Particle simulations: status and plans

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On behalf of WP2- Task 2.3 collaborators

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* Moved to other tasks

Collaborating Institutes: BINP, CEA, CERN, CSIC-IFIC, EPFL, INFN-Frascati, SLAC, Uni-Liv, Uni-Man

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Outline

- Introduction
- Field quality of new magnets
- Non-linear fringe fields
- Field quality of crab cavity
- Numerical simulation tools
- Next steps
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Introduction - I

- Goals of Task 2.3 of WP2:
  - To study the field quality tolerances for new magnetic elements for the LHC upgrade.
  - To specify the circuits for the non-linear correction of the triplets field quality.
  - To study also more subtle items:
    - Impact of field quality of crab cavities
    - Impact of non-linear fringe fields of new large aperture magnets.
  - At the end of the specification process, the detailed analysis of the phase space should be performed to detect possible pathologies.

Introduction - II

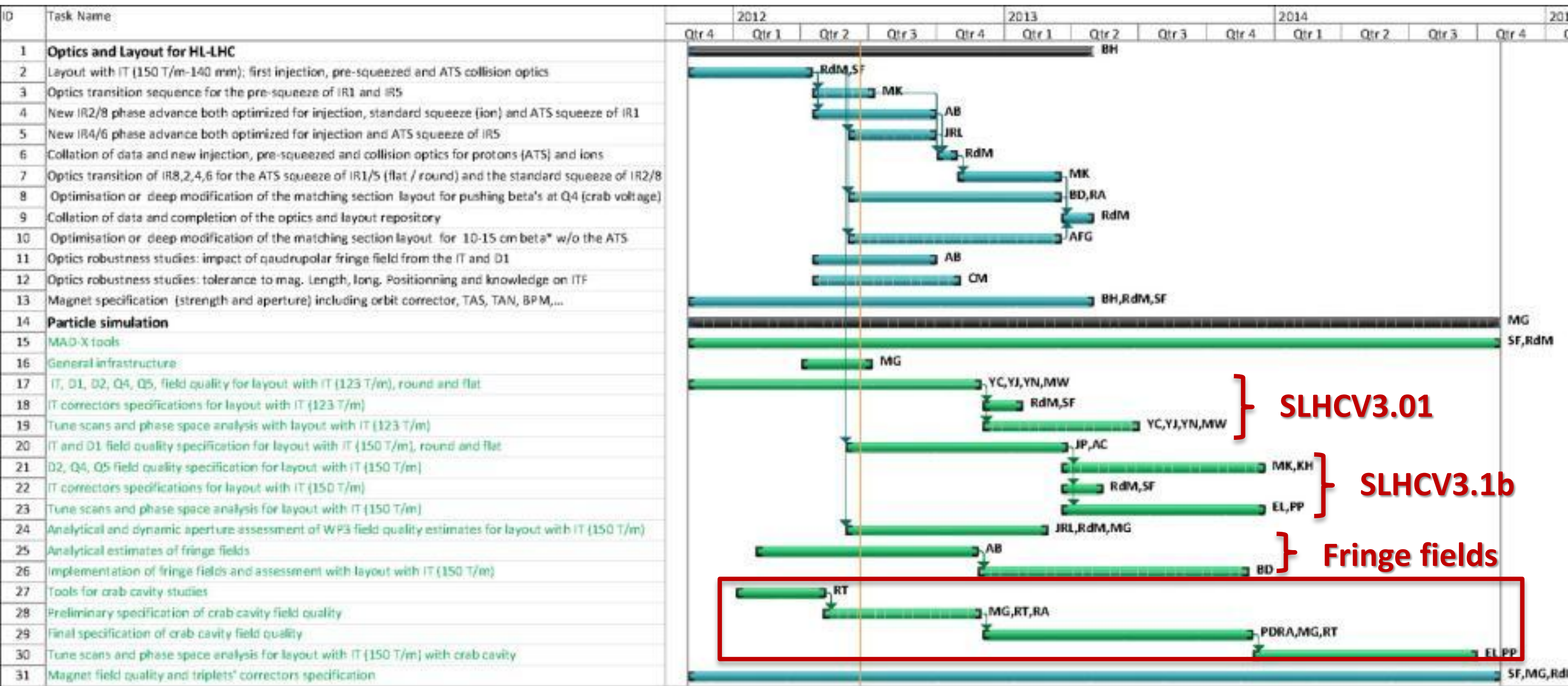
- At the beginning of the activities no final layout available, but two intermediate configurations
  - SLHCV3.01: layout with triplets at 123 T/m
  - SLHCV3.1b: layout with triplets at 150 T/m
- Task organisation
  - Apparent dilemma: work by layout or by magnet families?
  - Mixed solution:
    - Work on SLHCV3.01 under the responsibility of one team (SLAC).
    - Work SLHCV3.1b divided over several teams each one responsible for certain magnet classes (CEA, Uni-Liv, BINP).

Introduction - III

- Other tasks:
  - Non-linear fringe fields: analytical estimates and long-term impact on beam dynamics (BINP and CEA teams).
  - Crab cavities: long-term impact on beam dynamics and specification of field quality (CERN, Uni-Man, BINP teams).
  - Analysis of field quality estimates provided by WP3 (CSIC-IFIC).

Introduction - IV

- Disclaimer: next to impossible to represent actual resources (in FTE or ppm) to a Gantt chart. Time line is indicative and not to be used to evaluate allocated resources.



Crab cavities

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Field quality of new magnets - I

- Two situations to consider:
  - Injection energy: persistent current effects
  - Collision energy: geometric effects
- Figure-of-merit: long term dynamic aperture
  - 11 angles
  - 30 amplitudes in 2 σ range
  - 60 seeds
  - $\Delta p/p$ set to 2/3 of bucket height
  - 10^5 turn
  - 3.75 μm normalised emittance
- Baseline configuration: machine as-built
- Strategy:
  - Add one new class of magnets at a time
  - Scan multipoles around an initial field quality estimate. Such an estimate can be based on:
    - Measured data for existing similar magnet classes
    - Expected field quality for proposed magnets

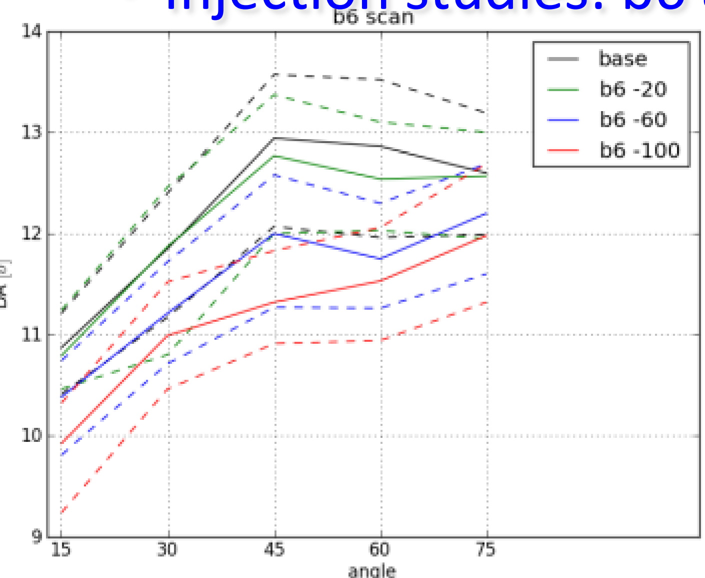
Target DA: ≈11-12 σ at injection and collision (to leave margin for even lower β^*)

High Luminosity LHC

Field quality of new magnets- II

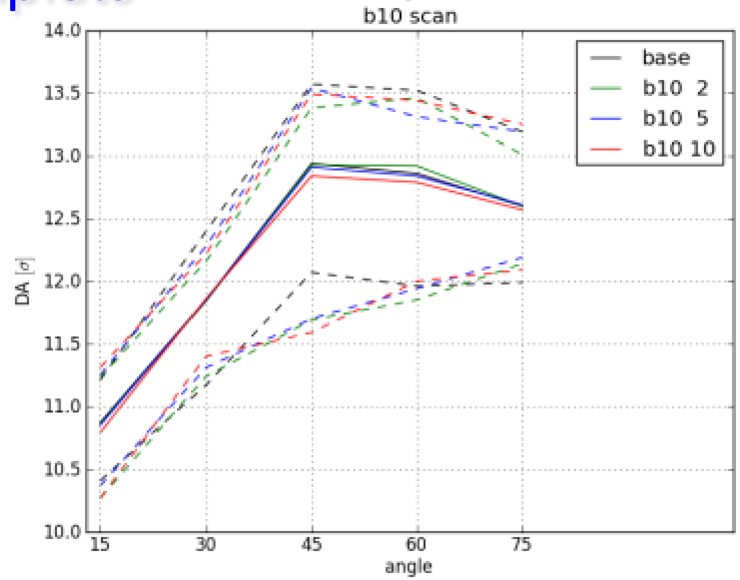
- Injection studies: b6 and b10 of new triplets

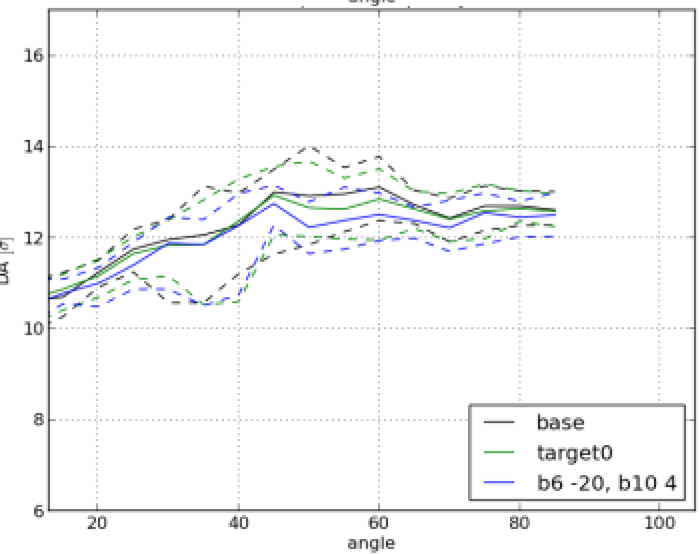
Courtesy R. De Maria



Scan of systematic b6, b10.
Random set to 20% of systematic.
Selected:

- **b6(syst)=-20 units**
- **b10(syst)=4 units**

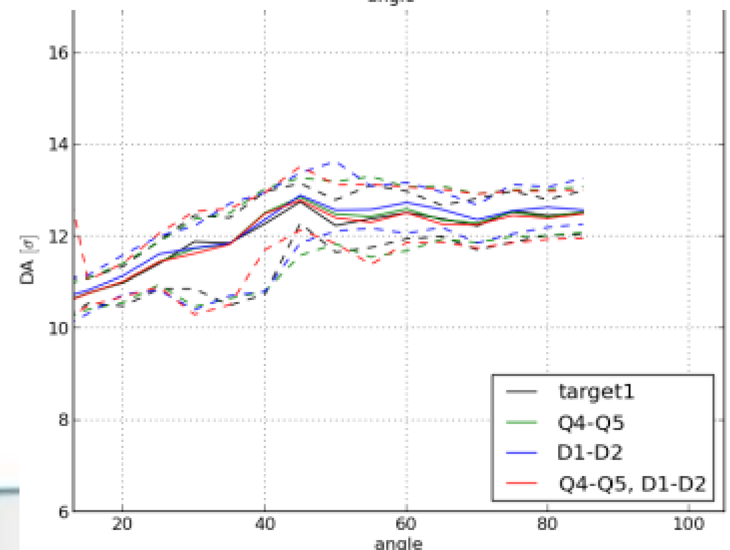




Injection studies: triplets and other magnets.

Estimated field quality:

- **D1: DX magnet**
- **D2: existing D2**
- **Q4, Q5: existing MQY**



Field quality of new magnets - III

- Collision studies: new triplets
  - Detailed scan of multipoles starting from estimate of field quality based on measured existing triplets performed with SLHCV3.01.

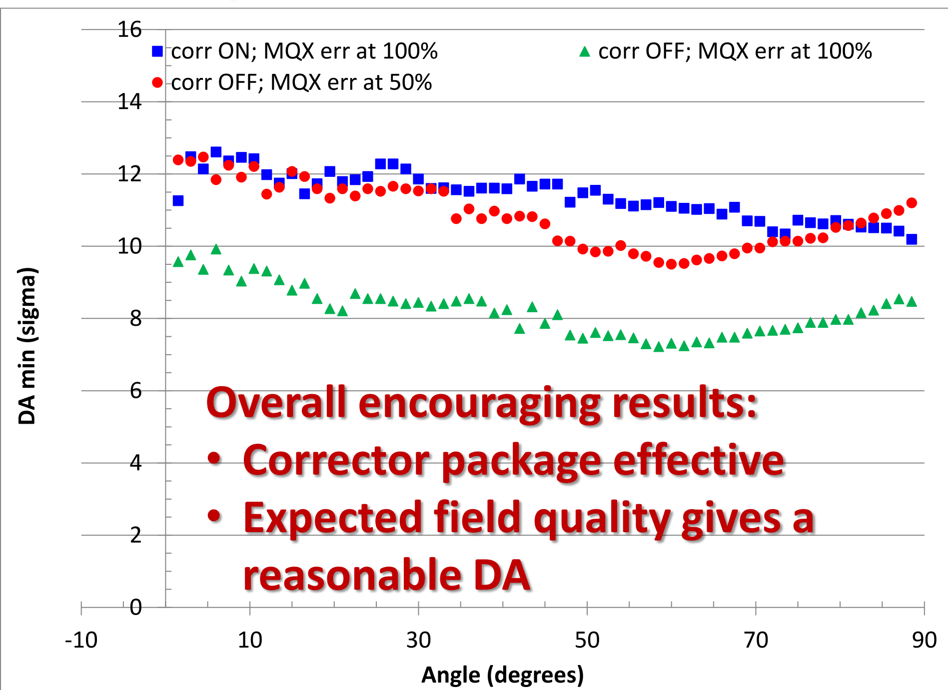
Presented at IPAC12, Y. Nosochkov *et al.*

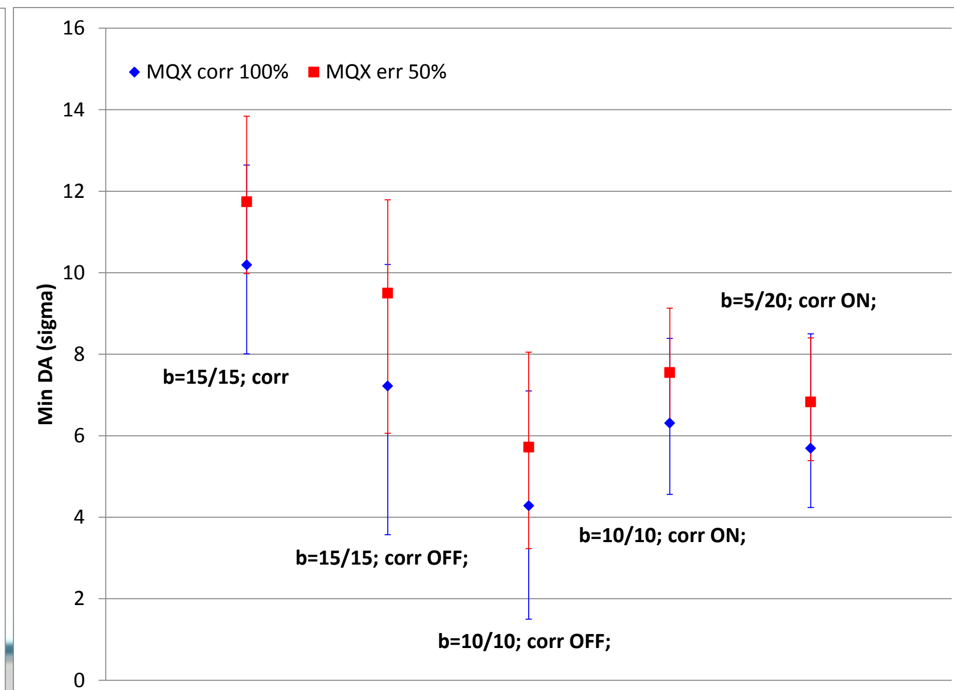
  - As from June 2012 an estimate of the field quality of new triplets has been made available by WP3.
  - Two activities launched in parallel:
    - Analysis of SLHCV3.01 performing multipoles scans starting from expected field quality (see talk by Y. Nosochkov: Optimization of triplet field quality in collision)
    - Pre-analysis of SLHCV3.1b with expected field quality.

High Luminosity LHC

Field quality of new magnets - IV

- Preliminary study for SLHCV3.1b in collision:
  - No multipole scans
  - Two error tables for triplets used:
    - Original error table from WP3
    - Error table from WP3 with multipoles reduced by a factor of 2.
  - Impact of non-linear correctors’package tested.
  - Impact of beta* tested.





Overall encouraging results:
- **Corrector package effective**
- **Expected field quality gives a reasonable DA**

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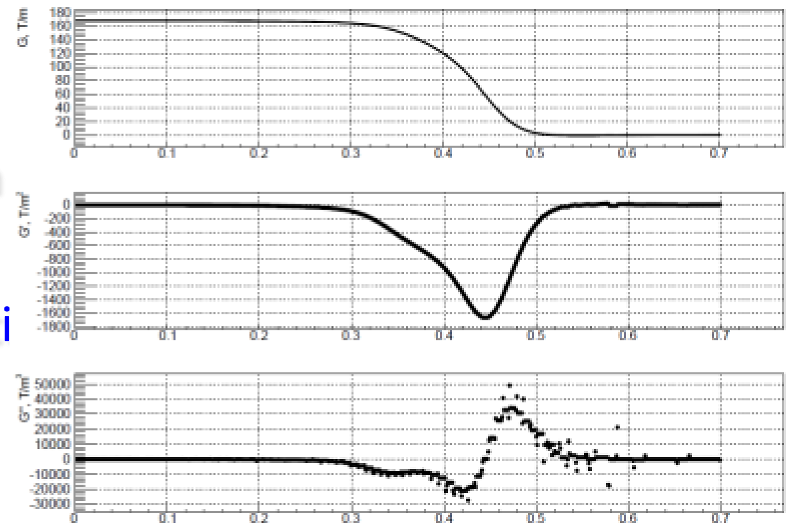
Non-linear fringe fields - I

- The proposed HL-LHC layout relies on larger-than-nominal aperture magnets.
- Estimate of fringe fields effects is mandatory (the linear part is evaluated by Task 2.2, then non-linear part by Task 2.3).
- The starting point is analytical estimate of the impact on detuning with amplitude and chromaticity.
- If the effect is not negligible, then long-term tracking should be performed (but this require changes to the tracking code SixTrack).
- Triplets and separation dipoles have been considered.

Non-linear fringe fields - II

- Approach:
  - Estimate field, derive Hamiltonian, average over the phases, then derive by action (detuning with amplitudes).
  - Similar, but including chromatic effects (chromati No special difference between quadrupoles or dipoles.
  - As usual, optics, or orbit, are assumed to be unperturbed.
  - The shape of the fringe fields has been taken from measurements of HQ magnet (from WP3).



Courtesy A. Bogomyagkov

Name	α_{xx}	$\alpha_{xy} = \alpha_{yx}$	α_{yy}
MQXC.3L5	$3.7 \cdot 10^3$	$8.8 \cdot 10^3$	$6.7 \cdot 10^3$
MQXC.B2L5	$6.3 \cdot 10^3$	$-10 \cdot 10^3$	$3.1 \cdot 10^3$
MQXC.A2L5	$4.1 \cdot 10^3$	$7 \cdot 10^2$	$5.6 \cdot 10^2$
MQXC.1L5	$2.9 \cdot 10^3$	$-1.7 \cdot 10^3$	$4 \cdot 10^2$
MQXC.1R5	$4 \cdot 10^2$	$1.7 \cdot 10^3$	$2.9 \cdot 10^3$
MQXC.A2R5	$5 \cdot 10^2$	$7 \cdot 10^2$	$4.1 \cdot 10^3$
MQXC.B2R5	$3.1 \cdot 10^3$	$10 \cdot 10^3$	$6.3 \cdot 10^3$
MQXC.3R5	$6.7 \cdot 10^3$	$-8.6 \cdot 10^3$	$3.7 \cdot 10^3$
Total	$2.8 \cdot 10^4$	$1.6 \cdot 10^3$	$2.8 \cdot 10^4$

The effect is not dramatic, but not completely negligible too. Tracking studies will be performed.

Name	ξ_{xx}	$\xi_{xy} = \xi_{yx}$	ξ_{yy}
MQXC.3L5	$-3.6 \cdot 10^3$	$-8.7 \cdot 10^3$	$-6.5 \cdot 10^3$
MQXC.B2L5	$-6.2 \cdot 10^3$	$10 \cdot 10^3$	$-2.8 \cdot 10^3$
MQXC.A2L5	$-3.7 \cdot 10^3$	$-7 \cdot 10^2$	$-5.6 \cdot 10^2$
MQXC.1L5	$-2.5 \cdot 10^3$	$1.7 \cdot 10^3$	$-4 \cdot 10^2$
MQXC.1R5	$-4 \cdot 10^2$	$-1.7 \cdot 10^3$	$-2.5 \cdot 10^3$
MQXC.A2R5	$-5 \cdot 10^2$	$-7 \cdot 10^2$	$-3.8 \cdot 10^3$
MQXC.B2R5	$-2.8 \cdot 10^3$	$-10 \cdot 10^3$	$-6.2 \cdot 10^3$
MQXC.3R5	$-6.5 \cdot 10^3$	$8.7 \cdot 10^3$	$-3.6 \cdot 10^3$
Total	$-2.6 \cdot 10^4$	$-1.4 \cdot 10^3$	$-3.1 \cdot 10^4$

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Field quality of crab cavities - I

- Essential element for HL-LHC.
- Impact of field imperfections on long-term beam dynamics to be analysed.
- The first step is the description of the field and its imperfections
  - A development of an appropriate formalism has been recently carried out. The result is the introduction of so-called RF multipoles.
  - The new type of multipoles has been implemented in MAD-X and SixTrack.

Electro-magnetic kick

$$\Delta p_\perp (x,y,z) = \frac{e}{c} \int \left[\mathbf{E}_\perp (x,y,s=z+ct,t) + \left(c\,\hat{\mathrm{s}} \wedge \mathbf{B}(x,y,s,t)\right)_\perp \right] \mathrm{d}t$$

Development of the kick

$$\Delta p_x (x,y,z) - i \Delta p_y (x,y,z) = \sum_{n=0}^{N} C_n(z) (x+iy)^n$$

Z-dependent coefficient of the RF multipole

$$C_n = B_n + i\, A_n$$

$$\tilde{B}_n(z) = \mathrm{Re}\left[B_n\, e^{j(\vartheta_n - k_{\mathrm{RF}} z)}\right] = B_n \cos\left(\vartheta_n - k_{\mathrm{RF}} z\right)$$

$$\tilde{A}_n(z) = \mathrm{Re}\left[A_n\, e^{j(\varphi_n - k_{\mathrm{RF}} z)}\right] = A_n \cos\left(\varphi_n - k_{\mathrm{RF}} z\right)$$

Field quality of crab cavities - II

Presented at IPAC12, A. Grudiev *et al.*

- Estimate of RF multipoles for three layouts via electromagnetic simulations

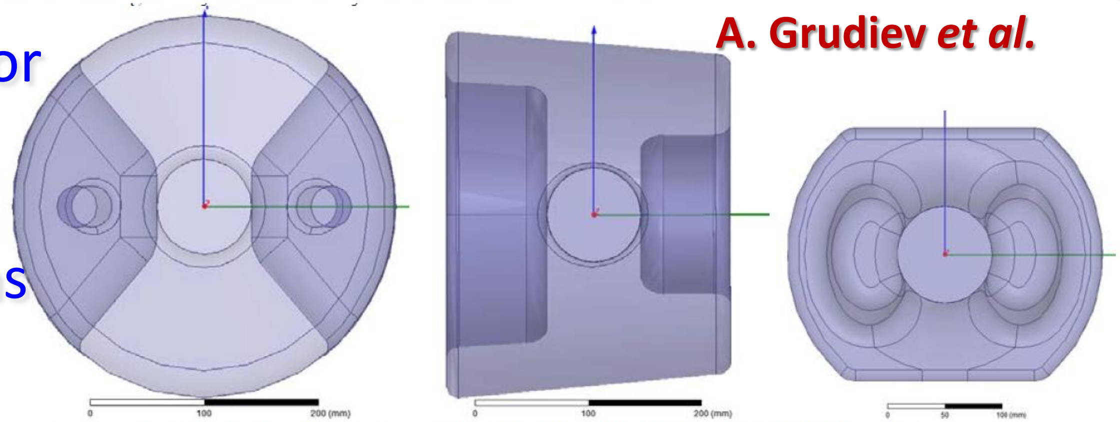

Figure 1: Geometry of the LHC CC prototypes: RWCAV (left), QWCAV (middle), 4RCAV (right).

- Estimate of static impact of RF multipoles to beam dynamics.

	RWCAV	QWCAV	4RCAV
$\|\Delta Q_{x,y}\|[10^{-3}]$	0	1.4	0
$\|\Delta\xi_{x,y}\|[10^{-3}]$	7.96	3.13	2.24
$\|\Delta Q\|[10^{-6}]$	0	5.06	0

	MBRC	RWCAV	QWCAV	4RCAV
b_2	55	0	114	0
b_3	7510	3200	1260	900
b_4	82700	0	1760	0
b_5	2.9×10^6	-0.52×10^6	-0.15×10^6	-2.44×10^6
b_6	52×10^6	0	-1.66×10^6	0
b_7	560×10^6	-14×10^6	0	-650×10^6

- First estimate of long-term impact of RF multipoles in progress (see presentation by J. Barranco: *RF multipoles: modelling and impact on the beam*).

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Numerical simulation tools - I

- Tools
  - MAD-X: used to generate the lattice, optics, and files for subsequent numerical simulations (SixTrack).
    - Large set of tools for dealing with (HL-)LHC studies.
    - All optical configurations stored under afs:
    - **/afs/cern.ch/eng/lhc/optics/SLHCV3.01**
    - **/afs/cern.ch/eng/lhc/optics/SLHCV3.1b**
  - SixTrack: workhorse of LHC simulation studies (single particle, weak-strong beam-beam, collimation). On-line documentation can be found at
  - **http://sixtrack-ng.web.cern.ch/sixtrack-ng/**
  - Resources are being oriented to the further development of the code.

Numerical simulation tools - II

- Tools
  - Development of SixTrack:
    - RF multipoles (required for crab cavity studies)
    - Exact Hamiltonian
    - Special multipoles for non-linear fringe fields
    - Implement physics of ions
    - Integration of FLUKA for collimation studies
    - Re-factoring of tracking engine
      - Possibility of adapting the code for GPUs
      - Possibility of re-using the SixTrack tracking engine for other codes (e.g., instabilities)
    - Implement time-dependence of magnets' strength.

Quadrupole, sextupole, octupole components (normal and skew) already implemented.

Future implementation

Numerical simulation tools - III

- Tracking resources:
  - CERN batch system (LSF)
  - Volunteers' based tracking system LHC@home (based on Boinc architecture). Web site at **http://lhcathome.web.cern.ch/LHCathome/**

LHC@home
SixTrack

log in

Server software version: 25137M / 11 Nov 2012 | 15:59:19 UTC

Server status

Program	Host	Status
data-driven web pages	boinc05	Running
upload/download server	boinc05	Running
scheduler	boinc05	Running
feeder	boinc05	Running
transitioner	boinc05	Running
file_deleter	boinc05	Running
sixtrack_assimilator	boinc05	Running
sixtrack_validator	boinc05	Running
db_purge	boinc05	Running

Running: Program is operating normally
Not Running: Program failed or the project is down
Disabled: Program is disabled

Computing status

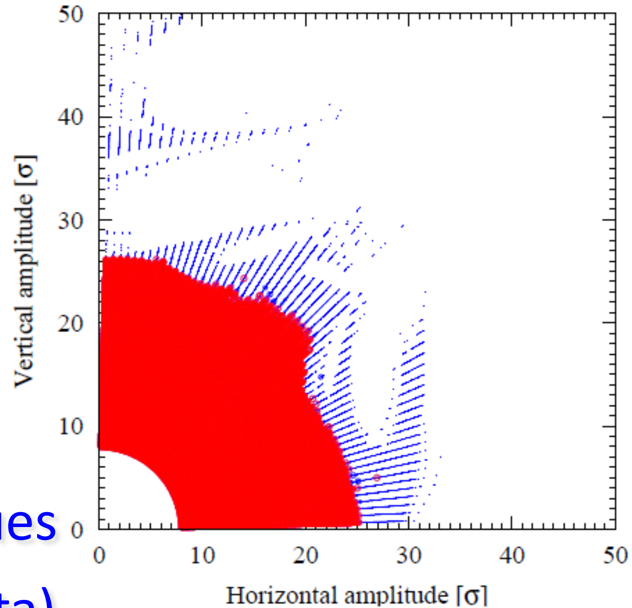
Work	#
Tasks ready to send	108,070
Tasks in progress	93,736
Workunits waiting for validation	8
Workunits waiting for assimilation	2
Workunits waiting for file deletion	0
Tasks waiting for file deletion	0
Transitioner backlog (hours)	0

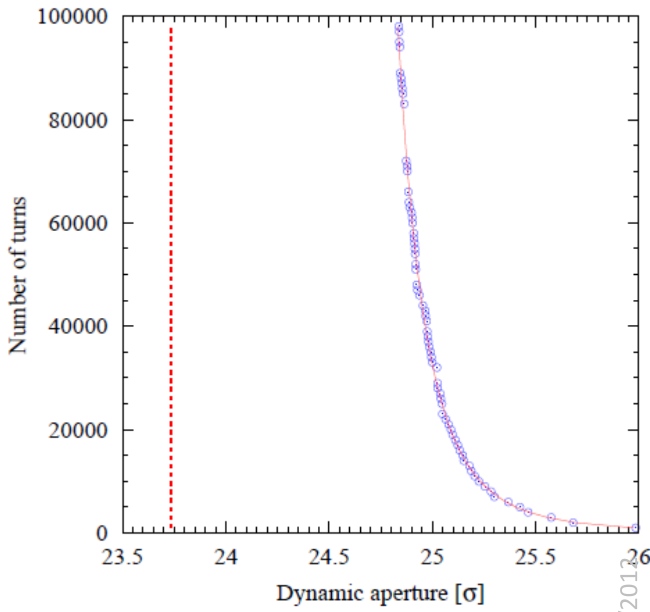
Users	#
with recent credit	15,505
with credit	107,216
registered in past 24 hours	28
Computers	**#**
with recent credit	25,779
with credit	277,762
registered in past 24 hours	137
current GigaFLOPs	34,917

Tasks by application				
application	unsent	in progress	avg runtime of last 100 results in h (min-max)	users in last 24h
SixTrack	107,820	92,741	4.78 (0.05 - 12.29)	6,271

Numerical simulation tools - IV

- Well-tested chain of tools:
  - Tracking code
  - Tracking environment. Documentation at
    - **http://sixtrack-ng.web.cern.ch/sixtrack-ng/doc/sixdesk/sixdesk_env.html**
    - Required to launch massive numerical simulations in an automatic way, i.e., starting from a single mask file generate all the jobs corresponding to the scan over:
      - Angles
      - Amplitudes
      - Seed
  - Post processing tools (on-going studies to improve current tools and find new techniques to exploit available data)





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Next steps

- Consider the field quality (collision and injection) of the other magnet classes, i.e., separation dipoles (D1, D2) and insertion quadrupoles (Q4, Q5).
- Finalise the studies of crab cavities producing a target error table.
- Implement and study the long-term impact of non-linear fringe fields.
- Analysis of the details of the phase space topology when all the pieces are put together.

High Luminosity LHC

Summary and outlook

- After one year of HiLumi activities
  - Detailed studies of triplet field quality in advanced status for SLHCV3.01
  - First exploratory studies of impact of expected triplet field quality performed for SLHCV3.1b
  - First studies of long-term impact of crab cavities field quality performed
  - Analytical studies of the impact of non-linear fringe fields carried out

Excellent progress for Task 2.3!

- This a very solid ground to build on the next steps (analysis of other magnet classes is the next task)!
- The release of the HLLHCV1.0 layout will require to cross-check some of the results obtained so far, but the strategy adopted should avoid bad surprises.

High Luminosity LHC

Once more…thanks a lot to all collaborators and collaborating institutes!

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Thank you for your attention

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