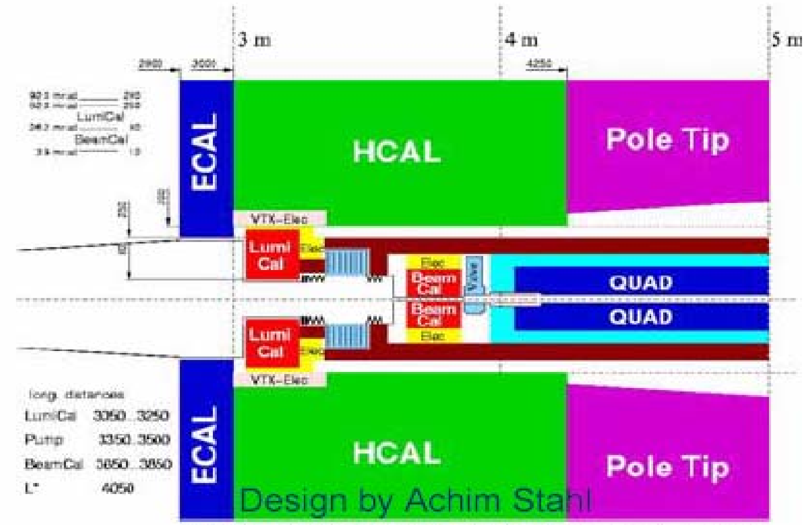
Cold LC can choose zero or non-zero angle

- **Minimum angle has hard limit, set by:**
  - **Need enough transverse space for QD0 magnet, given**
    - L* (a semi-free parameter) ***(e.g. 3.51m)***
    - Exit aperture at LUM ***(1.2cm→2.0cm→1.5cm)***
    - QD0 bore size ***(1.0 cm)***
    - Design choice that exit beam goes (or not) outside of QD0
- **Maximum angle has softer limit, set by**
  - **Estimated performance of Crab Cavities that rotate bunches on either side of IP (Δt = 50 fs @ 7 mrad, 16 fs @ 20 mrad)**
  - **Beam optics effects: ε growth due to SR, ~ $(B_s L^* \theta)^{5/2}$**
  - **Wider pair distribution, but partly mitigated by larger exit hole**
  - **Modest loss of efficiency for dark matter/SUSY candidates / rejection of background. Physics study needs to advance.**

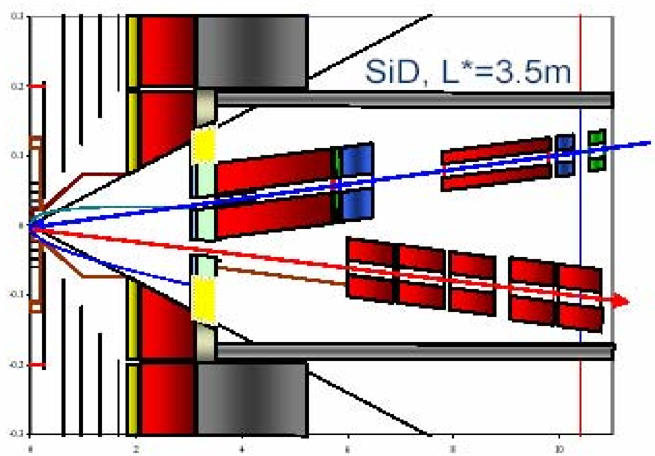
Difficult to quantify, but clear decrease of performance at 35 mrad with respect to optimal 7-20mrad

IR LAYOUT, L*, QD0

- **Choice of L* (3, 4, 5m)**
  - → optics design, tolerances, luminosity & collimation performance
  - ⇔ Xing angle, detector size, field, layout, VXD radius, masking



TESLA proposed design for L*>4.05m



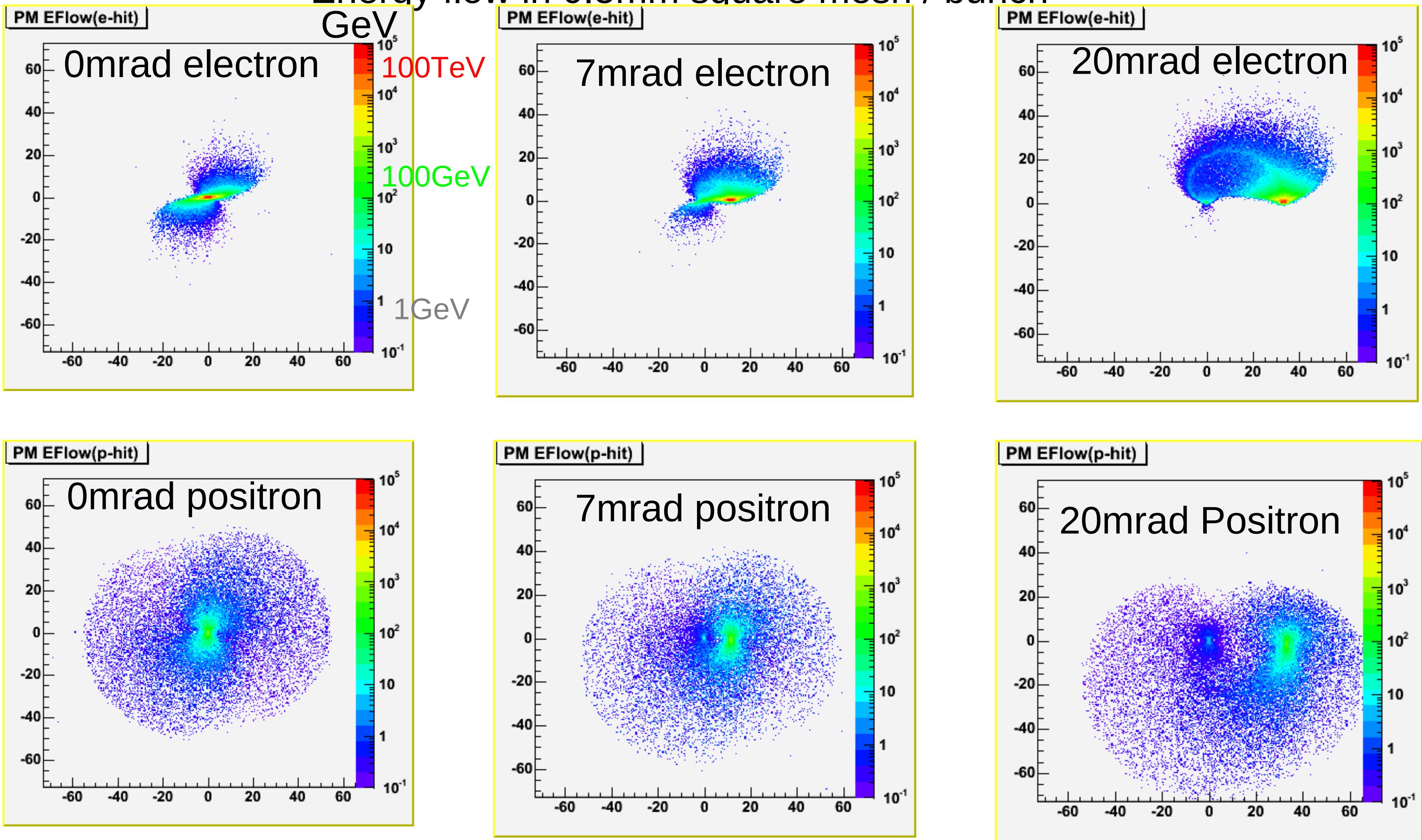
- **Availability + energy flexibility of final quad (QD0) techn'lgy ?**
  - large bore SC quad (Tesla)
  - compact SC quad
  - compact PM quad (NLC)
  - warm iron quad (GLC)

PAIR DISTRIBUTION AT Z=330CM, B=4T

TRC500

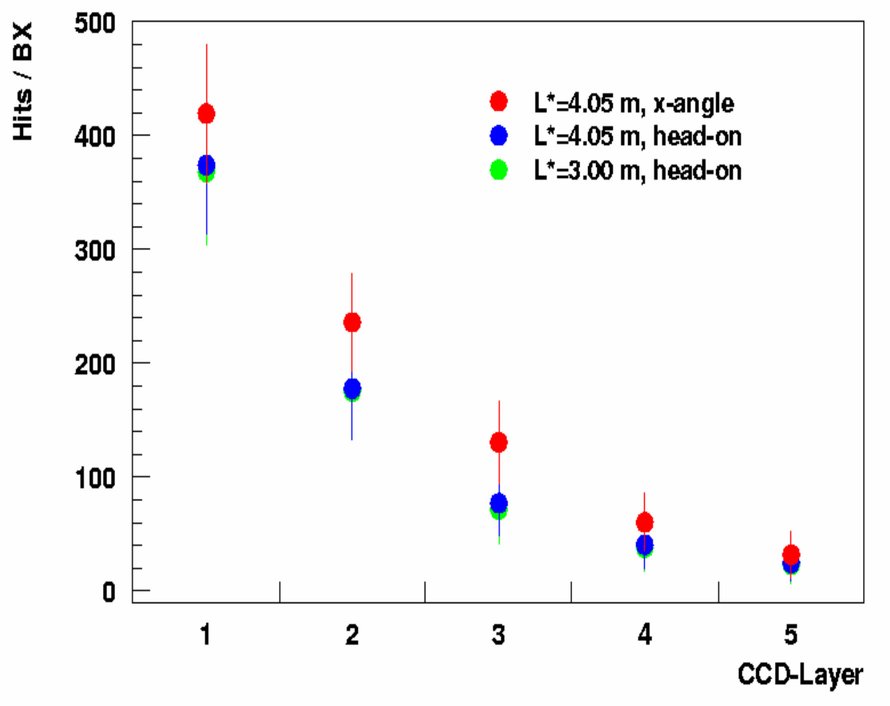
Aso

Energy flow in 0.5mm square mesh / bunch



VXD HITS FROM e+e- PAIRS

Büßer



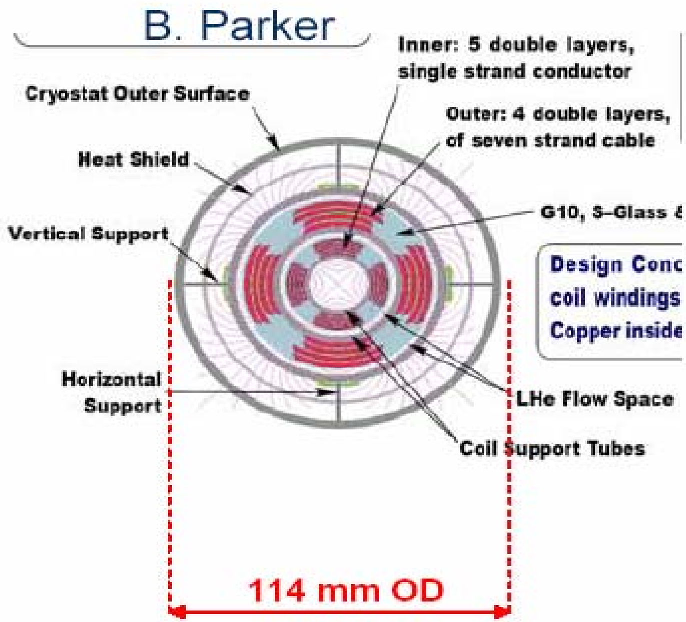
Depends on:
- VTX radius
- Solenoid field
- Crossing angle

Aso

Crossing Angle	VTX Radius	Solenoid Field	Hit density (/mm2/train)
Head-on	15mm	4Tesla	0.99
7mrad	15mm	4Tesla	1.00
7mrad	24mm	3Tesla	0.38
20mrad	15mm	4Tesla	1.03
20mrad	15mm	3Tesla	1.71

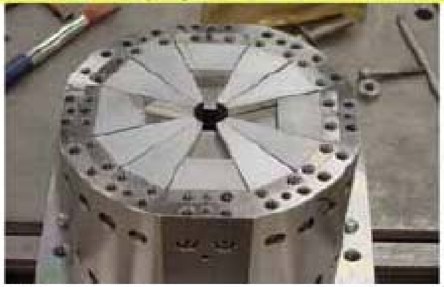
FINAL QUAD QD0

Compact SC FD quad or Compact variable PM FD quad



The design also allows combining with dipole, sextupole, or other n-pole for better optics correction

Measured GL value was 28.5T
(calculated value 29.7T)
@ L=100mm, Ø14mm
(Gmax=300T/m, Bmax=2T@boreR)

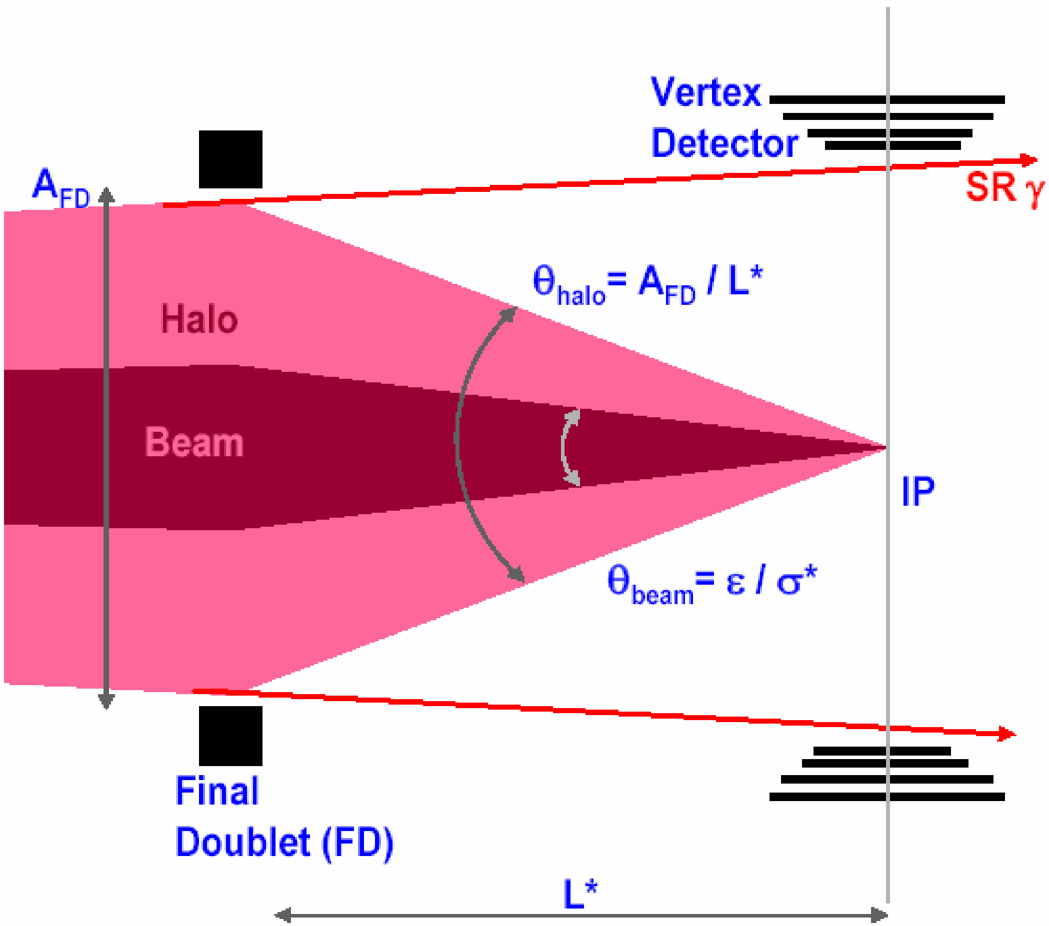


2nd model mechanically adjustable
in discrete steps of ΔGL=1.6
M.Kumada, T.Mihara et al. LINAC2004

MAIN OPEN ISSUES FOR X-ING ANGLE LAYOUTS

- **"Zero": head-on or very small vertical Xing angle**
  - R&D needed to demonstrate feasibility (ES @ 1 TeV, septum)
  - is it practical @ 1 TeV (extraction losses, parasitic Xings) ?
  - how important are the post-IP diagnostics ? (needed most at m_Z)
  - on a grander scale, is the physics gain in one specific area worth the risks & operational constraints ?
  - 0.3 mrad: are the vertical-crab challenges (tight tols!) worth it?
- **small (2 mrad) horizontal Xing angle**
  - understand halo SR, beam-beam backgrounds, fringe field effects
  - clean extraction @ 1 TeV c.m. to be designed
  - compatibility w/ post-IP diagnostics?
- **intermediate horiz. Xing angle (3-7 mrad)**
  - warm FD operation at 1 TeV c.m. ? solenoid compensator?
  - clean extraction @ 1 TeV c.m. to be demonstrated
- **"large" horizontal Xing angle: separate beam lines → flexibility**
  - increased reliance on crab cavities
  - how small can we make the hor. Xing angle? (B. Parker: 12 mrad?)
- **what is the overall optimum ? (2 IR's with "similar" $\mathcal{L}$ + preserve $\gamma\gamma$)**

IR DEPENDENCIES: X-ING ANGLE CASE



Halo must be collimated upstream in such a way that SR γ & halo e^{+-} do not touch VX and FD

=> VX aperture needs to be somewhat larger than FD aperture

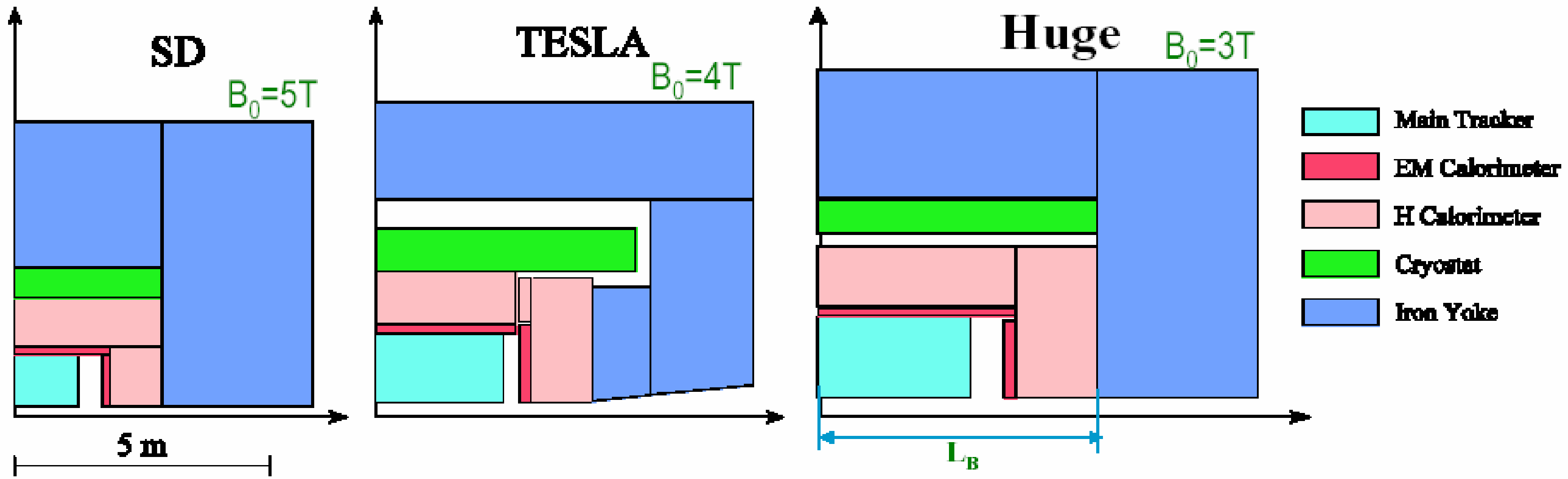
Exit aperture is larger than FD or VX aperture

Beam convergence is fixed, halo convergence ~1/L*
=> $\theta_{halo}/\theta_{beam}$ (collimation depth) becomes tighter with larger L*

Tighter collimation => MPS issues, collimation wake-fields, higher muon flux from collimators, etc.

MACHINE-DETECTOR INTERFACE

- Larger detectors => drive desire to increase L*, but this has a limit
- FD in solenoid field => beam coupling, need for compensating antisolenoids in FD region (θ_c independent)
- Synchrotron radiation in detector field (strong function of θ_c, field and detector size)



layouts from Satoru Yamashita, ECFA LC Workshop@ Durham, 3 Sep. 04

		SD	TESLA	LD	Huge
Solenoid field strength	B_0 (T)	5	4	3	3
IP to Yoke length	L_B (m)	3.15	4.25	4.8	~ 5.5

MACHINE BACKGROUNDS

Synchrotron radiation, spray from the dumps and extraction lines, beam-gas and beam halo interactions with collimators and other components in BDIR create fluxes of muons and other secondaries which can exceed the tolerable levels at a detector by a few orders of magnitude.

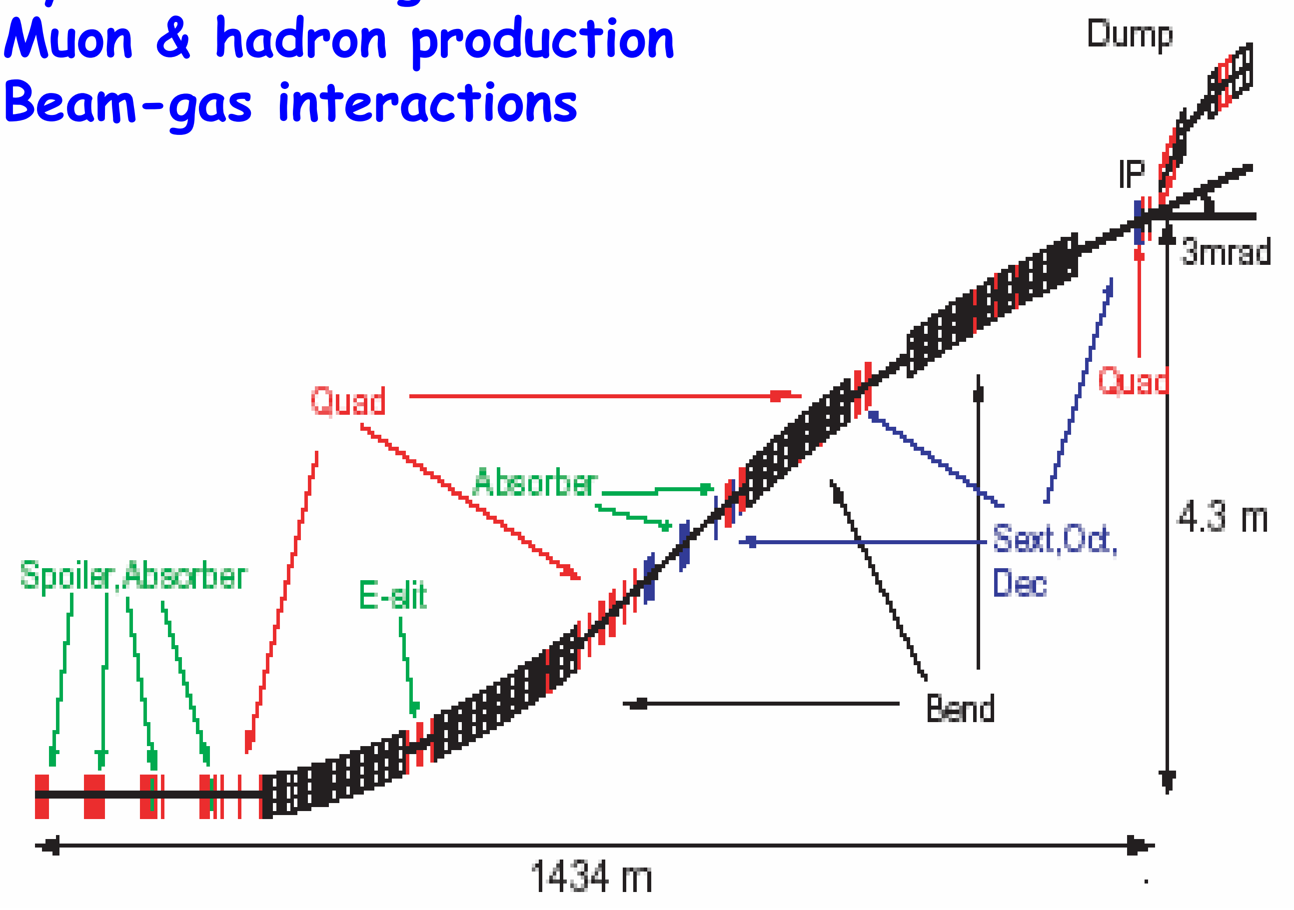
With a multi-stage collimation set and a system of magnetized iron spoilers (which fill the tunnel), one can hopefully meet the design goal of allowing a continuous 0.1% beam loss, resulting in a tolerable muon flux at the detector.

Much more studies are needed including detector tolerance levels, muon suppression, contribution of photons, hadrons and low-energy neutrons in all the beam loss mechanisms.

MODELING IN BDS

Collimation system design
Beam loss calculation
Sync radiation generation
Muon & hadron production
Beam-gas interactions

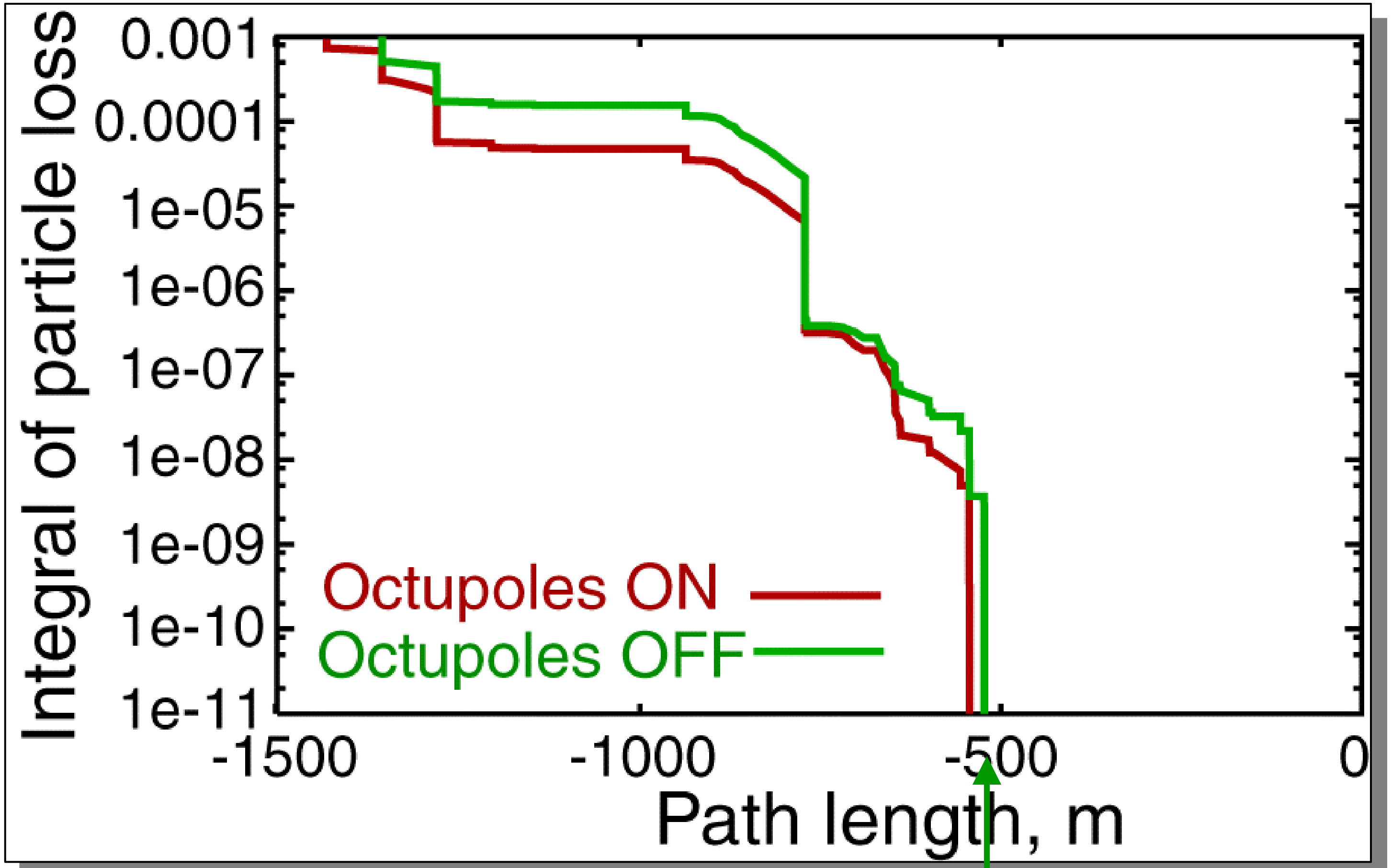
DECAY TURTLE
STRUCT
MARS15
GEANT3
GEANT4



ENERGY DEPOSITION ISSUES IN BDIR

1. Machine-related backgrounds and damage in collider detectors.
2. Collimation system and mask design and optimization under realistic engineering constraints.
3. Short- and long-term survivability of the critical components (spoilers, absorbers, magnets, septa, dumps etc).
4. Dynamic heat loads and lifetime of collimators, magnets and other components: total and peak radiation dose and limits for various materials.
5. Residual dose rates: hands-on maintenance.
6. Environmental aspects (prompt dose, ground-water and air activation).
7. Models of operational and accidental beam loss (abort kicker prefire, sparks in ES septa, accident dynamics etc).
8. Beam instrumentation.
9. Development of adequate reliable computational tools.
10. Benchmarking and uncertainty analysis.

NLC COLLIMATION SYSTEM



E=250 GeV

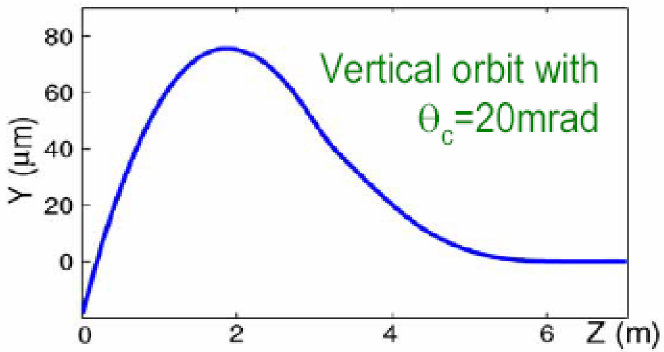
N=1.4E12

0.1% Halo distributed as 1/X and 1/Y for $6<A_x<16\sigma_x$ and $24<A_y<73\sigma_y$ with **$\Delta p/p=0.01$** gaussian distributed

Last Lost e- 500m from IP

SR EFFECTS IN DETECTORS

Crossing detector field leads to vertical deflection => beam size growth due to synchrotron radiation



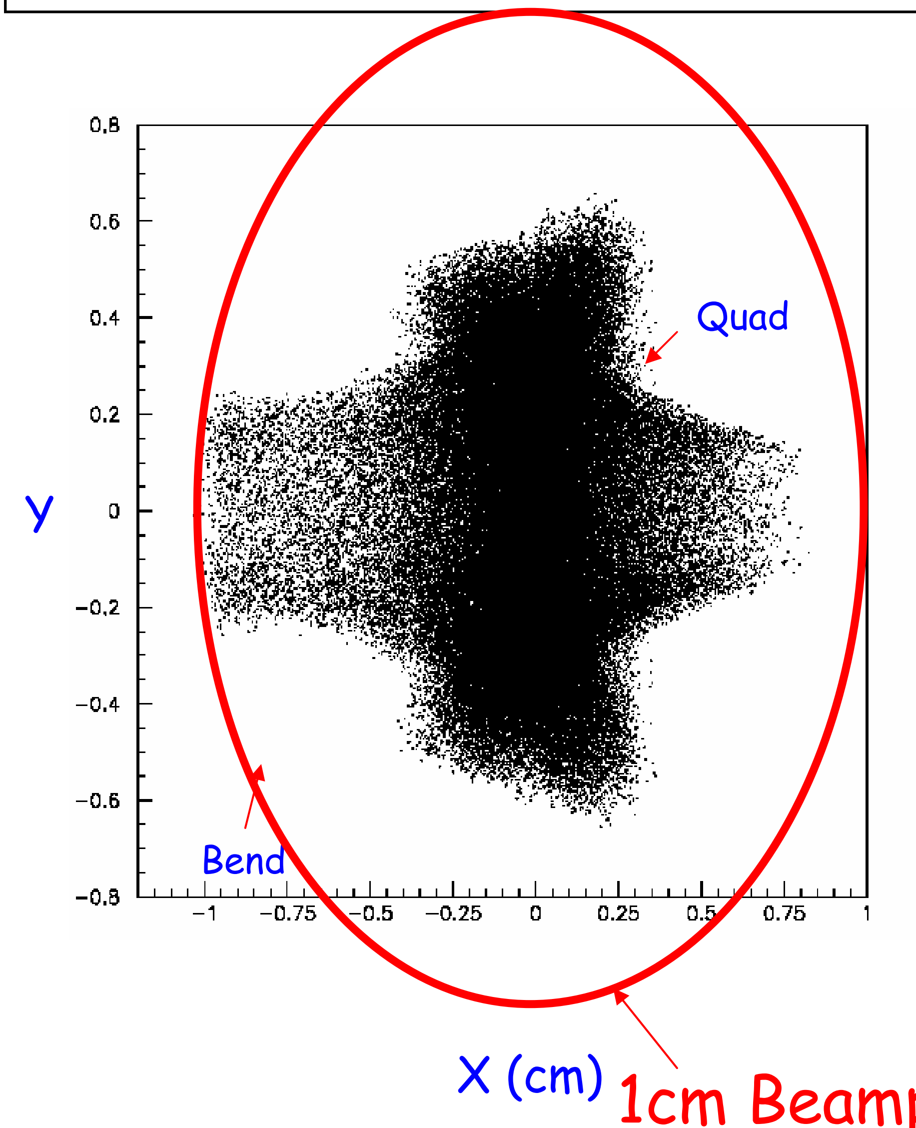
Incremental IP size strongly depends on detector length, field and crossing angle

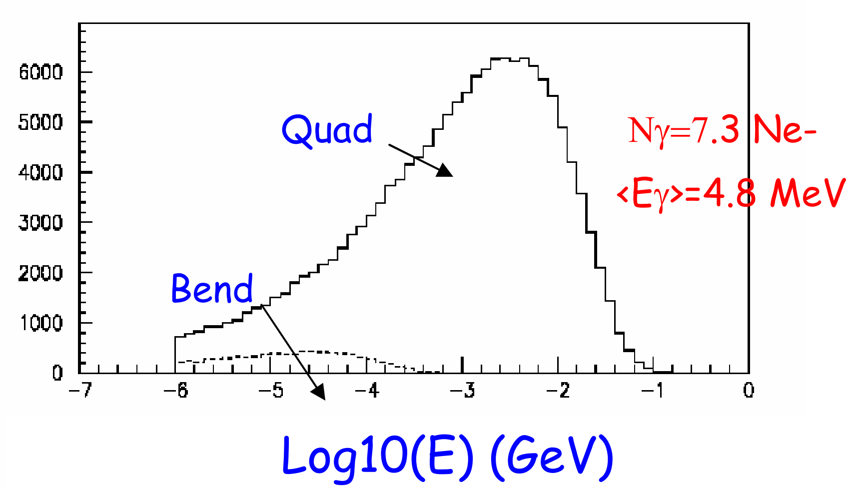
$$\Delta\sigma_{SR} \sim (B_0\ \theta_c\ L)^{5/2}\ F(optics)$$

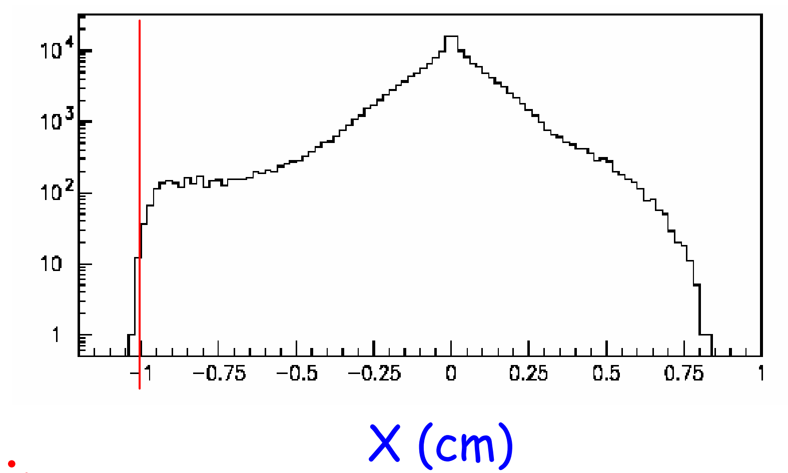
For θ_c = 20 mrad this beam size growth is noticeable; for θ_c = 35 mrad it is too large

		SD	TESLA	LD	Huge
Solenoid field strength	(T)	5	4	3	3
IP to Yoke length	(m)	3.15	4.25	4.8	~ 5.5
$\Delta\sigma_{SR}$ **for 20 mrad crossing angle**	(nm)	0.31	~ 0.9	0.57	~ 0.8
$\mathcal{L}$ **impact @ 0.5 [1] TeV (σ_0=5 [2.1] nm)**	(%)	0.2 (1)	~ 1.6 (8)	0.6 (3.5)	~ 1.2 (7)
$\Delta\sigma_{SR}$ **for 35 mrad crossing angle**	(nm)	1.26	~ 3.6	2.3	~ 3.2
$\mathcal{L}$ **impact @ 0.5 [1] TeV (σ_0=5 [2.1] nm)**	(%)	3 (14)	~ 18 (50)	9 (32)	~ 15 (45)

SR AT IP DUE TO HALO







SR AT IP MASKS DUE TO BEAM CORE

	TESLA	NLC	CLIC
# bunches/(eff. train)	150	192	154
Losses on SR mask upstream of FD			
Mean photon energy(MeV)	0.450	0.032	0.034
# photons/bunch /eff.train	1.38E10 2.07E12	0.93E9 1.79E11	5.93E8 9.13E10
Tot. photon E (GeV)/bunch /eff.train	6.21E6 9.32E8	2.96E4 5.68E6	2.03E4 3.13E6
Losses on SR mask dwn of outgoing-side FD			
Mean photon energy(MeV)	0.467	-	-
# photons/bunch /eff.train	4.75E8 7.14E10	- -	- -
Total photon energy (GeV) /bunch /eff.train	2.22E5 3.33E7	- -	- -

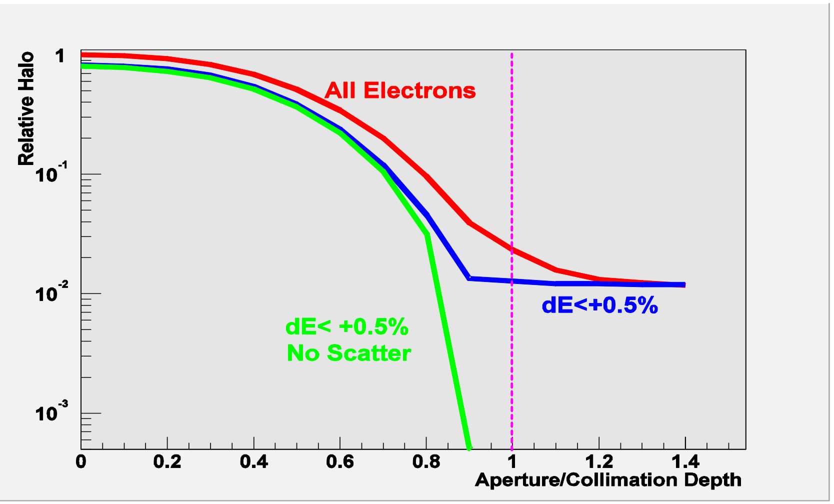
STRUCT by A. Drozhdin

Synchrotron radiation from beam core hitting IP mask. The losses tabulated refer to mask DUMP1 for TESLA and DUMP2 for NLC and CLIC. The number of bunches per "effective" train reflects the sensitivity window of the TPC. It is equal to 150 bunches (50 μsec) for TESLA, and to the nominal number of bunches per train for NLC and CLIC.

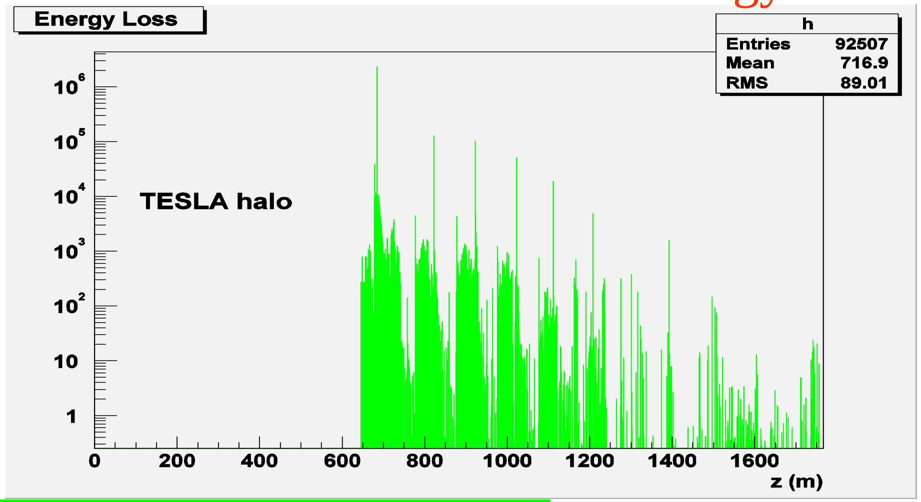
UK/RHUL COLLIMATION STUDIES

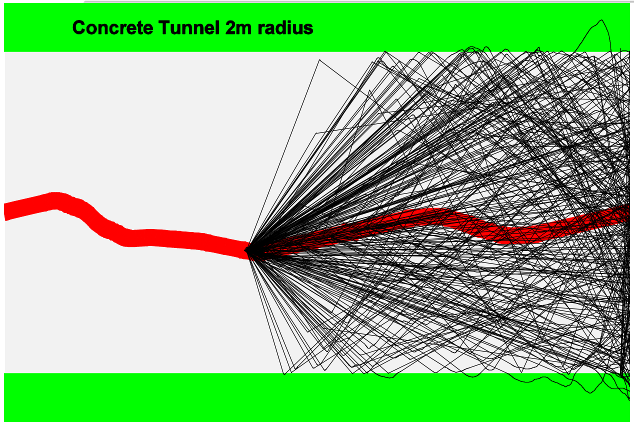
BDSIM: A Geant4-based accelerator tracking code. Uses efficient transfer-matrix style tracking within the beampipe; otherwise 'normal' G4 tracking inside materials.

(TESLA) Collimation efficiency



Energy Loss

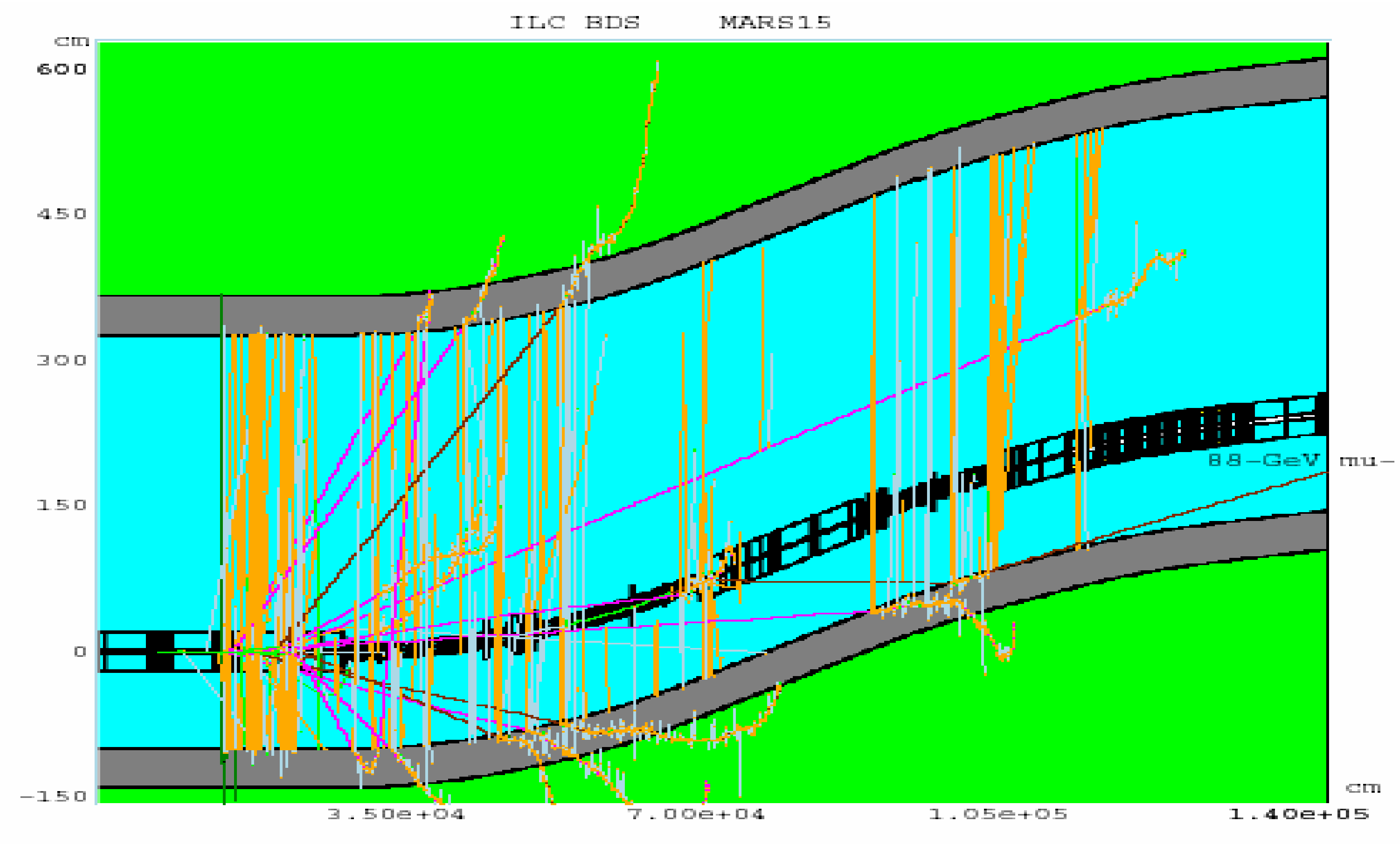




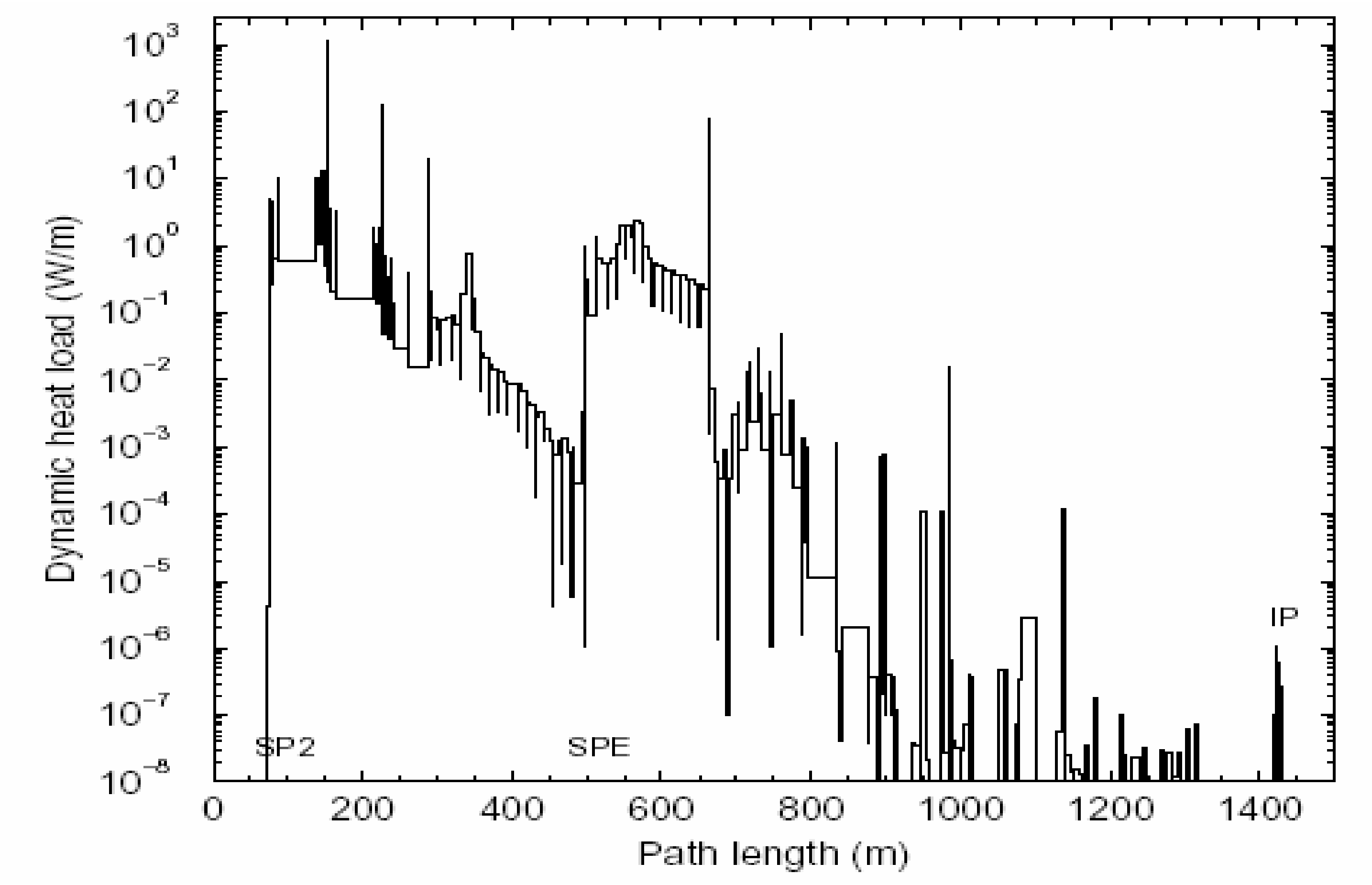
Other processes:
Muons, SR, neutrons …

UK/RHUL:
G. Blair
A. Agapov
J. Carter
M. Price
+ new collabs

MARS15 MODELING OF BDIR



DYNAMIC HEAT LOAD IN BDIR

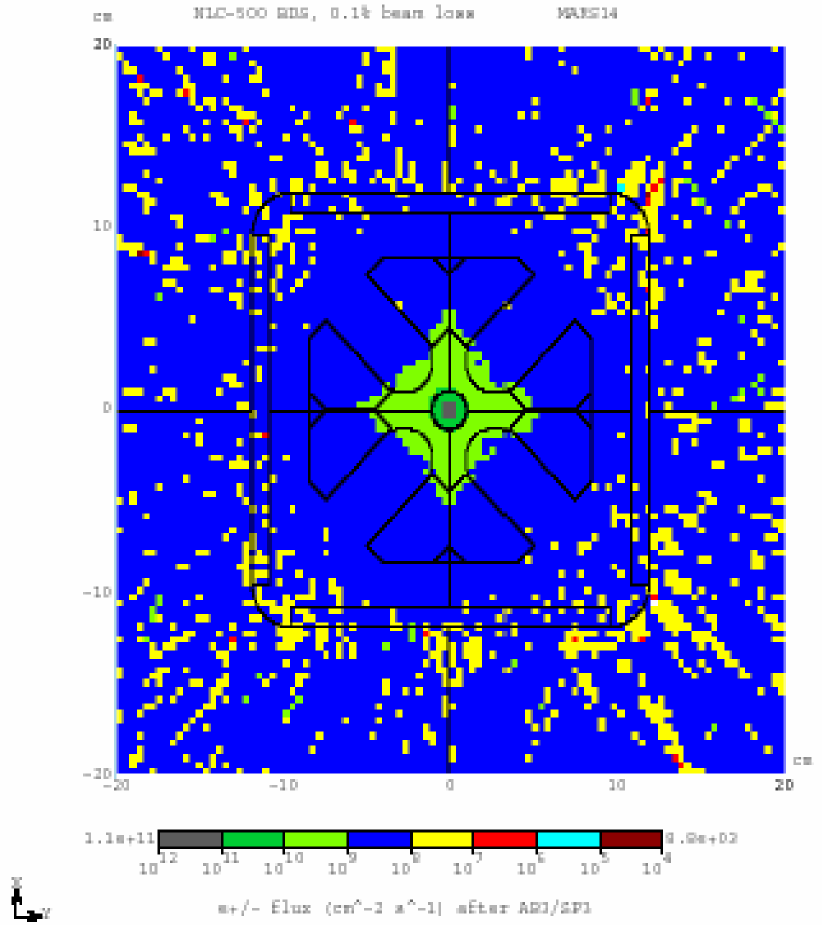


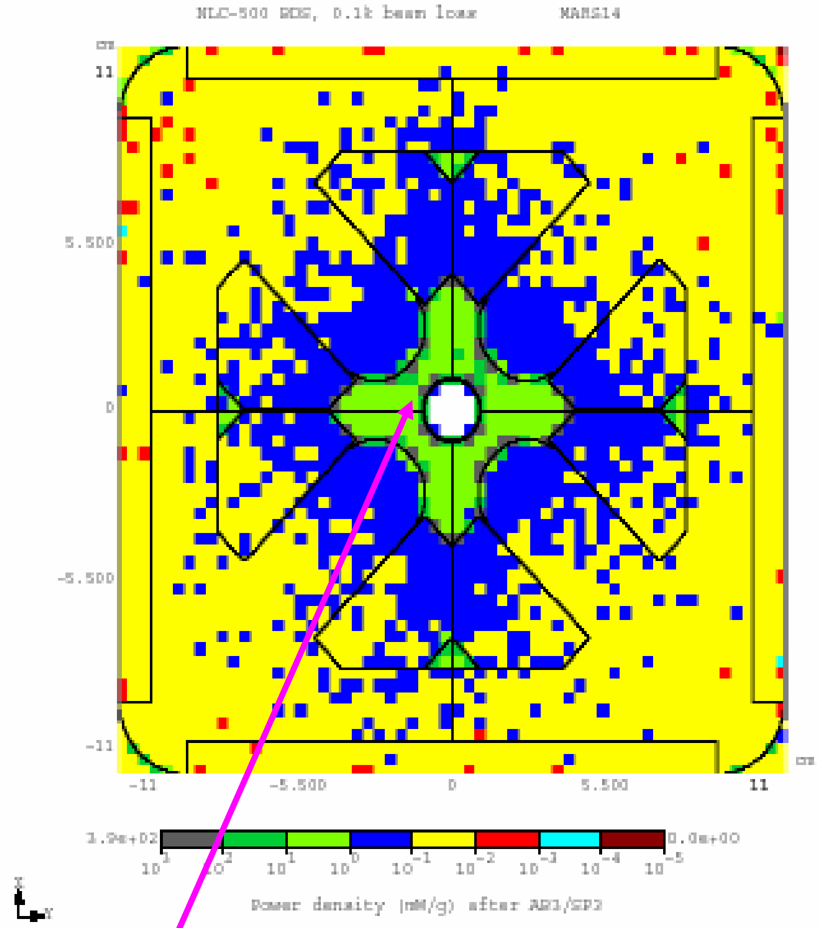
MARS15

Main features are similar to STRUCT, but details/values are quite different: STRUCT 50-GeV cutoff, MARS15 full shower simulation down to 100 keV.

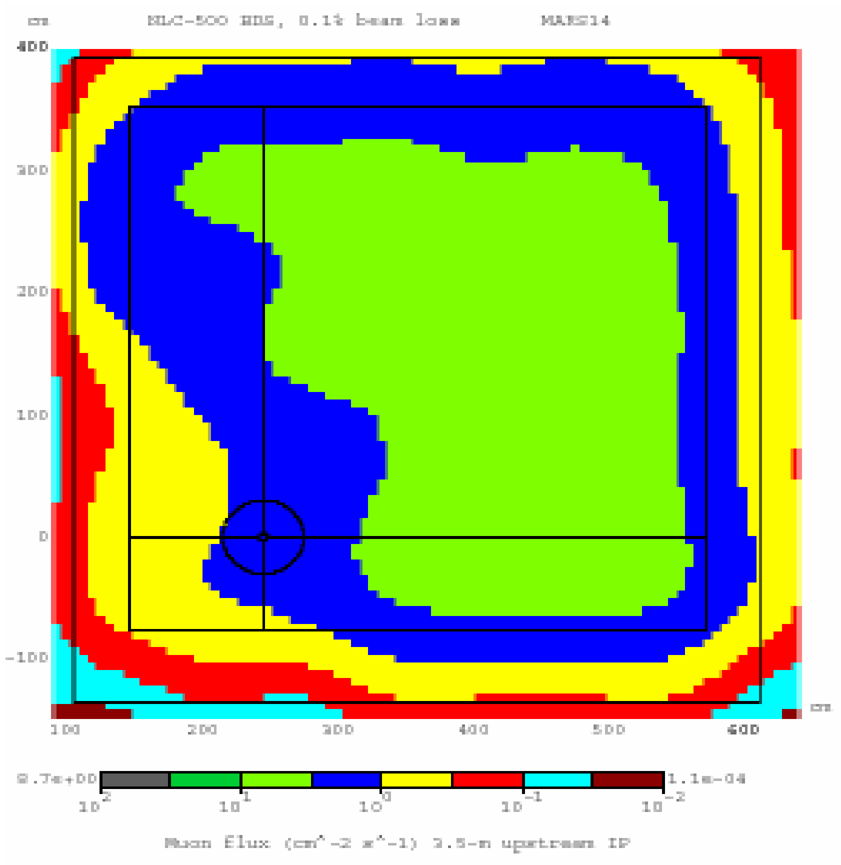
RADIATION LOADS AFTER SP3/AB3

MARS15





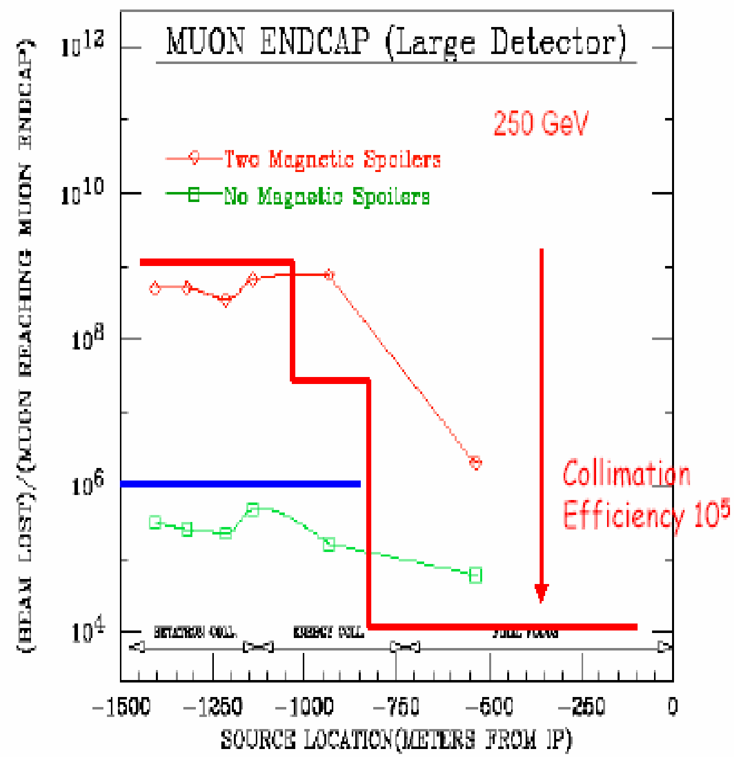
MUONS AT DETECTOR



Bunch Train $=10^{12}$

Engineer for 10^{-3} Halo

Calculated Halo is 10^{-6}

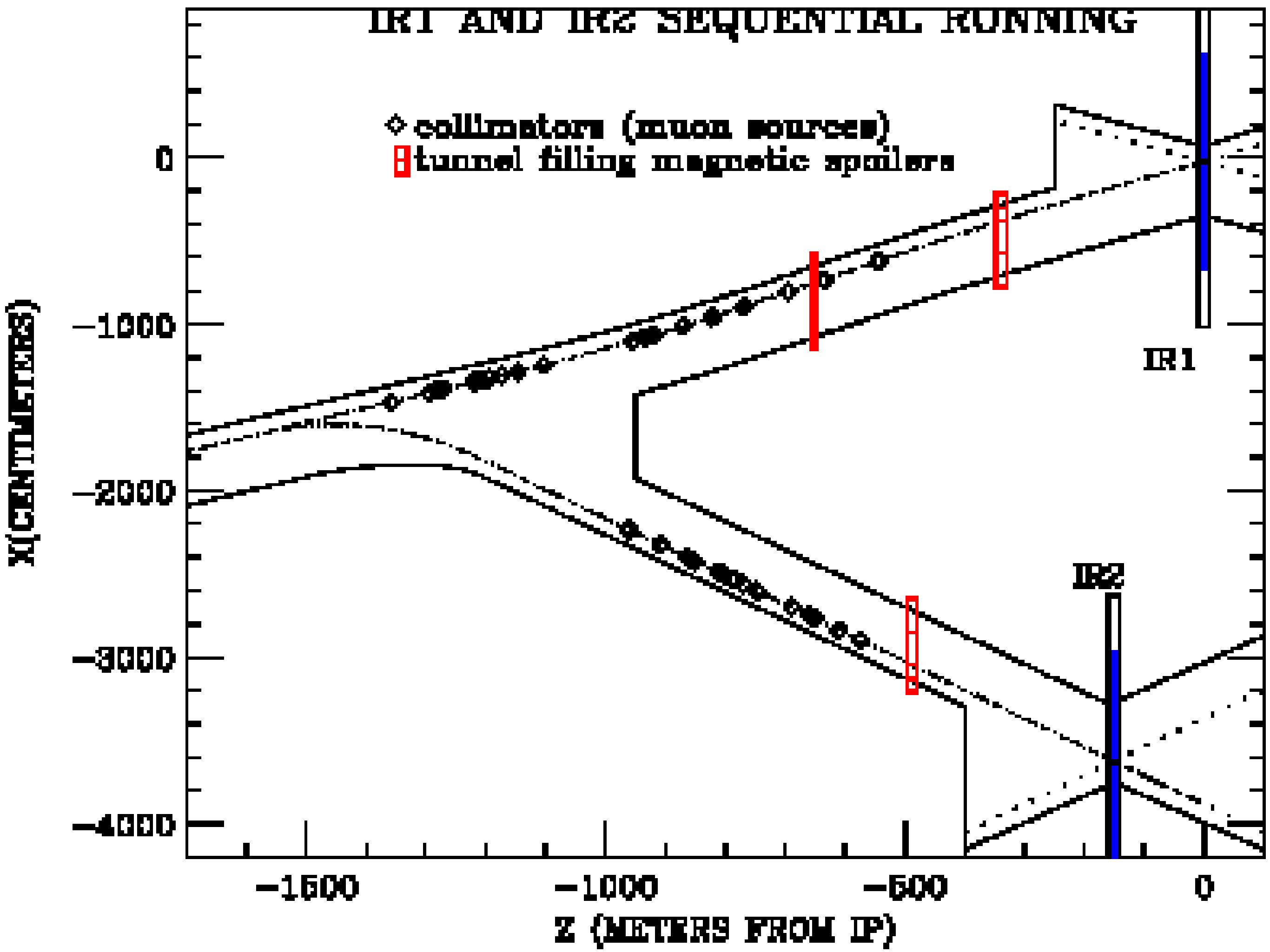


MARS15

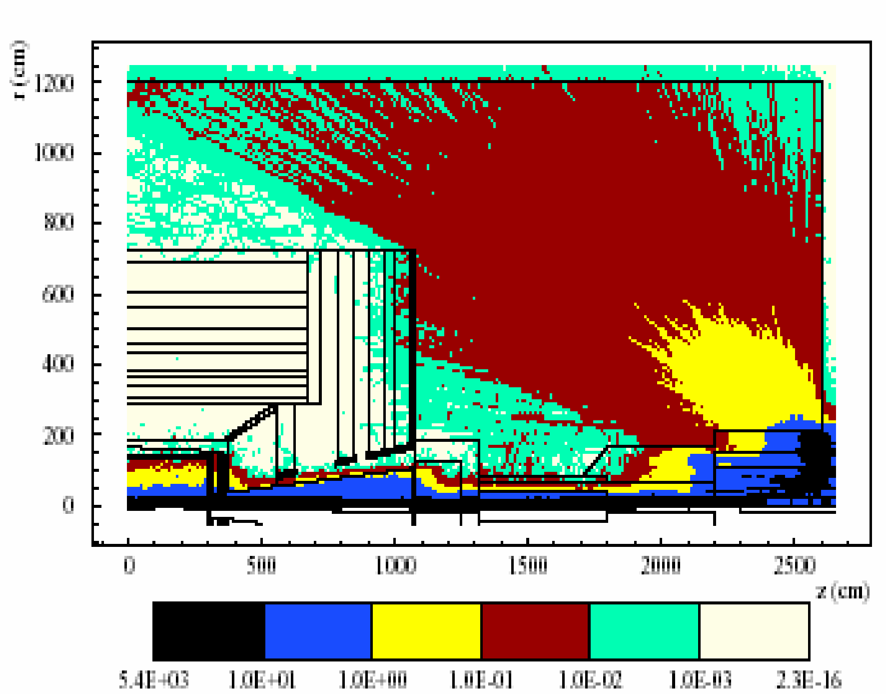
MUCARLO

COLLIMATORS AND SPOILERS

Three magnetic spoilers in tunnel by L. Keller



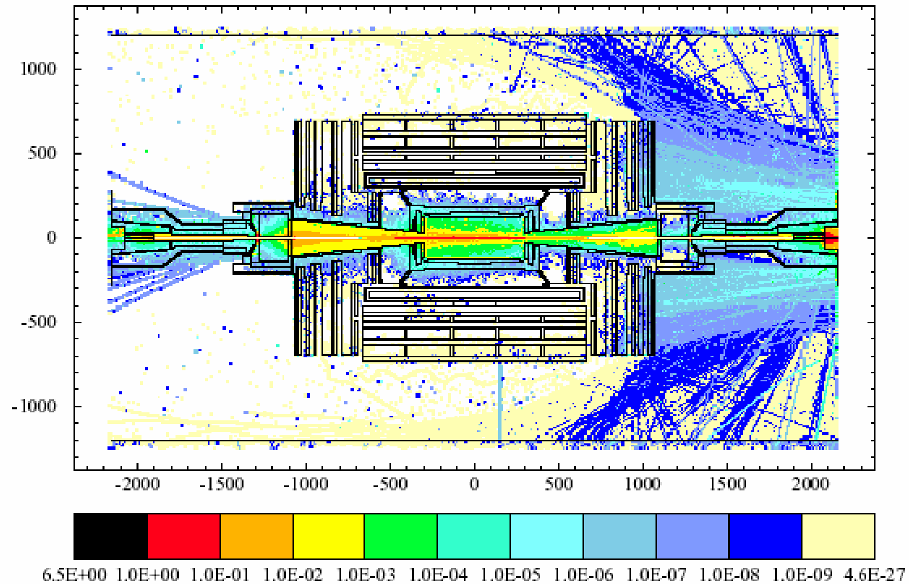
MACHINE BACKGROUNDS: CMS EXAMPLE



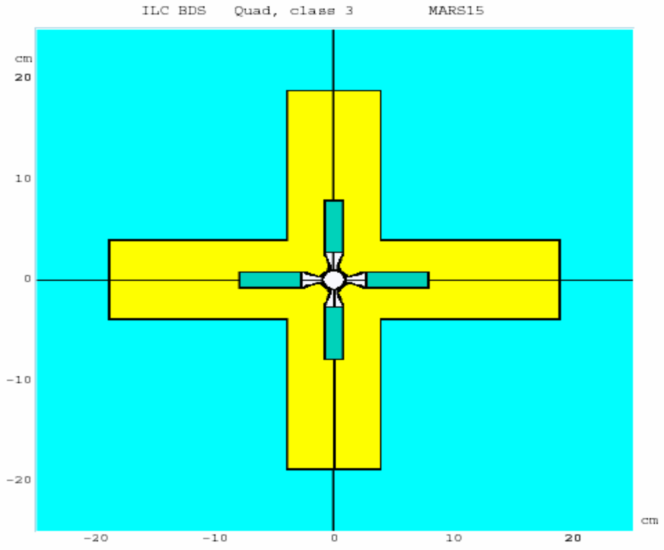
Charged hadron flux (cm^{-2} s^{-1}) due to operational beam loss in LHC IP5.

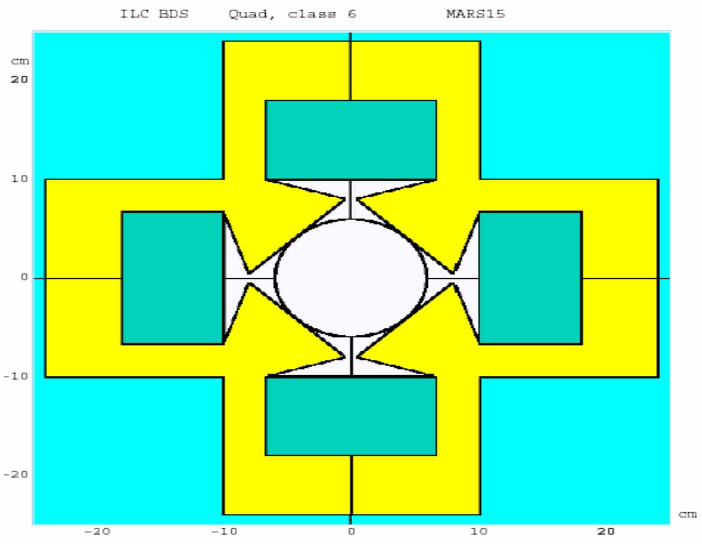
MARS15

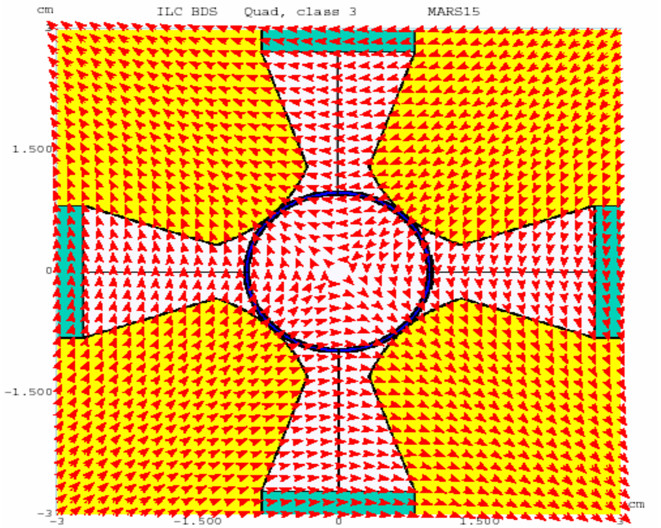
Isodose contours (Gy) for unsynchronized abort: 10^{12} protons lost in IP5 over 0.26 µs.
A peak dose rate at the inner pixels 6.2 MGy/s, $4x10^8$ the nominal.

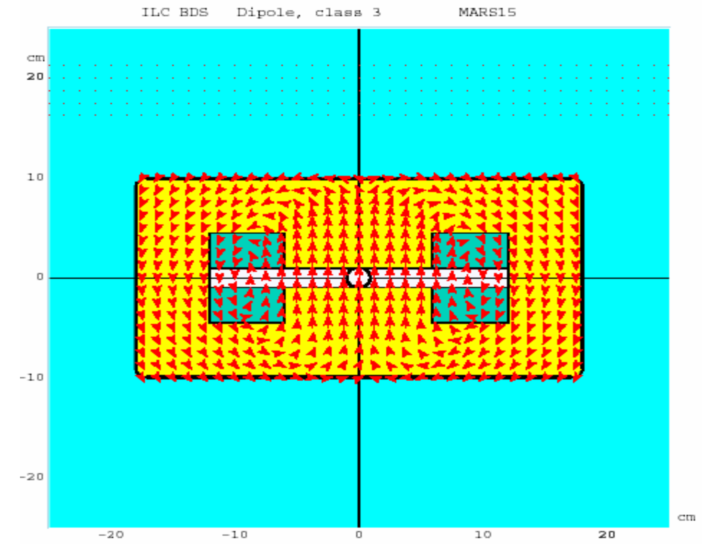


MAGNETS IN BDIR MARS15 MODEL



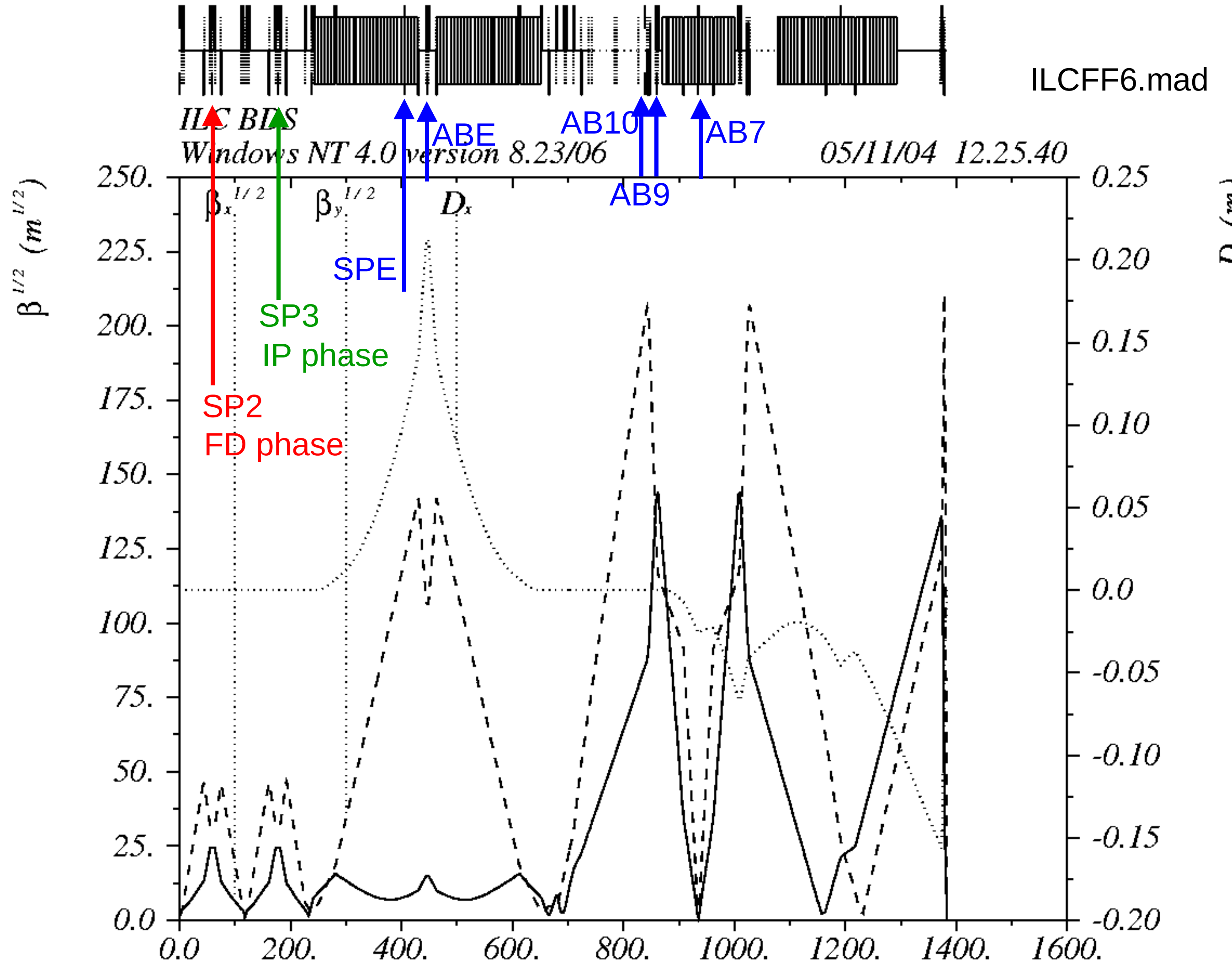






NEW ILC BDIR FOR NON-ZERO X-ING

A. Seryi



Betatron spoilers survive two or one bunches of $2\text{x}10^{10}$ at 250 and 500 GeV, respectively.

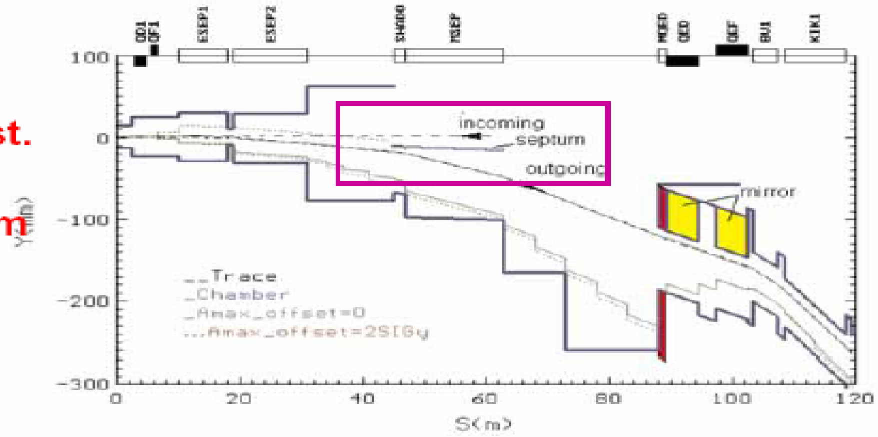
MACHINE PROTECTION & COLLIMATION

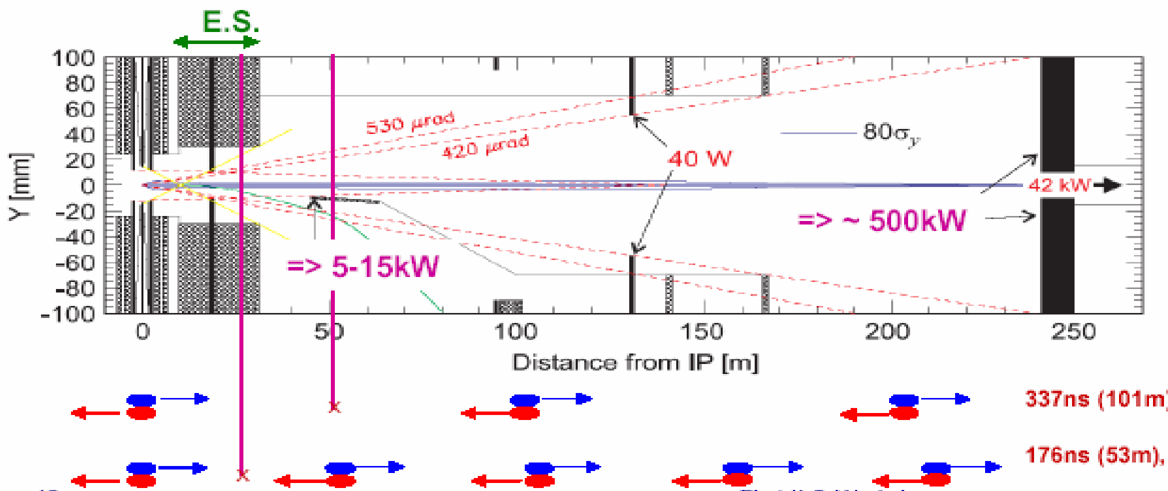
- **MPS Questions**
  - Protection of beam line components, e.g.
    - Fast emergency extraction line (FEXL)
      - » before/after e+ undulator source? separate or main-beam dump?
    - collimator spoilers & absorbers + nearby components:
      - » how many bunches are tolerable?
    - extraction septum (head-on & small vertical Xing)
      - » ⇔ upstream jitter & machine imperfections (studies by AS, GW, KB)
  - Detector survival, e.g.
    - ES reliability ? (only for head-on & small vertical Xing)
- **Collimation System Choices**
  - Collimation system layout
    - before/after IP switch ?
    - order of betatron & energy collimation?
    - How tight do we dare to collimate ?
(wakefields, low-energy $\mathcal{L}$, operational flexibility)
  - Passive (TESLA βtron: 2 b) or consumable (NLC βtron) ?
    - consumable easier for optics, tolerances, etc
  - Material? shape?

EXTRACTION OF SPENT BEAMS

Beam extraction in head-on TESLA scheme

- Large losses in extraction line, especially at 1 TeV
- Incompatible with post-IP E/Pol. diagnst.
- Electrostatic separator (ES) needs 50kV/cm (LEP: 30 kV ops) and 100kV/cm at 1TeV – feasibility in high SR environment?
- MPS issues (detector survival if ES sparks?)





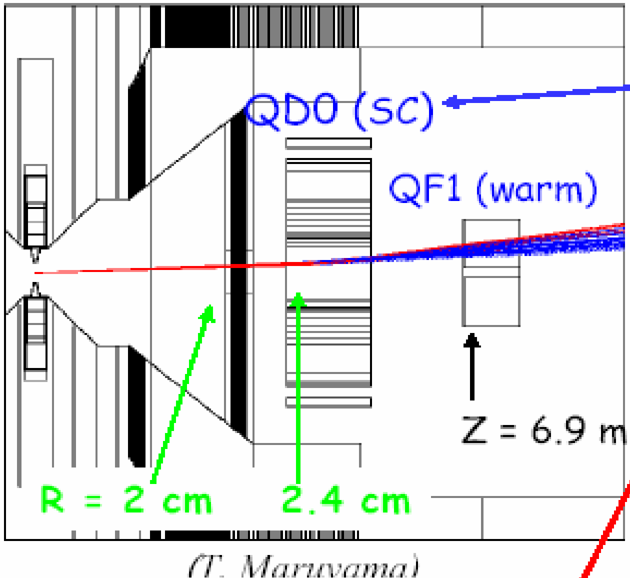
- γ losses at (or near) septum: ~5-15kW, irradiation, background, survivability
- Parasitic collision 26.5 m from IP @ 1TeV
- SR masking overconstrained

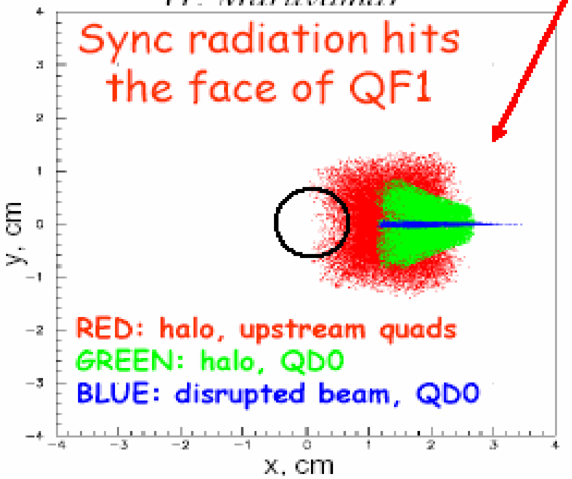
337ns (101m), 500 GeV CM

176ns (53m), 1TeV CM

13 First ILC Workshop Nov 15, 2004 WG4 Summary

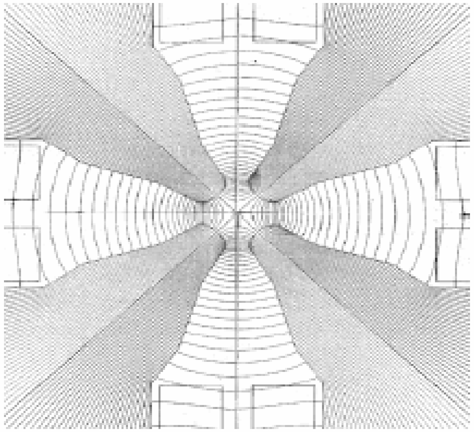
SMALL HORIZONTAL ANGLE (~2 mrad)





<u>Issues</u> (open / in progress)

1. Heat load on QD0 (disrupted e^{+-}): OK?
2. Halo SR γ hitting QF1 (& reflecting back → VXD): OK?
3. SR, halo & pair masking
4. Effect of fringe field on disrupted beam
5. Clean extraction @ 1 TeV c.m. ?



ILC KEK WG4: PHYSICS NEEDS

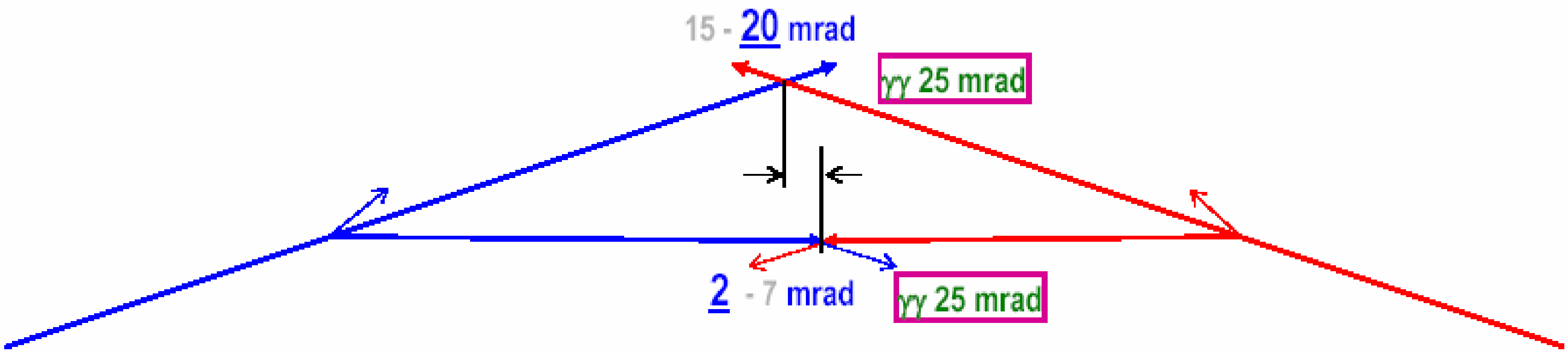
- Physics prefers L* beyond front of calorimeter
- Physics prefers a small vertex detector radius
- Some physics channels prefer small x-ing angle
- Some physics needs downstream instrumentation

BUT:

- Physics needs above all a reliable well diagnosed luminosity delivering machine!

- Studies done, comparing “0” to “20” mrad => modest losses in efficiencies for dark matter/SUSY candidates/ rejection of background (loss of tagging electrons close to beam)
- In the scenario where $\gamma\gamma$ needs > 20 mrad and around 20 mrad there is impact on e+e- physics
  - Optimize initial IR & detector for e^+e^- i.e run at x-angle less or equal to at most 20 mrad
  - Modify detector & IR for $\gamma\gamma$ running when needed

ILC KEK WG4: STRAWMAN LAYOUT



- One of impacts of configuration choice on other WGs
  - Longitudinal separation of collider halls may require the bunch separation to be fixed
    - Not 337ns @ 500GeV and 176ns @ 1TeV,
      but, for example, 2*176ns @ 500GeV and 176ns @ 1TeV
  - Alternative: provide IR halls separation by lengthening the site

COLLIMATOR&BACKGROUNDS WORK TASKS (1)

1. Critical choices: detector tolerances, beam loss models, muon spoilers, E or betatron collimators first, apertures+pair&halo masking, consumable vs passive (survivable) collimators.

2. Iterations with optic designers on collimator locations and parameters.

3. Optimization of individual spoiler and absorber configurations, dimensions and material w.r.t. to their performance, survivability and impedance.

4. Modeling of beam loss in BDS, IR & extraction line followed by realistic energy deposition simulations in BDIR, detector and extraction components (including tunnels and experimental halls) to minimize backgrounds, radiation loads and environmental impact.

COLLIMATOR&BACKGROUNDS WORK TASKS (2)

5. Iterations with detector group on background tolerances and creation of an integrated IR-detector model (including mask and SC quad optimizations).

6. Based on results of simulations, iterations with conventional construction group on tunnel magnetic spoilers, tunnel and experimental hall parameters.

7. Validation, inter-comparison and improvements of simulation codes used in the BDIR studies: tracking, production models, energy deposition, thermal/stress/DPA analyses, wakefield.

8. Bent crystal as a primary collimator (spoiler)? Materials and particle production beam tests? BDIR materials handbook?