Summary of WG1 on IR optics, energy deposition, magnets

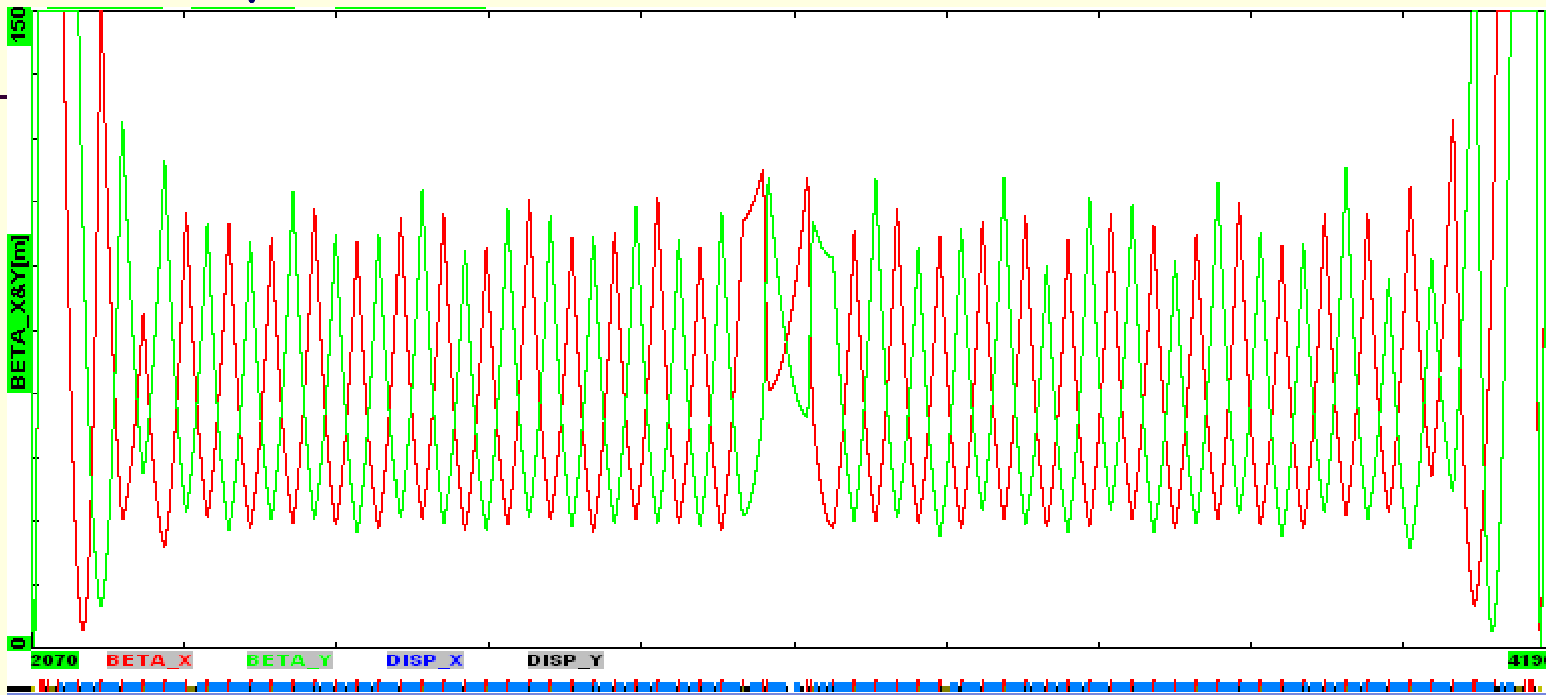
- Presentations
- Questions for WG1
- Discussions/comments/action items

Optics Measurements at the Tevatron
Alexander Valishev, Fermilab

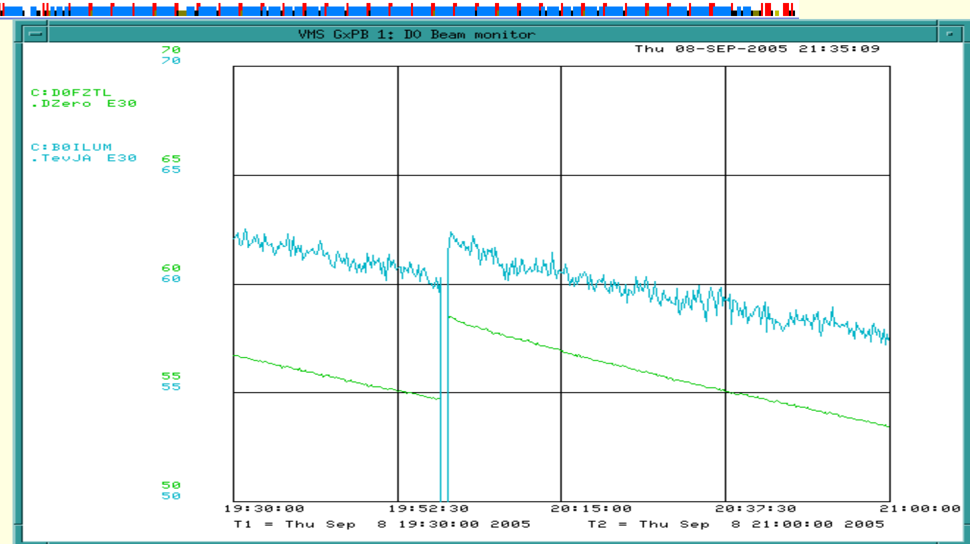
- The response matrix fit method allows to pinpoint gradient errors in the Tevatron of the order of 2E-3. The β-function measurement error is ~ 5%
- Measurements are in good agreement with results obtained by turn-by-turn and tune-shift methods. Single measurement requires ~ 1 hour of the machine time. Data analysis takes ~ 6 hours.
- Based on the fitted model, optics modification have been done to:
  - Correct beta-beating in the arcs
  - Eliminate the difference between the two IPs
  - Decrease β^* from 35 to 28 cm
- Peak luminosity of the collider with the new optics increased by 10% (5% at end of stores owing to hourglass effect for longer bunches)
- **Second order Q' increased by ~30% after reduction of β^* ⇒ decreased luminosity lifetime due to larger tune spread to be accommodated between 5th and 12th order resonances**
- 8.5σ beam separation at the first parasitic collision, can in principle be increased to 12σ by increasing bunch spacing from 21 to 23 buckets ⇒ not accepted by experiments owing to higher event pile-up
- Further improvements are required to achieve better prediction accuracy, e.g. determination of parameters of individual trim elements

Tevatron Beta Functions (short arc)

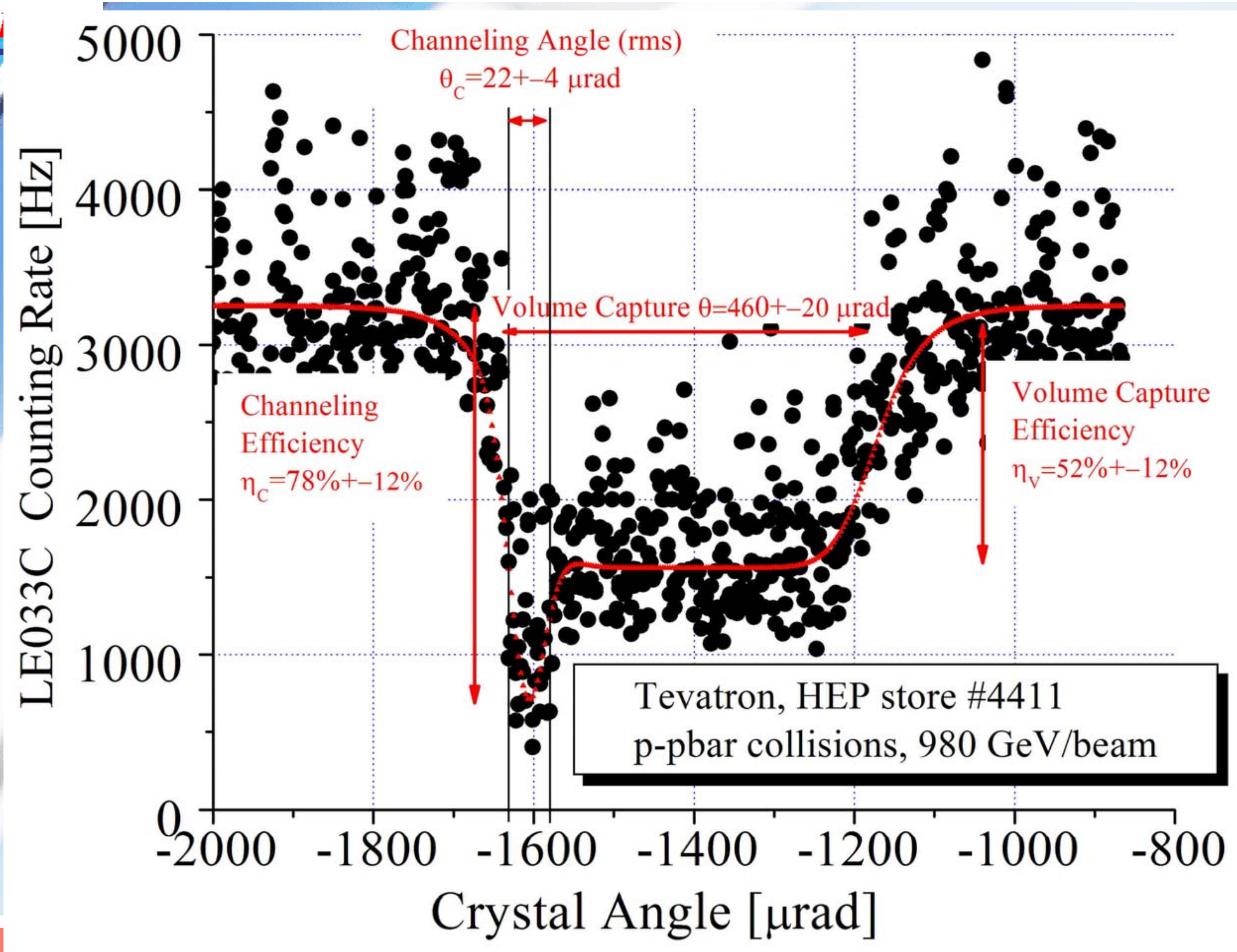
"28cm optics" after 9/21/05



	β_x^* (cm)	β_y^* (cm)
CDF	30.3	29.1
D0	29.2	28.2



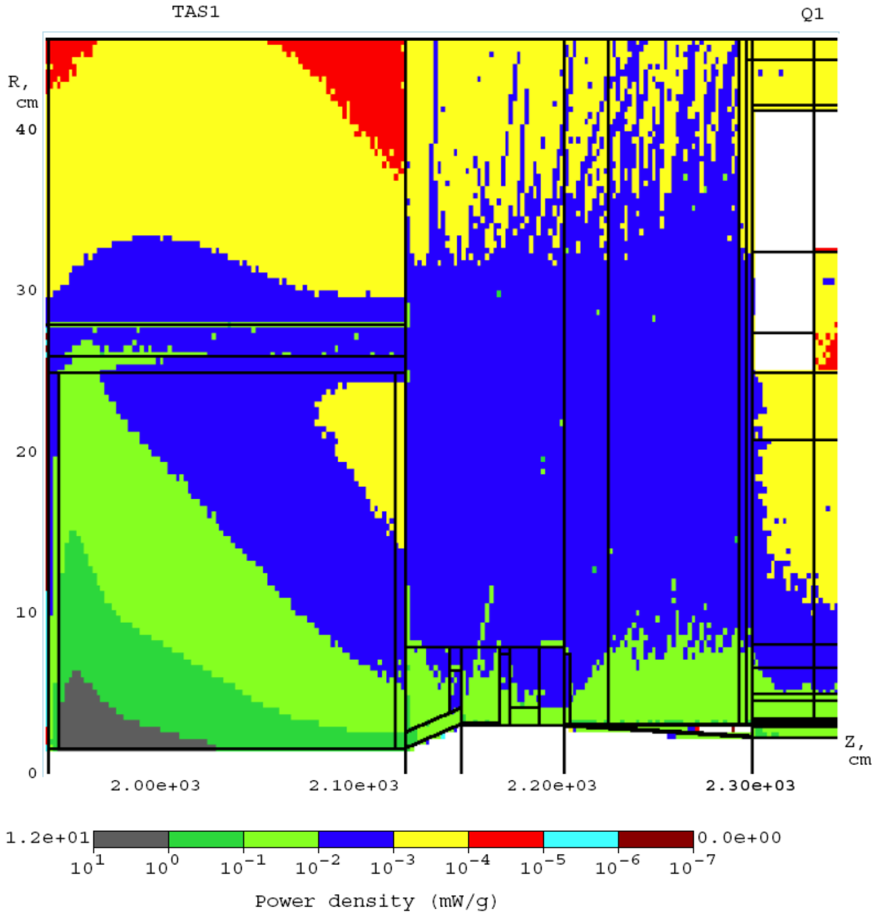
Bent Crystal: 1TeV Channeling

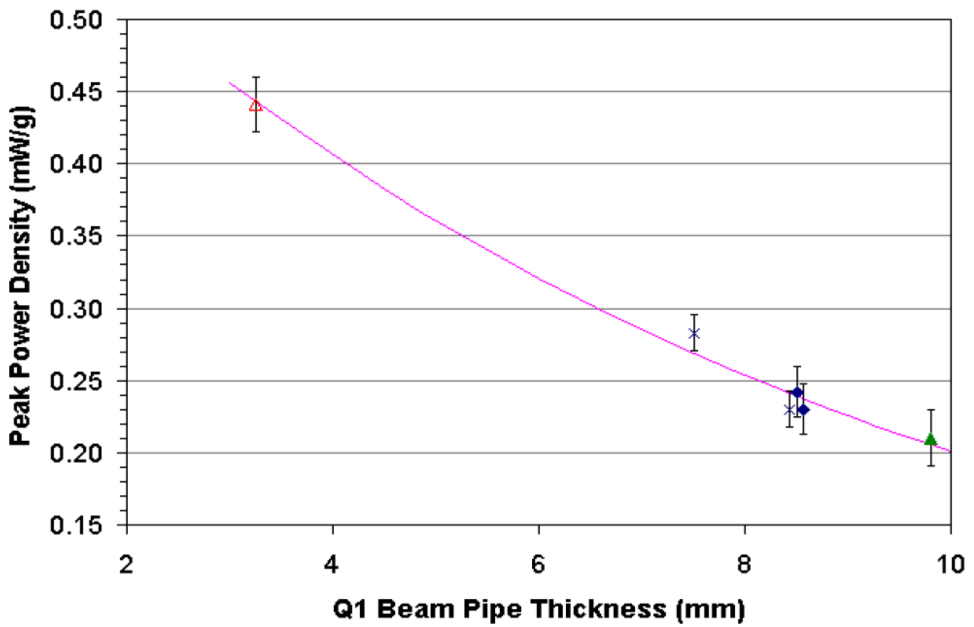


Energy Deposition Issues in LHC IR Upgrades, Nikolai Mokhov, Fermilab

- Quench levels in the LHC IR quads are well understood, more work is needed on other magnets.
- All energy deposition issues have been addressed in IR in detailed modeling at nominal and upgraded luminosities.
- IP1 and IP5 SC magnets and CMS and ATLAS detectors are adequately protected at normal operation and accidental conditions with the local (TAS, liners etc) protection systems, main collimation system in IP3/IP7, IP6 collimators (TCDQ etc), and tertiary collimators TCT.
- LHC upgrade scenarios are quite challenging from energy deposition standpoint, simulation results are encouraging, but more work is needed.
- All three aspects, i.e. *i)* quench limit, *ii)* radiation damage (magnet lifetime), and *iii)* dynamic heat load on the cryo system should be simultaneously addressed in the IR magnet design. *i)* and *ii)* are linked.

TAS AND LINER OPTIMIZATION





Beam screen together with cold bore

Reduces power density at IP-end of Q1 300 times and dynamic heat load to inner triplet by 185 Watts. 5% of incoming energy punch through 1.8-m copper TAS body

Chosen: 6.5 mm in Q1 and 3 mm in Q2-Q3

WG1 Questions/Answers
Energy deposition

- Estimated dipole field with TAS in quad first option to reduce peak energy deposition "well below" quench limits ⇒ **15-20 Tm for magnetic TAS**

  Estimated thickness of internal absorbers?

  ⇒ **a 5 mm thick SS absorber reduces peak power by a factor ~2**

  Choose ℓ^*=19 m ⇒ **no results available yet**
- Scaling laws for energy deposition. What are the limits of validity and how can they be improved? Variation with ℓ^*?

  ⇒ **see next action items**
- Impact of orbit corrector D0 inside the experiment on energy deposition in downstream magnets, including detector solenoid field

  ⇒ **see next action items, modest impact of solenoid field on energy deposition (more from fringe fields)**

Action items/comments on energy deposition, Nikolai Mokhov

- Refine and test scaling law for energy deposition in IR magnets with MARS simulations (including dependence on ℓ^*)
- Introduce quench limits to JPK's spreadsheet for NbTi and Nb_3Sn
- Address radiation damage/lifetime issues in all IR magnet design analyses: 7 years at 10^{34} become 8 months at 10^{35} with currently used materials ⇒ new (ceramic type) materials for 10^{35}?
- Launch R&D program on beam tests for SC and insulating materials asap: BNL, FNAL, MSU
- Arrive at a clear picture on Dynamic Heat Load limits. How serious is the current 10 W/m limit or 120 W on each side of IR? This becomes 100 W/m and 1.2 kW for 10^{35}. Cooling scheme? Cryoplant capability?

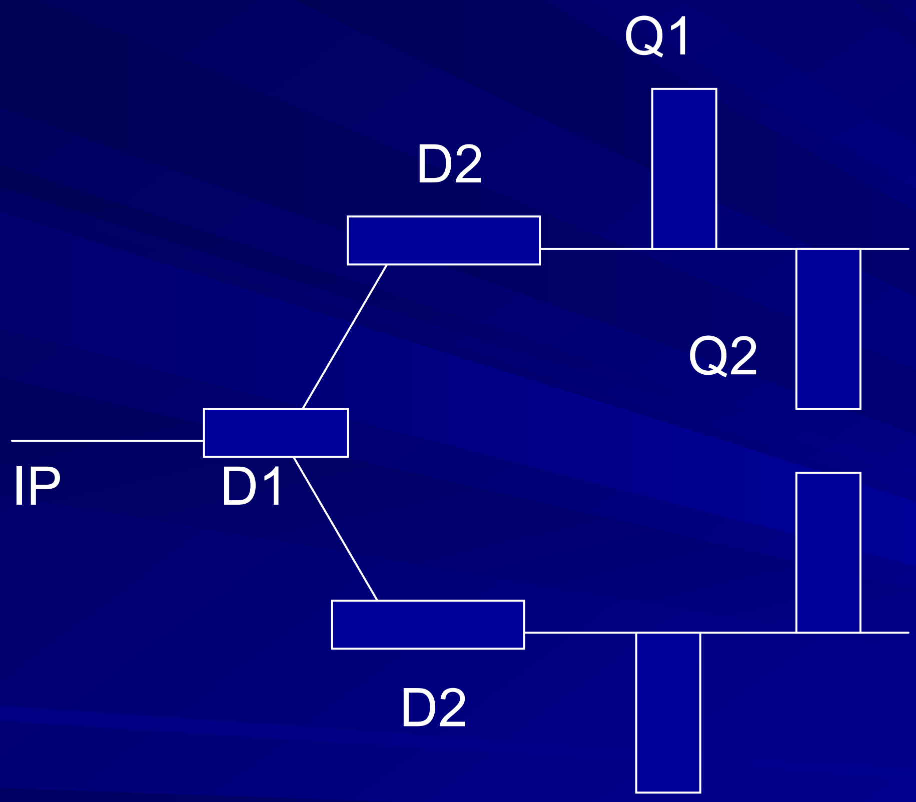
Action items for Nikolai Mokhov (cont'd)

- Perform realistic MARS calculations on viability of a D0 dipole close to the IP: address both energy deposition and background/interference with detectors
- The peak power deposition at the non-IP end of IR magnets is approximately proportional to $\int B d\ell \Rightarrow$
  look at the possibility of shortening IR quads: "quadruplet" focusing with alternating (skew?) FDFD quads or long helical quads as an extreme. One may gain up to a factor 10 in peak power density from smearing energy deposition.
- Refine results on power density reduction versus TAS (passive and active) and liner parameters
- Mid-plane (low-Z) spacers

Doublet focusing optics
John Johnstone (Fermilab)

- Interesting approach, elliptic beams could increase luminosity by ~30% with reduced crossing angle
- Symmetric triplet requires separate magnetic channels (dipole-first) or very special quadrupoles (old VLHC idea)
- Tune footprints are broader than for round beams. More work needed to evaluate nonlinear resonance excitation.
- Probably requires BBLR compensation

Dipoles first and doublet focusing

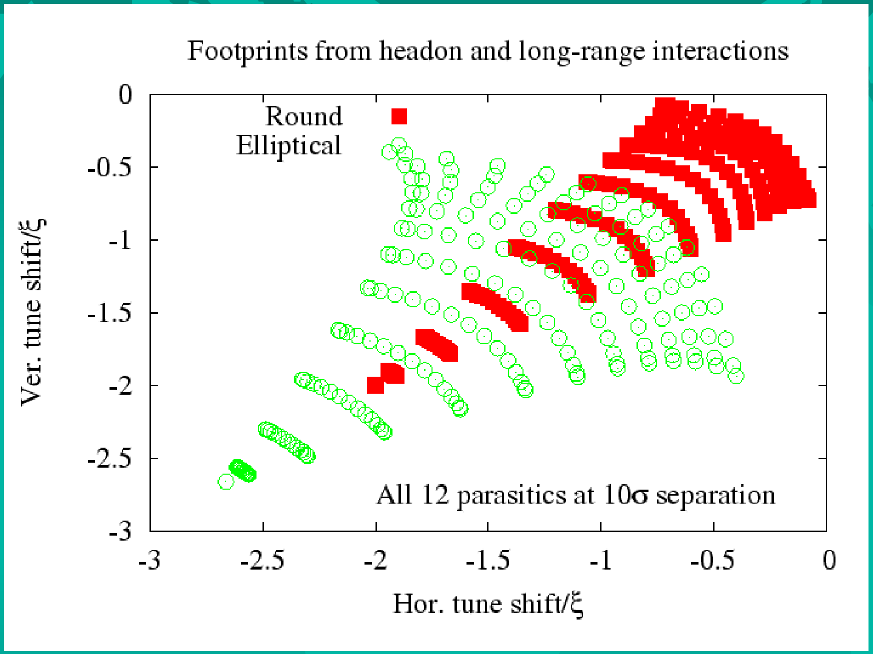


Focusing symmetric about IP

Features

- Requires beams to be in separate focusing channels
- Fewer magnets
- Beams are not round at the IP
- Polarity of Q1 determined by crossing plane – larger beam size in the crossing plane to increase overlap
- Opposite polarity focusing at other IR to equalize beam-beam tune shifts
- Significant changes to outer triplet magnets in matching section.

Tune Shifts (cont'd)



Courtesy of T. Sen 10.02.05

- Tune footprints extending to 6σ have been calculated for round & elliptical beams assuming 12 parasitics per IR.
- The elliptical beam footprint is significantly larger than that of round beams.

† Long range tune shifts are a concern that needs to be addressed. Avenues to explore might include a D0 trim to separate beams earlier, or re-examine wire compensation schemes, or ....

WG1 Questions/(some) Answers Optics

1. What is the largest coil aperture required (beta*=0.25 m) for each optics layout ?
2. How does the luminosity scale with ℓ^* for a fixed magnet aperture (for quads first and dipoles first, assuming Nb_3Sn technology)
3. Limits on chromaticity, b6 and b10 at collision. What are the upper limits beyond which they cannot be corrected by nonlinear correctors?

   ⇒ **see action item on chromatic performance of IR solutions**

1. What are the field quality requirements at injection? How does it differ for the different scenarios: quad first, dipole first
2. What is the impact of beam-beam compensation wires on the IR optics? beam size at IP, beam offsets, nonlinear fields?
3. What is the length required for crab cavities and where should they be placed? Constraints on optics functions at the crab cavities.

   ⇒ **~30-40 m can in principle be accommodated after the triplet, where the beam separations is ~50 cm for a large crossing angle of ~8 mrad**

Magnet R&D: Gianluca Sabbi and Paolo Ferracin

- R&D models with 90 mm aperture address the critical design issues (magnetic, mechanical, quench etc)
- Using a larger aperture for magnet R&D would likely be less effective (due to cost considerations and other practical constraints)
- There is good confidence that successful results of 90 mm models can be extended to the range of apertures under consideration
- The maximum coil field is a critical parameter to establish the performance characteristics
- "High-gradient" models with 90 mm aperture (HQ) will be used to establish the maximum design field
- IR optimization studies should assume constant pole tip field and optimize aperture/gradient accordingly
- Using 13 T peak field (JPK) is ok for now, but the program aims at 15 T
- JPK model calibration using TQ design: 11 T peak field corresponds to 210 T/m in the 90 mm aperture

LARP Magnet Program Goals

LARP

FY09 Milestone:

Demonstrate viability of Nb_3Sn technology for "Quad-first" option

1. Capability to deliver predictable, reproducible performance:

TQ (Technology Quads, 2005-07) D = 90 mm, L = 1 m, G_{nom} > 200 T/m

2. Capability to scale-up the magnet length:

LQ (Long Quadrupoles, 2008-09) D = 90 mm, L = 4 m, G_{nom} > 200 T/m

3. Capability to reach high gradient (pole tip field) in large aperture:

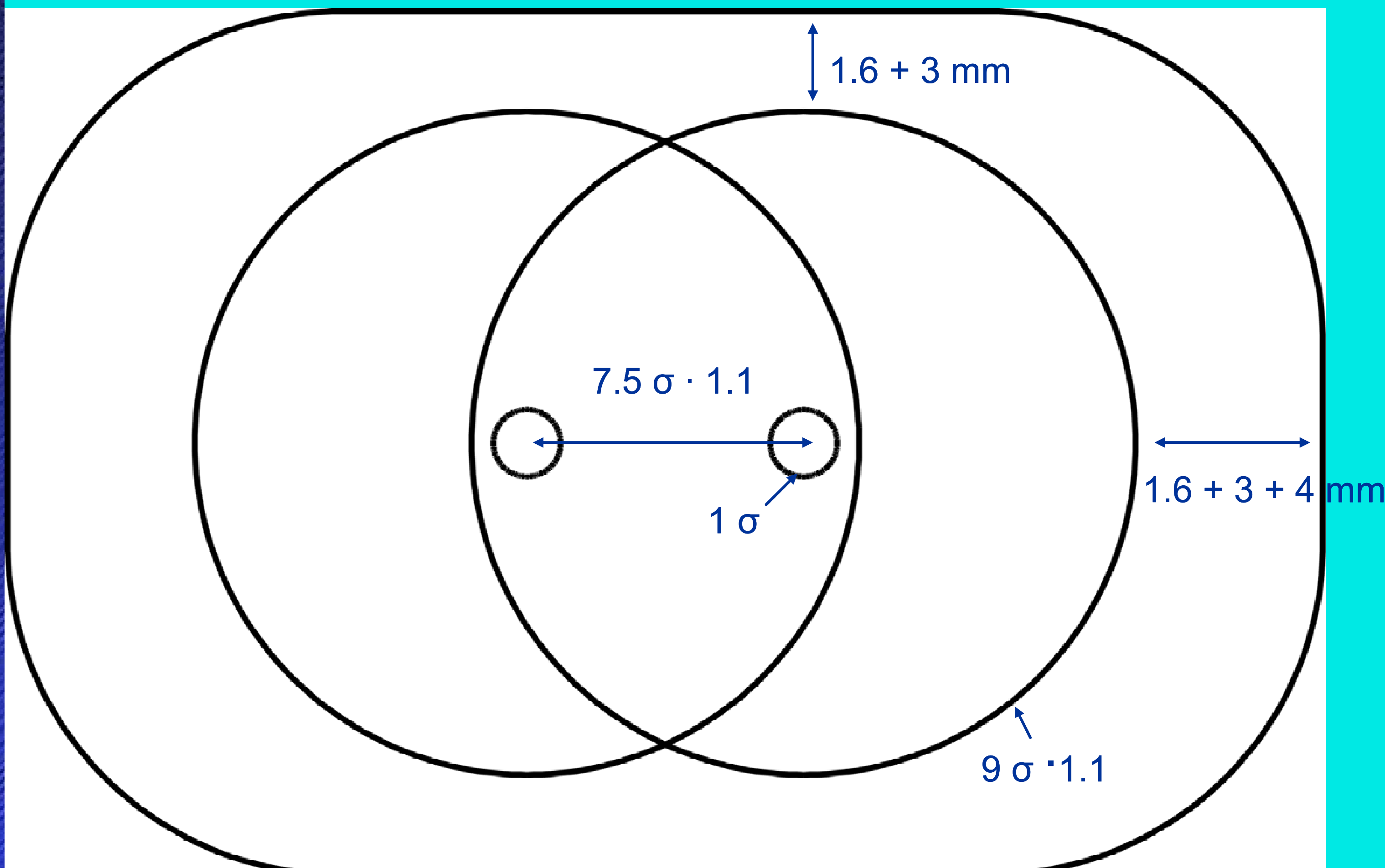
HQ (HighGradient Quads, 2008-09) D = 90 mm, L = 1 m, G_{nom} > 250 T/m

- *Fabrication of the first two TQ quads (TQS01 and TQC01) has started*
- *TQS01 test in February/March 2006; TQC01 test in April/May 2006*

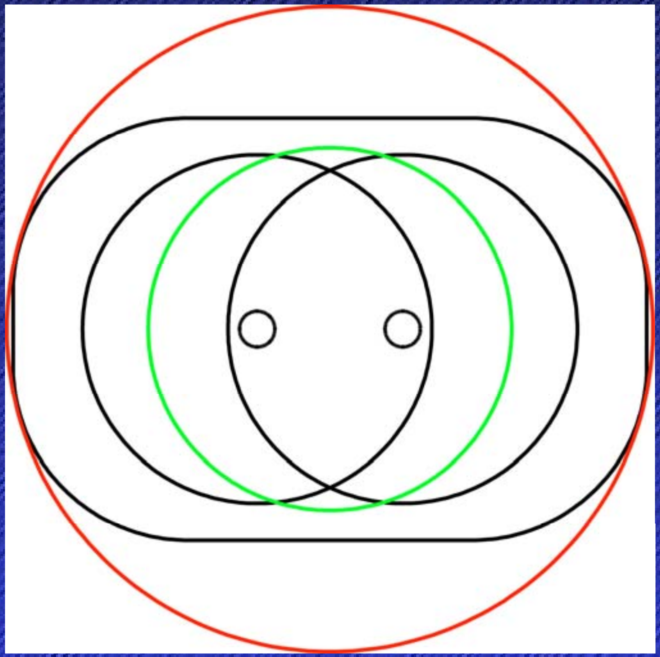
Coil aperture requirements

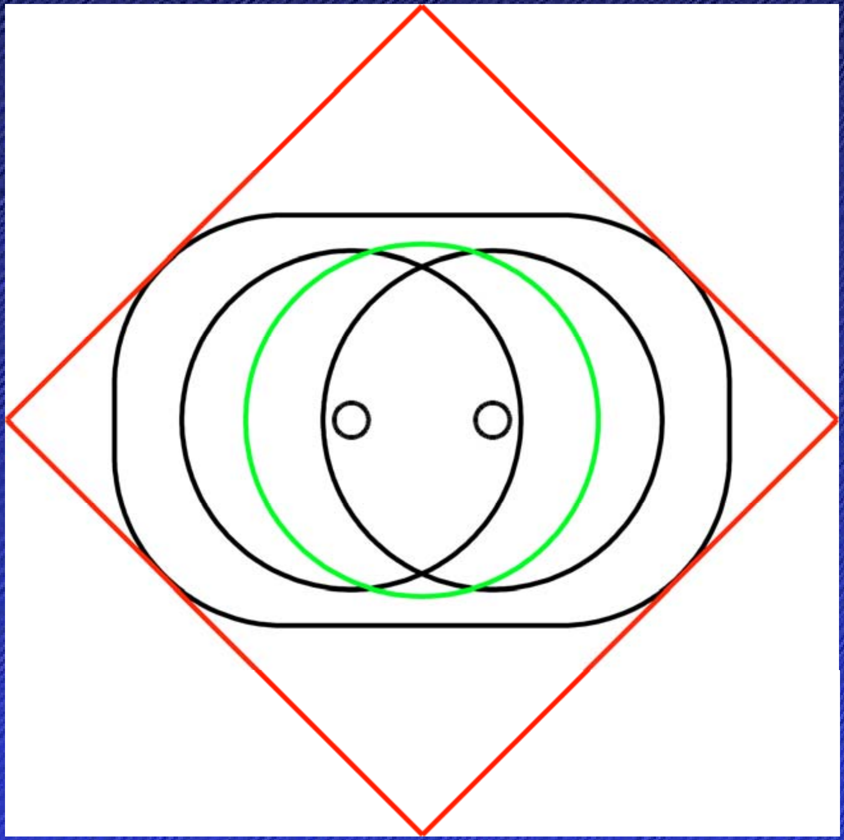
Coil aperture estimates need to be clarified/debugged/improved

$$D_{trip} > 1.1 \times (7.5 + 2 \times 9) \cdot \sigma + 2 \times (1.6 + 3 + 4)\ \text{mm}$$



- The beam envelope formula does not correspond to a good field region (green circle)
- Equivalent aperture comparisons should include heat deposition considerations





Action Items

- CERN beam physicists will circulate a draft proposal for aperture and field quality requirements
- CERN beam physicists will circulate a draft proposal to assess and compare the chromatic performance of any IR solution, including quantitative considerations for luminosity or lifetime (possibly based on tune footprints for off-momentum particles)

Questions to WG1 - Magnets

1. What is the limit on quad aperture from magnet design at constant pole tip field? Is the aperture limit different for NbTi and Nb_3Sn?
2. Is there a quad design with either an absorber or low-Z spacers in the horizontal and vertical planes? to minimize energy deposition.
3. Are there lower limits to the systematic errors on b_6 and b_{10} with Nb_3Sn? How does this scale with the pole tip field and aperture?
4. If 90 mm quads with 11-12 T field are demonstrated by 2009, how much confidence is there that larger aperture quads can be built with the same pole tip field?

1. Aperture limits

- From the magnet design standpoint, there is no fundamental limit to increasing the quadrupole aperture (for both NbTi and Nb_3Sn magnets) but more detailed magnet design studies are needed in support of IR designs using very large apertures (120-150 mm?)
- Space considerations will limit the quad aperture, in particular for some of the IR layouts
- Coil volume will increase with aperture; mechanical considerations (stress) may lead to a rate of increase faster than linear

2. Energy deposition issues

- Absorbers and mid-plane spacers can be included in all magnet designs
- Additional space for absorbers (in particular at mid-plane) can be obtained by increasing the coil aperture

3. Field Quality

- Geometric errors are very small and comparable in Nb_3Sn and NbTi quadrupole designs
- Fabrication tolerances will likely dominate the field errors
- Further studies are needed to determine the practical limits on field quality achievable in Nb3Sn quads
- Conventional scaling with aperture applies; field errors can be minimized for all operating fields

4. Aperture scaling

- There is good confidence that the 90 mm models will address the critical R&D issues, applicable to the entire range of apertures being considered
- Based on results from R&D, it will be possible to fabricate prototypes of larger aperture in the same time frame as for 90 mm aperture quads

Tuesday presentations

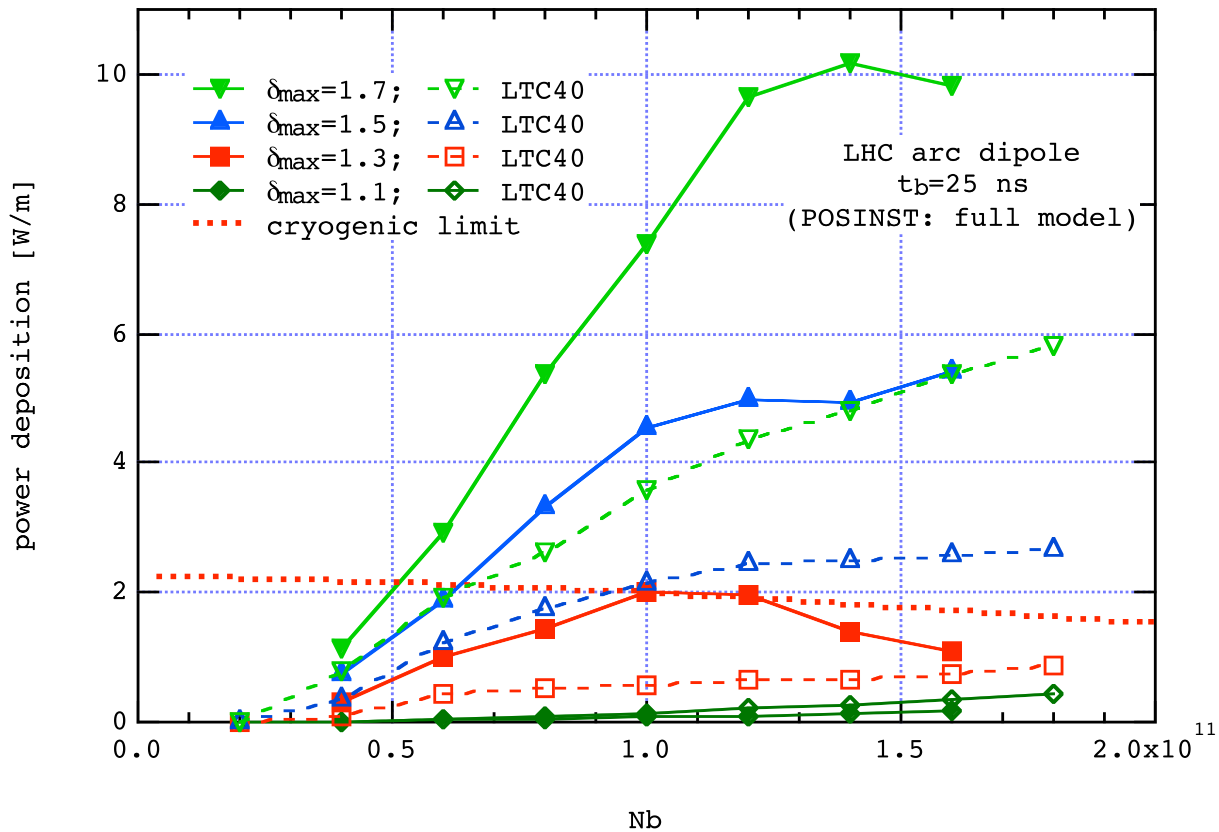
- A Review of Open Midplane Dipole Design Study, Ramesh Gupta (BNL)
- Inner Triplet Cryogenics and Heat Transfer, Roger Rabehl (Fermilab)
- A Structured-Cable Superconducting Quadrupole for High-Heat-Load Applications, Peter McIntyre (Texas A&M Univ.)
- Levitated-Pole Superconducting Dipole for Use in Beam Separators for LHC, Peter McIntyre (Texas A&M Univ.)

Potential impact of novel magnet technology for IR elements, Peter McIntyre

- Designs have been suggested for novel magnet technology to mitigate limitations from heat deposition and radiation damage from deposition of secondary particles in the quadrupole triplet and separation dipole. One example is an ironless quadrupole using structured-cable Nb3Sn conductor, which could provide 390 T/m gradient at a location as close as 12 m from the IP, and compatibility with supercritical helium flowing throughout the coils. A second example is a 9 T levitated-pole dipole for D1, which would open the transverse geometry so that secondaries are swept into a room-temperature flux return.
- In order to evaluate the potential benefit of these concepts it is necessary to model the heat deposition and radiation damage in the more compact geometries, and to examine potential interference with the performance of the detectors.
- Of particular importance is to undertake a consistent examination of the impact of reducing ℓ^* on the ensemble of issues that impact achievable β^* the interface of the IR with the machine lattice (chromaticity and dispersion, multipole errors, orbit errors, etc.), and the strategy for accommodating long-range beam-beam effects.
- Also of interest is to evaluate the pros and cons of the alternatives for operating temperature (superfluid, two-phase, or supercritical cooling) for the IR elements that must operate with substantial heat loads.

Simulated LHC arc dipole power deposition bunch spacing: t_b=25 ns

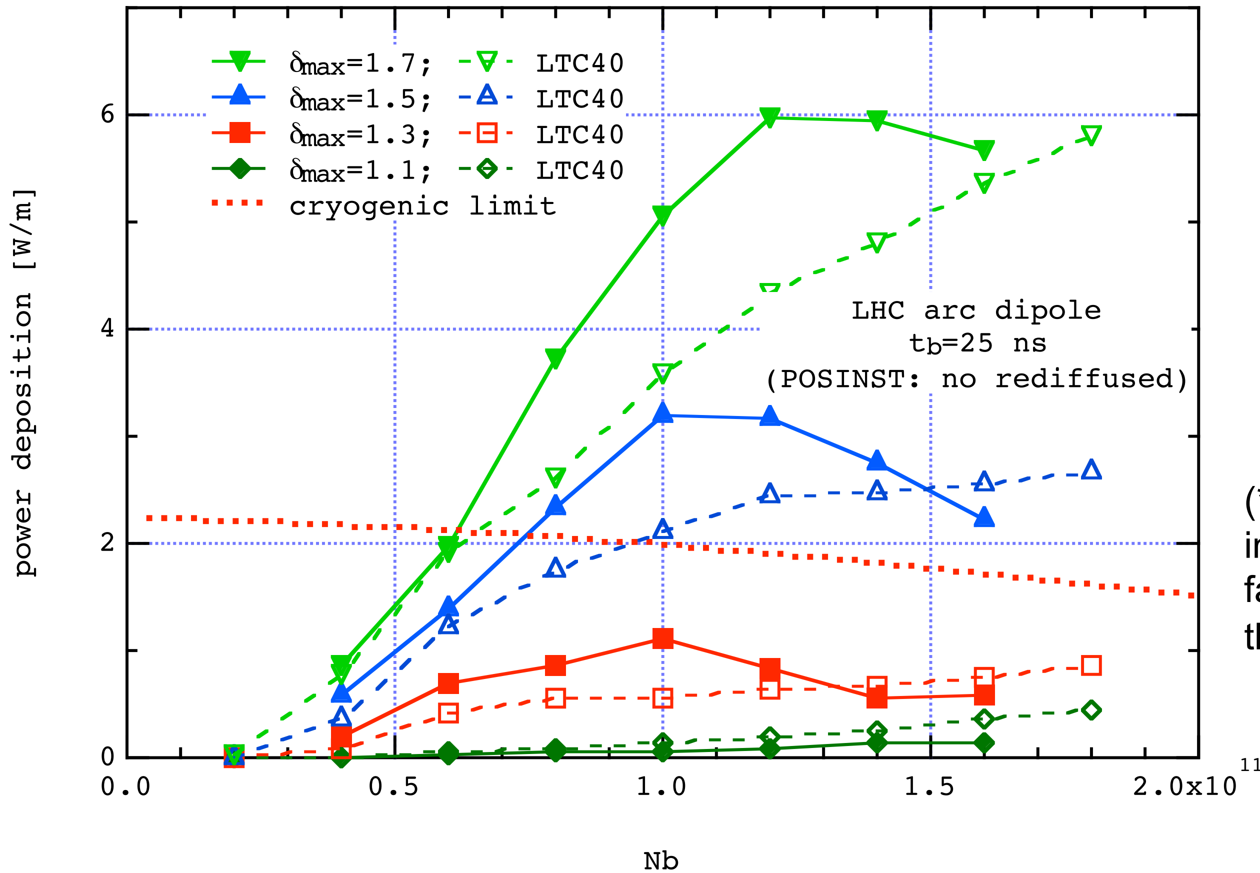
Aver. power deposition vs. bunch intensity
for a given peak value of the SEY
(POSINST and ECLOUD codes)



* "LTC40": LHC Tech. Committee. Mtg #40, April 2005 (CERN simulations, presented by F. Zimmermann)

Same as previous (t_b=25 ns) but no rediffused electrons(*)

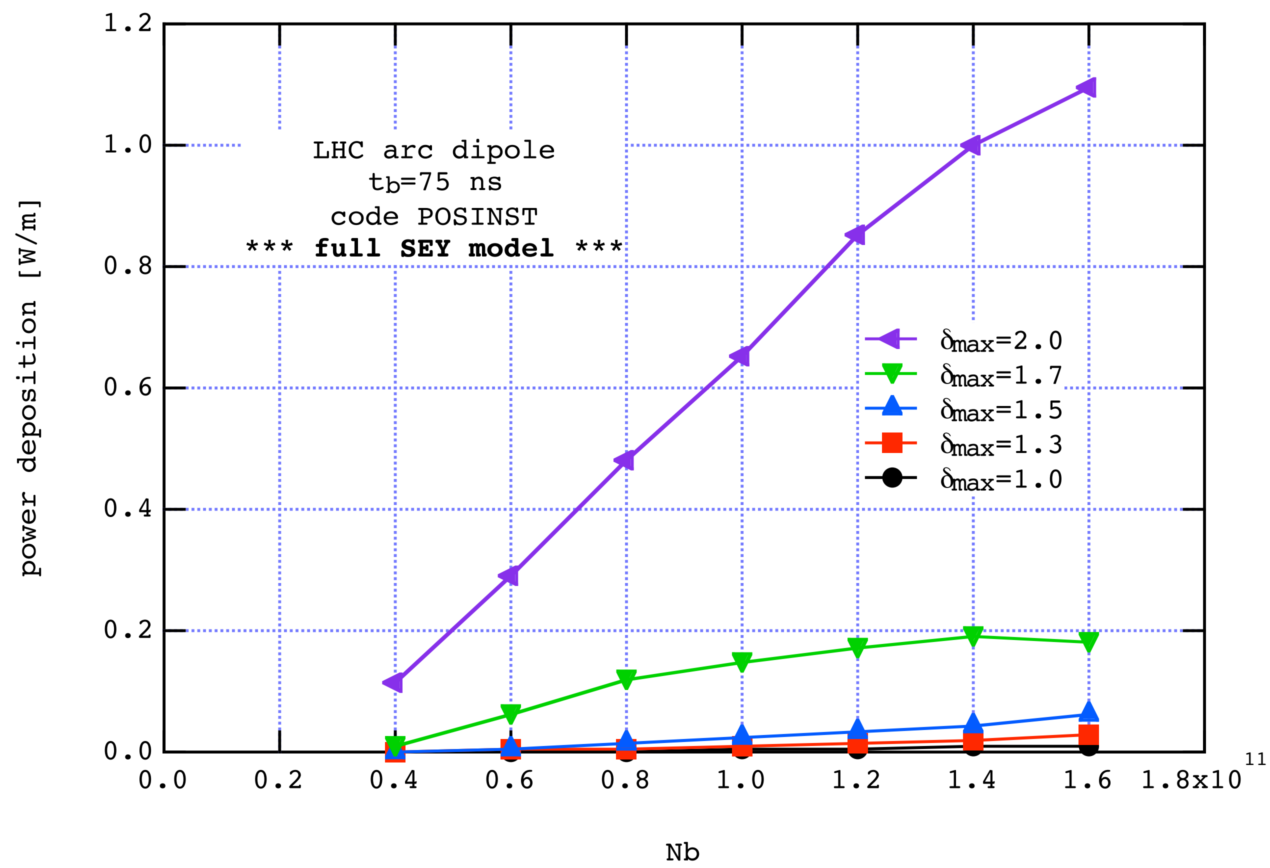
Motivation: POSINST model w/o rediffused ≈ ECLOUD model



(*) We set δ_r=0 and simultaneously increased δ_e and δ_{ts} by a common factor such that δ_{tot} remained the same

This is "good agreement" by the standards of the trade (IMHO)

Bunch spacing: t_b=75 ns (POSINST code)

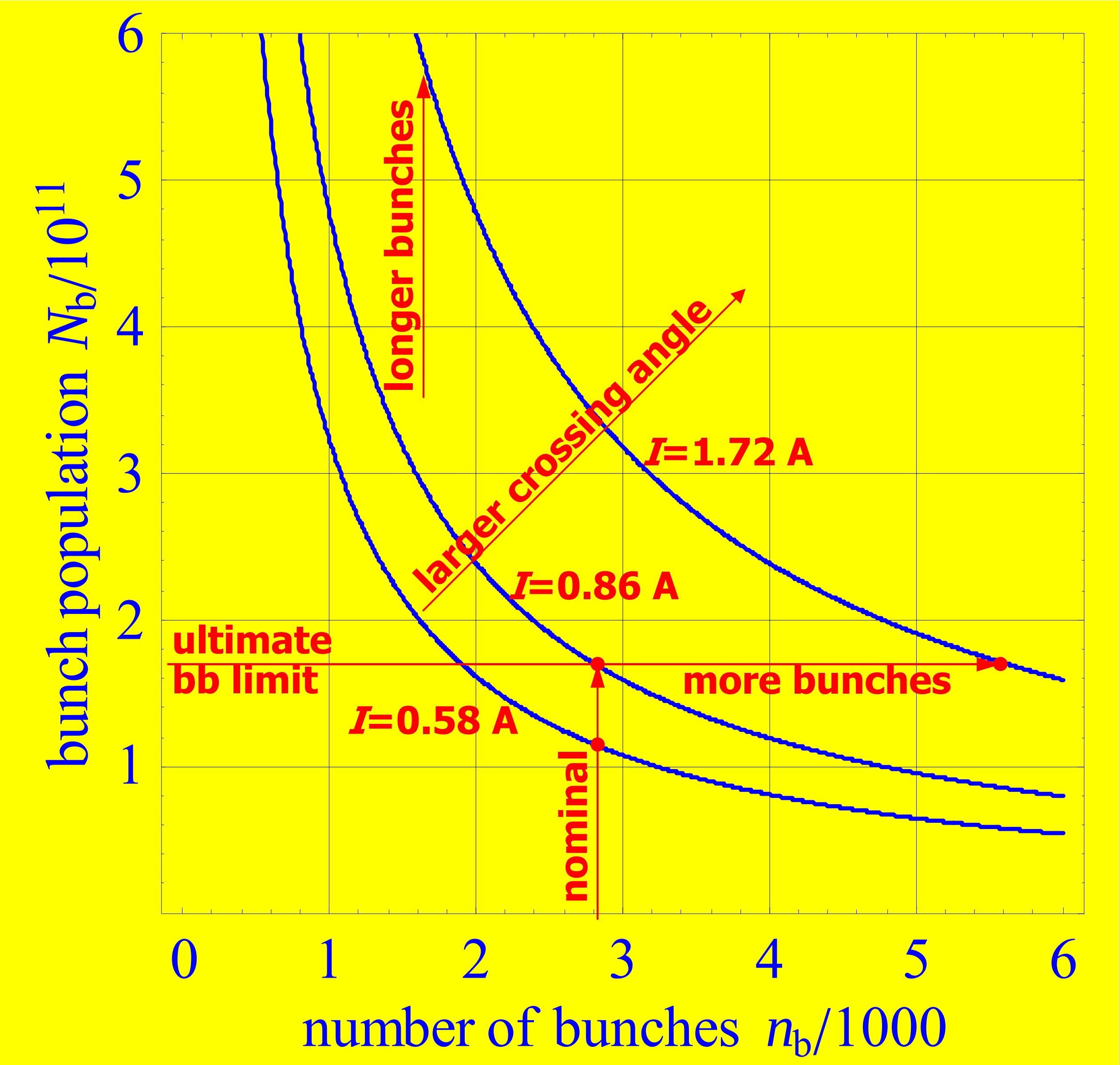


Updated LHC dipole simulations: conclusions

- No problem for t_b=75 ns, even up to $N_b=1.6x10^{11}$ and $\delta_{max}=2$
  - In qualitative agreement with CERN results
- If rediffused electrons ignored, good agreement with CERN simulations
  - As expected (similarity of models)
  - No problem up to $\delta_{max}\approx1.4$ (for $N_b=1x10^{11}$)
- But rediffused electrons are there
  - Our model is based on bench measurements of emission spectrum for Cu
  - Maximum acceptable $\delta_{max}\approx1.3$ (for $N_b=1x10^{11}$)

- Caveats:
  - Power depos. estimates above are based on 1 batch (=72 bunches + gap)
    - Steady-state estimates are higher by ~30-40%
  - $\delta(0)$ varies in 0.3-0.5 depending on δ_{max}; we have not assessed sensitivity to $\delta(0)$ separately from δ_{max}

LHC upgrade paths/limitations



- Peak luminosity at the beam-beam limit $L \sim I/\beta^*$
- Total beam intensity I limited by electron cloud, collimation, injectors
- Minimum crossing angle depends on beam intensity: limited by triplet aperture
- Longer bunches allow higher bb-limit for N_b/ε_n: limited by the injectors
- Less ecloud and RF heating for longer bunches: ~50% luminosity gain for flat bunches longer than β^*
- Event pile-up in the physics detectors increases with N_b
- Luminosity lifetime at the bb limit depends only on β^*

Luminosity optimization

$\sigma^* = \sqrt{\varepsilon\beta^*}$ transverse beam size at IP

$\varepsilon_n = \gamma\varepsilon = \gamma\frac{\sigma^2}{\beta}$ normalized emittance

$$L = \frac{n_b f_{rev} N_b^2}{4\pi\sigma^{*2}} = \frac{\gamma}{4\pi\beta^*}\frac{N_b}{\varepsilon_n} I$$

peak luminosity for head-on collisions

round beams, short Gaussian bunches

N_b/ε_n beam brightness

- head-on beam-beam
- space-charge in the injectors
- transfer dilution

$I = n_b f_{rev} N_b$ total beam current

- long range beam-beam
- collective instabilities
- synchrotron radiation
- stored beam energy

Collisions with full crossing angle θ_c

reduce luminosity by a geometric factor *F*

$$F \cong 1/\sqrt{1+\left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$$

maximum luminosity below beam-beam limit

⇒ short bunches and minimum crossing angle (baseline scheme)

H-V crossings in two IP's ⇒ no linear tune shift due to long range

total linear bb tune shift also reduced by *F*

$$\Delta Q_{bb} = \xi_x + \xi_y \cong \frac{N_b r_p}{2\pi\varepsilon_n} F$$

If bunch intensity and brightness are not limited by the injectors or by other effects in the LHC (e.g. electron cloud) ⇒ luminosity can be increased without exceeding beam-beam limit ΔQ_{bb}~0.01 by increasing the crossing angle and/or the bunch length

Express beam-beam limited brilliance N_b/ε_n in terms of maximum total beam-beam tune shift ΔQ_{bb}, then

$$L \cong \frac{\gamma}{2r_p}\frac{\Delta Q_{bb} I}{\beta^*} \cong \frac{\gamma\pi f_{rev}}{r_p^2}\frac{\Delta Q_{bb}^2 n_b \varepsilon_n}{\beta^*}\sqrt{1+\left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$$

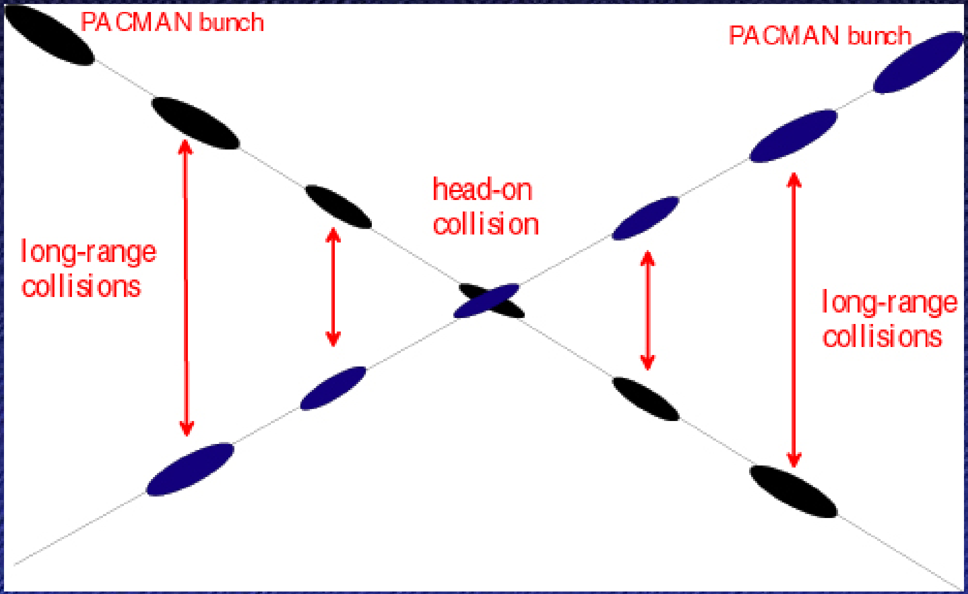
At high beam intensities or for large emittances, the performance will be limited by the angular triplet aperture

$$L \cong \frac{\gamma}{2r_p}\Delta Q_{bb} I \min\left\{\frac{1}{\beta^*}, \frac{1}{\varepsilon}\left(\frac{D_{tripl}/\ell^*}{20+\theta_c/\sigma_\theta}\right)^2\right\}$$

Minimum crossing angle

Beam-Beam Long-Range collisions:

- perturb motion at large betatron amplitudes, where particles come close to opposing beam
- cause 'diffusive' (or dynamic) aperture, high background, poor beam lifetime
- increasing problem for SPS, Tevatron, LHC, i.e., for operation with larger # of bunches



dynamic aperture caused by n_{par} parasitic collisions around two IP's

$$\frac{d_{da}}{\sigma} \approx \frac{\theta_c}{\sigma_\theta} - 3\sqrt{\frac{n_{par}}{32}\frac{N_b}{10^{11}}\frac{3.75\,\mu\mathrm{m}}{\varepsilon_n}} \Rightarrow \frac{\theta_c}{\sigma_\theta} \approx 6 + 3\sqrt{\frac{I}{0.5\mathrm{A}}\frac{3.75\,\mu\mathrm{m}}{\varepsilon_n}}$$

$$\sigma_\theta = \sqrt{\frac{\varepsilon}{\beta^*}}$$

angular beam divergence at IP

higher beam intensities or smaller β^* require larger crossing angles to preserve dynamic aperture and shorter bunches to avoid geometric luminosity loss

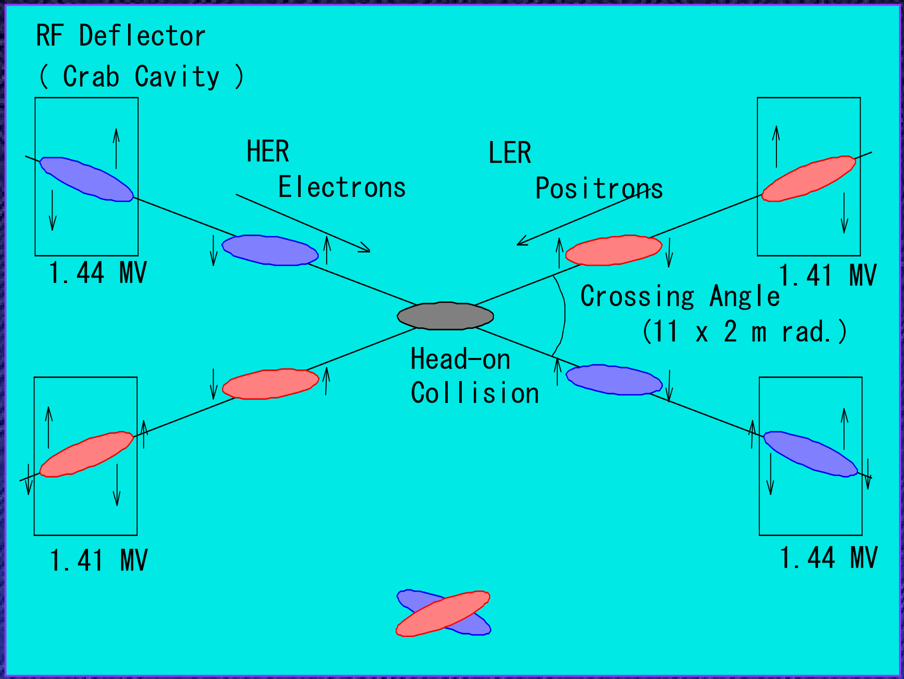
$\Rightarrow$ baseline scaling: $\theta_c \sim 1/\sqrt{\beta^*}$, $\sigma_z \sim \beta^*$

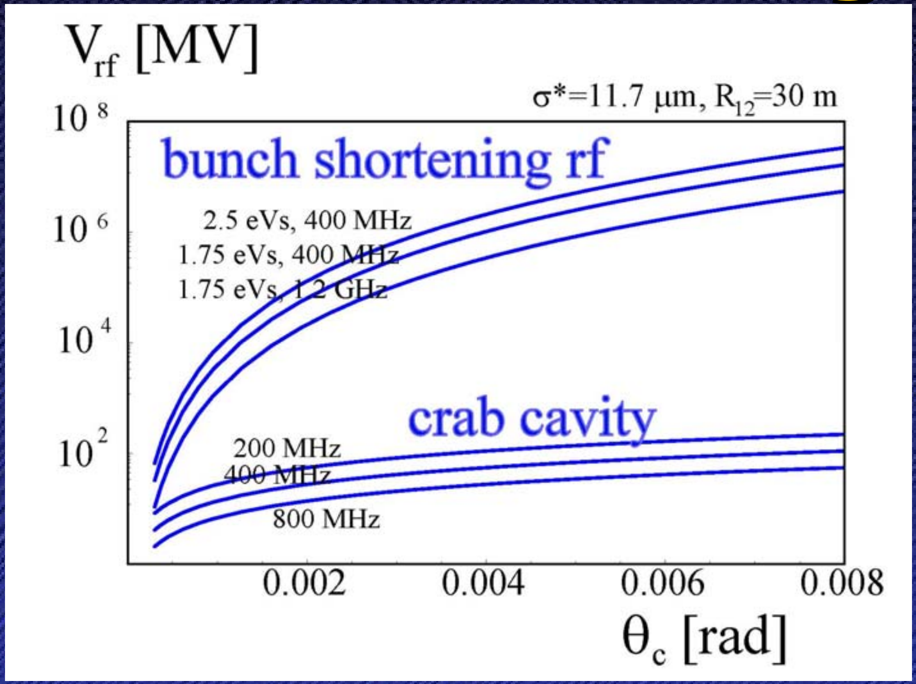
Alternative ways to avoid luminosity loss

1) **Reduce crossing angle and apply "wire" compensation of long range beam-beam effects**
2) **Crab cavities ⇒ large crossing angles to avoid long range bb effects w/o luminosity loss.** Potential of boosting the beam-beam tune shift (factor 2-3 predicted for KEKB, what about LHC?)
3) **Early beam separation by a "D0" dipole located a few metres away from the IP, as recently suggested by JPK at the LHC-LUMI-05 workshop.** The same effect could be obtained by tilted experimental solenoids, but the experiments don't seem to like the idea.

A potential drawback of 2) and 3) is that ΔQ_{bb} is no longer reduced by the geometric factor F ⇒ lower beam-beam limit?

Crab cavities vs bunch shortening





Crab cavities combine advantages of head-on collisions and large crossing angles

require lower voltages compared to bunch shortening RF systems

but tight tolerance on phase jitter to avoid emittance growth

Comparison of timing tolerances

	KEKB	Super-KEKB	ILC	Super-LHC
σ_x^*	100 μm	70 μm	0.24 μm	11 μm
θ_c	+/- 11 mrad	+/-15 mrad	+/-5 mrad	+/- 0.5 mrad
Δt	6 ps	3 ps	**0.03 ps**	**0.08 ps**

Tentative milestones for future machine studies

- **2006**: installation and test of a beam-beam long range compensation system at RHIC to be validated with colliding beams
- **2006/2007**: new SPS experiment for crystal collimation, complementary to recent (exciting!) Tevatron results
- **2006**: installation and test of Crab cavities at KEKB to validate higher beam-beam limit and luminosity with large crossing angles
- **2007**: if KEKB test successful, test of Crab cavities in a hadron machine (RHIC?) to validate low RF noise and emittance preservation

Several LHC IR upgrade options are currently being explored: we need to converge to a baseline configuration and identify a few alternative options

- quadrupole-first and dipole-first solutions based on conventional NbTi technology and on high-field Ni_3Sn magnets, possibly with structured SC cable
- energy deposition, absorbers, and quench limits
- schemes with Crab cavities as an alternative to the baseline bunch shortening RF system at 1.2 GHz to avoid luminosity loss with large crossing angles
- early beam separation by a "D0" dipole located a few metres away from the IP (or by tilted experimental solenoids?) may allow operation with a reduced crossing angle. Open issues: compatibility with detector layout, reduced separation at first parasitic encounters, energy deposition by the collision debris
- local chromaticity correction schemes
- flat beams, i.e. a final doublet instead of a triplet. Open issues: compensation of long range beam-beam effects with alternating crossing planes

Towards a baseline design

Following the approach proposed by Barry Barish for the ILC, I suggest to:

- **Define a Baseline,** i.e. a forward looking configuration which we are reasonably confident can achieve the required LHC luminosity performance and can be used to give an accurate cost estimate by mid-end 2006 in a "Reference Design Report."
- **Identify Alternative Configurations and rate them** in terms of technological and operational risks/advantages
- **Identify R&D** (at CERN and elsewhere)
  - To support the baseline
  - To develop the alternatives

What are Alternatives and Why?

Alternates: technologies or concepts, which may provide a significant cost reduction, improved performance (or both), but which will not be mature enough to be used in the baseline by end 2006

Alternatives will be part of the RDR, will form an important element in the R&D program and are the key to evolving the design

Reference LHC Luminosity Upgrade: workpackages and tentative milestones

accelerator	WorkPackage	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	after 2015
LHC Main Ring	Accelerator Physics											
	High Field Superconductors											
	High Field Magnets											
	Magnetic Measurements											
	Cryostats											
	Cryogenics: IR magnets & RF											
	RF and feedback											
	Collimation&Machine Protection											
	Beam Instrumentation											
	Power converters											
SPS	SPS kickers											
	Tentative Milestones	Beam-beam compensation test at RHIC	SPS crystal collimation test	LHC collimation tests	LHC collimation tests	Install phase 2 collimation	LHC tests: collimation & beam-beam			Install new SPS kickers	new IR magnets and RF system	
	Other Tentative Milestones	Crab cavity test at KEKB	Low-noise crab cavity test at RHIC	**LHC Upgrade Conceptual Design Report**		LHC Upgrade Technical Design Report	Nominal LHC luminosity 10^34			Ultimate LHC luminosity 2.3x10^34	beam-beam compensation	Double ultimate LHC luminosity 4.6x10^34
		LHC Upgrade Reference Design Report										

R&D - scenarios & models	(red)
specifications & prototypes	(yellow)
construction & testing	(green)
installation & commissioning	(blue)

Reference LHC Upgrade scenario: peak luminosity 4.6x10^34/(cm^2 sec)
Integrated luminosity 3 x nominal ~ 200/(fb*year) assuming 10 h turnaround time
new superconducting IR magnets for beta*=0.25 m
phase 2 collimation and new SPS kickers needed to attain ultimate LHC beam intensity of 0.86 A
beam-beam compensation may be necessary to attain or exceed ultimate performance
new superconducting RF system: for bunch shortening or Crab cavities
hardware for nominal LHC performance (cryogenics, dilution kickers, etc) not considered as LHC upgrade
R&D for further luminosity upgrade (intensity beyond ultimate) is recommended: see Injectors Upgrade