ADDITON OF "Q0" AND/OR "D0" THIN MAGNETS CLOSE TO THE IP FOR LHC UPGRADES

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Outline

- Concept of "Q0" quadrupoles & "D0" dipoles
- Q0/D0 combined function notion & subsequent death of Q0's 

- Doublet IR optics:
    - Brief history
    - Doublet with D0 early separation dipoles

Combined-Function Doublet Magnets Close to the IP

Motivation & Background Info

- Early separation ~1 m dipoles ('D0') in slots ~3.5 & 6.8 m from the IP have been suggested as a means to increase luminosity by decreasing the crossing angle*1.
- Thin doublet quadrupoles ~13 m from the IP ('Q0') have been claimed to modify the β functions such that, for $\beta^* = 25$ cm, β_{max} is no larger than for $\beta^* = 55$ cm*2. In this case the aperture & technology demands are diminished for upgraded triplet magnets.

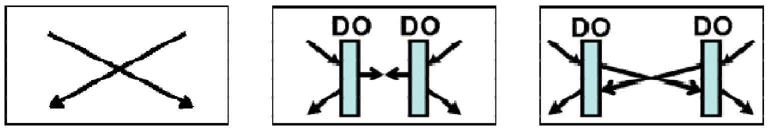
- The investigation into the feasibility of using gradient magnets in the 3.5 & 6.8 m slots was an effort to combine these 2 ideas.

*1 J.P. Kartchouk & G. Serbini, "An Early Beam Separation Scheme for the LHC Luminosity Upgrade", LHC Project Report 972, 2006, and; "D0 and Its Integrability", presented at LUMI '06, Valencia, 2006.

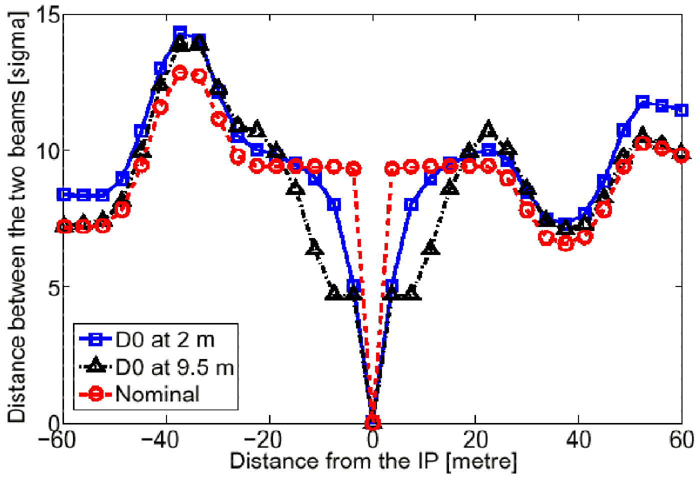
2 E. Laface, R. Ostojic, W. Scandale, D. Tommasin, C. Santoni, "Interaction Region with Slim Quadrupoles", EPAC proceedings, 2006; E. Laface, "Q0 with L=13 m", presented at LUMI '06, Valencia, 2006.

D0 Separation Dipoles — basic concept:

- Increasing beam-beam interactions at a 'few' close parasitic crossings by decreasing the crossing angle is an acceptable trade-off to obtain large luminosity gains.



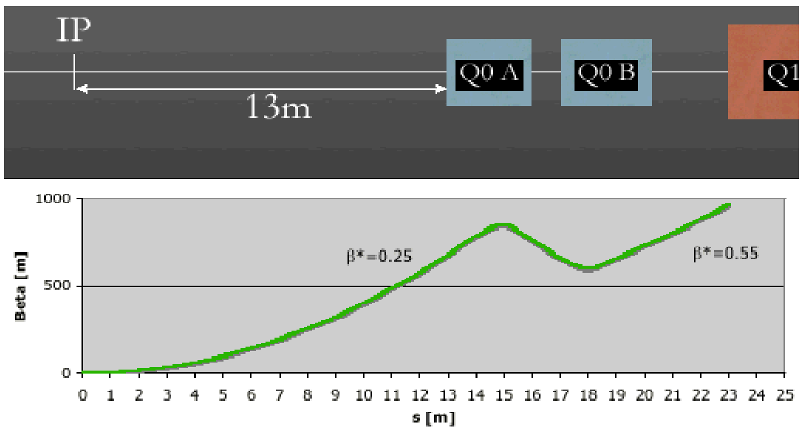
(a) (b) (c)

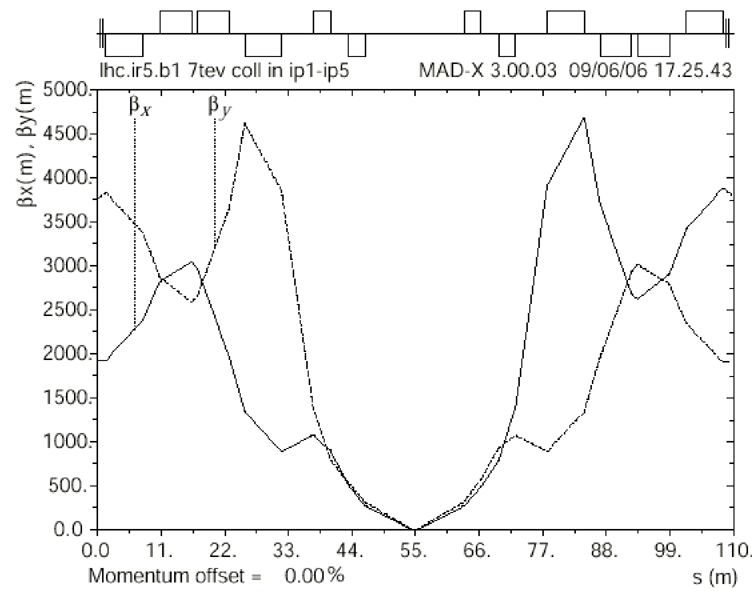


	$\beta^*[m]$	Integrated field $[T \cdot m]$	L/L_0
D0 at 2 m	0.25	6.1	5.7
	0.20	6.8	7.2
	0.15	7.9	9.5
D0 at 9.5 m	0.25	5.9 (6.8 if $n_b = 5616$)	4.6 (8.6)
	0.20	6.6 (7.6 if $n_b = 5616$)	5.2 (9.7)
	0.15	7.6 (8.7 if $n_b = 5616$)	5.9 (10.8)

Q0 Quadrupole Doublet — basic concept:

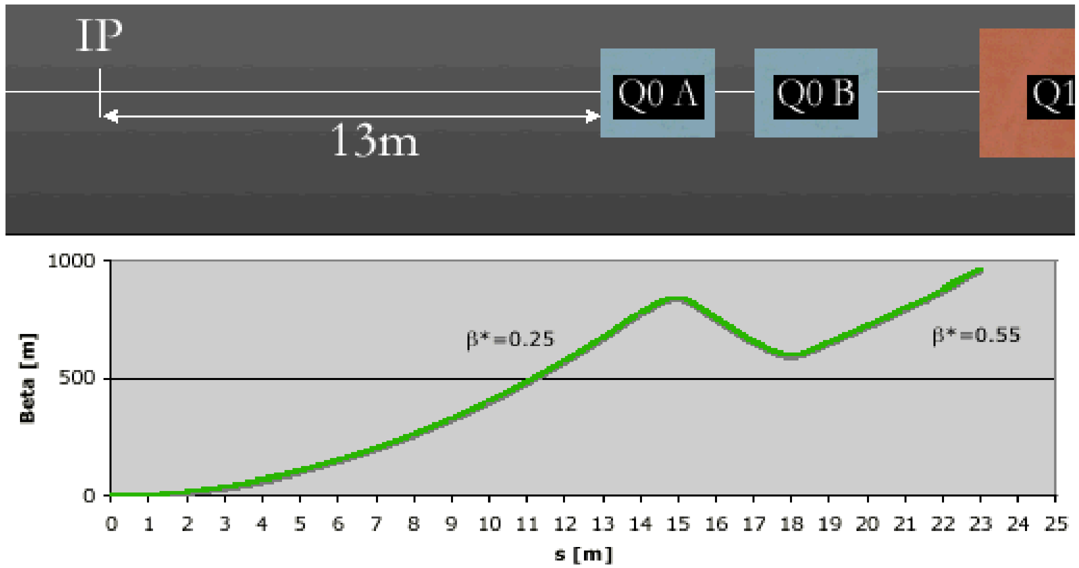
- An inner doublet allegedly alters the β growth curve for β* = 25 cm to match the β* = 55 cm curve (in one plane) entering the triplet. β_{max} in the triplet does not exceed the β* = 55 cm value in either plane.





Magnet	Length	Gradient	Min. diameter
SQ1	∼ 3 m	∼ 118 T/m	> 32 mm
SQ2	∼ 3.5 m	∼ 163 T/m	> 35 mm

A Note on Transforming the β Growth from β* = 25 cm to the β* = 55 cm Growth Curve via 'Q0' Inner Quadrupoles†



For β* = 25 cm:	at 14.5 m:	β = 841.250 m, α = -58.000
For β* = 55 cm:	at 18.0 m:	β = 589.641 m, α = -32.727
	at 23.0 m:	β = 962.368 m, α = -41.818

$$\beta(S) \approx \beta_i \cdot \left(1 - {\alpha_i}/{\beta_i} \cdot S\right)^2$$

† Quad locations & β functions pilfered from Emanuele Laface's "Q0 with L*=13 m" presentation at LUMI '06, Valencia, 2006.

A thin lens of inverse focal length q_1 14.5 m from the IP changes α by $\Delta\alpha = q_1 \cdot \beta_1$.

To change the β^* = 25 cm curve at 14.5 m to intersect β^* = 55 cm at 18 m α_1 must be:

$$\alpha_1 \approx \frac{841.25}{3.5} \cdot \left(1 - \sqrt{\frac{589.641}{841.250}}\right) = 39.129$$

$$q_1 = \frac{\Delta\alpha_1}{\beta_1} = \frac{(39.129 + 58.000)}{841.25} = +0.11546 m^{-1}$$

At 18 m β is now = 589.641 m, and $\alpha_2 = \alpha_1 - \gamma_1 \cdot \Delta S = 32.755$

Another thin lens q2 corrects α to match the β^* = 55 cm curve:

$$q_2 = \frac{\Delta\alpha_2}{\beta_2} = -\frac{(32.755 + 32.727)}{589.641} = -0.11105 m^{-1}$$

At 7 TeV/c $B_0\rho = 7 * 3335.64$ T·m, so the integrated gradients of the 2 thin lenses are:

$$G_1 L = q_1 \cdot B_0 \rho = +2695.9 \ldots T \cdot m / m$$
$$G_2 L = q_2 \cdot B_0 \rho = -2593.1 \ldots T \cdot m / m$$

For L = 3.5 m, $G_{1,2}$ ~ 750 T/m !

Summary & Comments

- The notion of a D0/Q0 combined function doublet situated close to the IP is a dead end. Far worse, the Q0 doublet proposal (which has sparked interest in the international community) has been discovered to be complete nonsense. [This has an impact on BNL, which has eagerly anticipated building these quads!]

  There *might* be some value in exploring the impact of a single, long, weak quad inboard of the triplet, but this isn't at all clear at this point....

DOUBLET IR FOCUSING WITH "D0" SEPARATION DIPOLES

MOTIVATION FOR DOUBLET IR OPTICS

- Doublets can provide elliptical beams at the IP, such that $\sqrt{\beta x^* \beta y^*} \equiv \beta_0^*$ (round beams). Luminosity can then be enhanced via a smaller crossing angle in the plane of larger β^*.
- For ***symmetric*** doublet focusing $\beta x(max) = \beta y(max) \leq \beta 0(max)$ of triplets & round beams at the IP.
- With half-crossing angle θ in a single plane, and short bunches, luminosity is reduced approximately by a factor:

$$R \approx \left[1+\left(\sigma_{\ell}\theta / \sigma_t^*\right)^2\right]^{-1/2}$$

- With horizontal crossing (IP5) and elliptical beams $\beta x^* > \beta_0^* \Rightarrow \theta x < \theta_0$ for the same $N\sigma$ separation, and the luminosity reduction is not as large:

$$R_e = \left[1 + \left(\frac{\beta_0^*}{\beta_x^*}\right)^2 \cdot \left(\sigma_l N \big/ 2\beta_0^*\right)^2\right]^{-1/2} > R_0$$

- Results for 10σ separation at 1st PC, β^*(equivalent) = 0.25m, and σ_l = 0.0755m:

Round beams; with $\beta 0^*$ = 0.25m $\Rightarrow$ $\theta 0$ = 224 μrad, then:

***R* 0 = 0.522**.

Elliptical beams; with $\sqrt{\beta x^* \beta y^*}$ = 0.25m & βx^* =0.469m

$\Rightarrow$ θx = 164 μrad, and:

***R* e = 0.779**

- Luminosity is enhanced using elliptical beams by ≈ 40% compared to the round beam result (*or*, the luminosity hit is only about 22% instead of 48%).

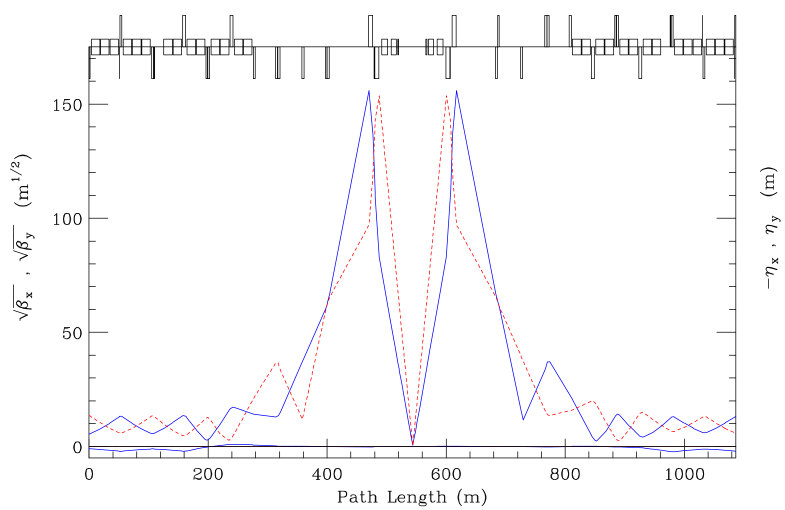
DOUBLET DESIGN ISSUES

- With elliptical beams the doublets must be optically symmetric with respect to the IP to ensure $\beta x(max) = \beta y(max)$ and thereby conserve aperture.
- Symmetric doublets imply that 'dipoles first' is the only option — the beams must be in separate channels to experience equivalent focusing.

- Transition from the symmetric final focus optics to the optics of an intrinsically anti-symmetric lattice should be seamless.

COLLISION OPTICS (IP5) @ 7 TEV

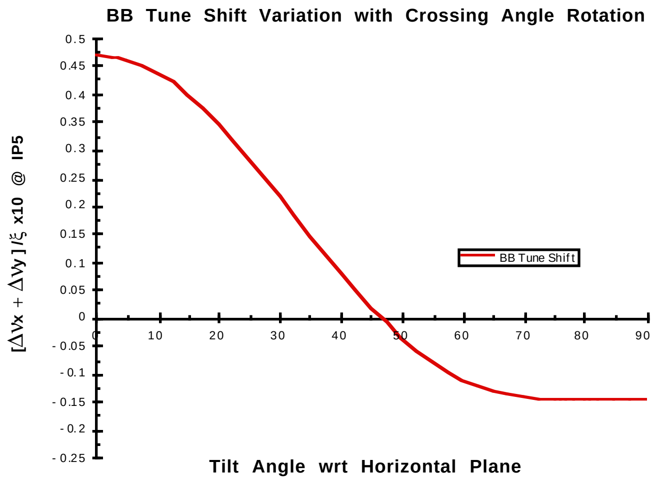
- $\sqrt{\beta x\ \beta y}$ = 0.25 m
  βx = 0.469m & βy = 0.133m
- βx(max) = βy(max) = 24.5 km

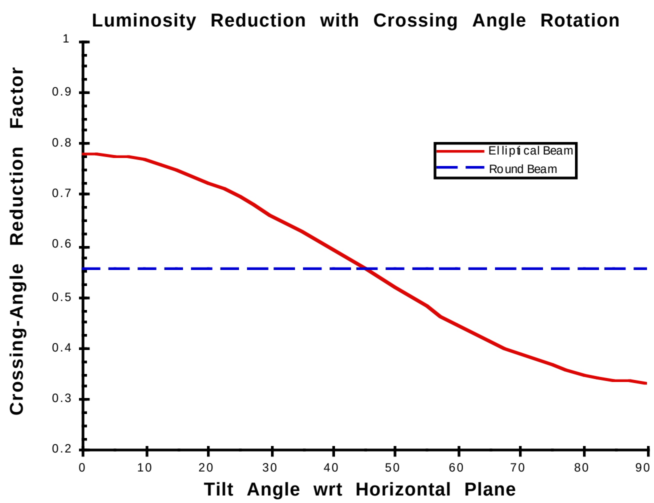


- 10σ horizontal separation at 1st parasitic for $\theta_{1/2}$ =164 μr

Quad	L(mag) (m)	#	Gradient LS (T/m)	Gradient RS (T/m)
Symmetric				
Q1	6.85	1	-199.658	-199.658
Q2	6.40	1	201.175	201.175
Q3	3.4	1	-97.635	+97.635
Antisymmetric				
Q4	3.4	1	90.277	-90.277
Q5	3.4	2	-167.452	167.452
Q6	4.8	1	81.839	-81.839
Q7a	2.4	1	-190.534	190.534
Q7b	3.4	1	-190.534	190.534
Arc & DS Cells				
Q8	4.8	1	119.912	-124.435
Q9	3.4	1	-200.00	200.00
Q10	3.4	1	191.43	-191.43
QTL11	1.15	1	-40.832	68.203
QT12	0.32	1	110.000	-58.394
QT13	0.32	1	-110.000	-101.218

Elliptical Beam Tune Shifts

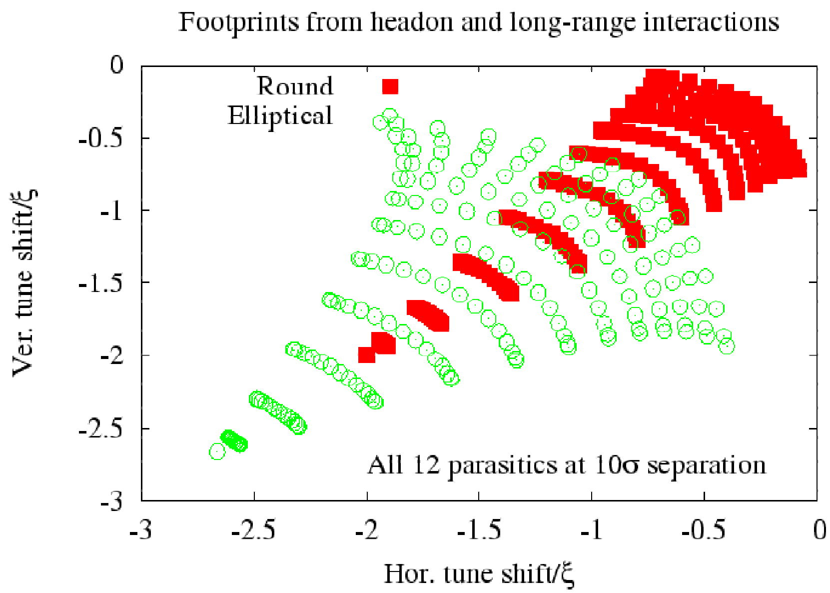




- Unlike triplets & round beams, elliptical long range beam-beam tune shifts do not cancel.

- Rotating the crossing angle plane reduces the tune shifts, but, *complete* cancellation, which occurs for a tilt of φ = 45o, leaves zero luminosity benefits, i.e;

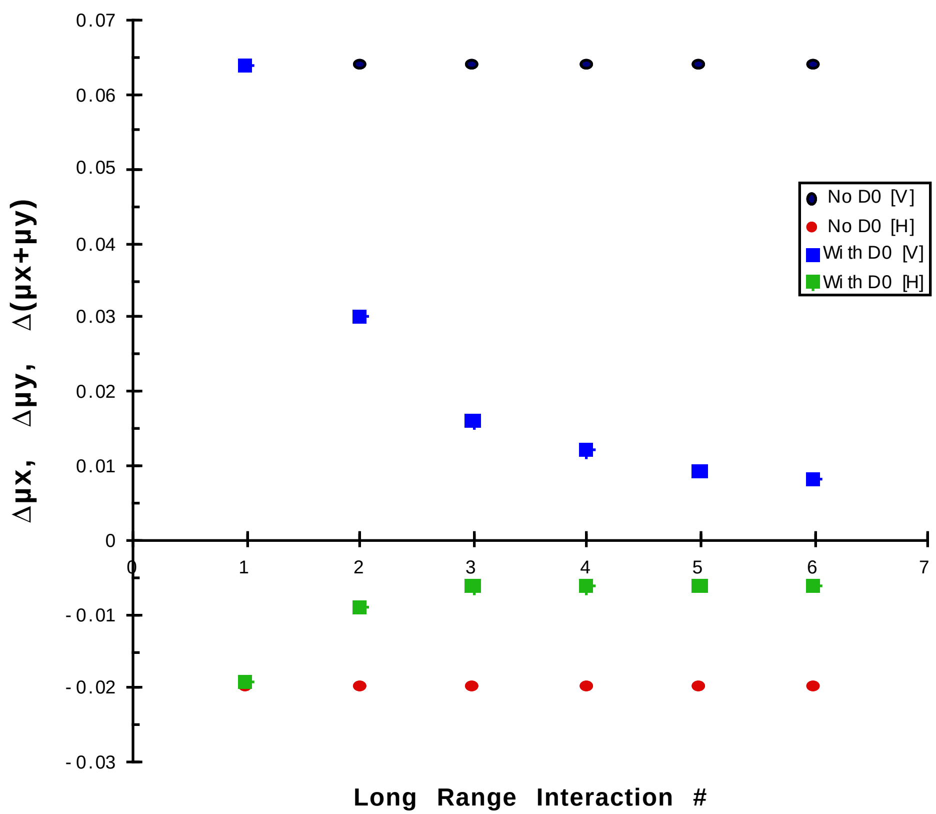
  Re(φ=45o) = *R0* = 0.522



- 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.

Spread of long range tune shifts with doublet optics are a concern. Avenues to explore might include wire compensation schemes, or........

Early Separation "D0" Dipoles



Zero amplitude tune shifts at the six closest PC's closest in units of ζ with and without the D0 dipoles

Tune Shifts (units of ζ) for β* (equivalent) = 25 cm

Round: β_0^*= 25

PX #	BBX	BBY	BBX + BBY
0	1.00	1.00	2.00
1	-0.199E-01	0.199E-01	-0.267E-07
2	-0.199E-01	0.199E-01	-0.280E-07
3	-0.199E-01	0.199E-01	-0.279E-07
4	-0.199E-01	0.199E-01	-0.281E-07
5	-0.199E-01	0.199E-01	-0.282E-07
6	-0.199E-01	0.199E-01	-0.282E-07
	-0.119	0.119	0.121E-13

Elliptical (no D0): $\sqrt{\beta x^* \beta y^*}$= 25

PX #	BBX	BBY	BBX + BBY
0	1.30	0.701	2.00
1	-0.190E-01	0.641E-01	0.451E-01
2	-0.188E-01	0.640E-01	0.452E-01
3	-0.187E-01	0.639E-01	0.452E-01
4	-0.187E-01	0.639E-01	0.452E-01
5	-0.187E-01	0.639E-01	0.452E-01
6	-0.187E-01	0.639E-01	0.452E-01
	-0.113	0.384	0.271

Elliptical (with D0): $\sqrt{\beta x^* \beta y^*}$= 25

PX #	BBX	BBY	BBX + BBY
0	1.30	0.701	2.00
1	-0.190E-01	0.641E-01	0.451E-01
2	-0.892E-02	0.300E-01	0.211E-01
3	-0.641E-02	0.159E-01	0.945E-02
4	-0.627E-02	0.115E-01	0.527E-02
5	-0.612E-02	0.942E-02	0.329E-02
6	-0.596E-02	0.817E-02	0.221E-02
	-0.527E-01	0.139	0.864E-01

SUMMARY

- Symmetric doublet focusing has the attractive potential to enhance luminosity via colliding elliptical beams at the IP.
- The long-range beam-beam tune shifts & spread are significantly larger for elliptical beams than for round beams and are a concern for the doublet approach.
- The use of "D0" early separation dipoles shows some early promise for improving the doublet performance, but much more remains to be studied.

Ω