# Summary HE-LHC

**Andrei A. Seryi (JAI)**

**On behalf of the HE-LHC design team**

**FCC meeting in Berlin**

**29 May – 2 June 2017**

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# Plan

- Overview
- Baseline parameters
- Collider optics
- Interaction region optics
- Dynamic aperture
- Photon flux and e-cloud
- Conclusions and outlook

# Overview

physics goals:

- 2x LHC collision energy with FCC-hh magnet technology
- c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T
- target luminosity ≥ 4 x HL-LHC (cross section $\propto 1/E^2$;

B. Richter, 2014 https://arxiv.org/abs/1409.1196 ; T. Rizzo, 2015 https://arxiv.org/abs/1501.05583 )

key technologies:

- FCC-hh magnets & FCC-hh vacuum system
- HL-LHC crab cavities & electron lenses

beam:

- HL-LHC/LIU parameters (25 ns baseline, also 5 ns option)

Slide from Frank Zimmermann

# Baseline parameters

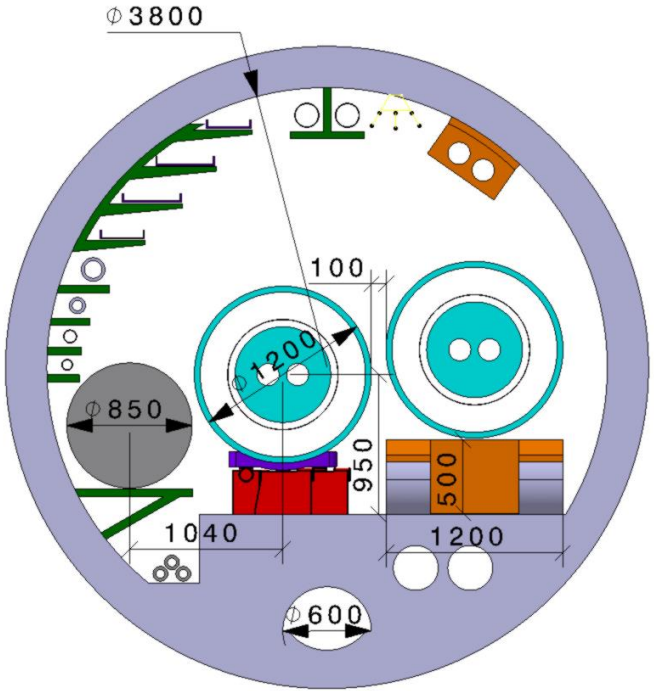
| parameter | FCC-hh | | HE-LHC | HL-LHC | LHC |
|---|---|---|---|---|---|
| collision energy cms [TeV] | **100** | | **27** | **14** | **14** |
| dipole field [T] | **16** | | **16** | **8.33** | **8.33** |
| circumference [km] | **97.75** | | **26.7** | **26.7** | **26.7** |
| beam current [A] | 0.5 | | 1.12 | 1.12 | 0.58 |
| bunch intensity [$10^{11}$] | **1** | **1 (0.2)** | **2.2 (0.44)** | **2.2** | **1.15** |
| bunch spacing [ns] | 25 | 25 (5) | 25 (5) | 25 | 25 |
| synchr. rad. power / ring [kW] | **2400** | | **101** | **7.3** | **3.6** |
| SR power / length [W/m/ap.] | 28.4 | | 4.6 | 0.33 | 0.17 |
| long. emit. damping time [h] | 0.54 | | 1.8 | 12.9 | 12.9 |
| beta* [m] | 1.1 | 0.3 | 0.25 | 0.20 | 0.55 |
| normalized emittance [$\mu$m] | 2.2 (0.4) | | 2.5 (0.5) | 2.5 | 3.75 |
| peak luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$] | 5 | 30 | 25 | 5 | 1 |
| events/bunch crossing | 170 | 1k (200) | ~800 (160) | 135 | 27 |
| stored energy/beam [GJ] | **8.4** | | **1.3** | **0.7** | **0.36** |

# HE-LHC integration

**Present working hypothesis for HE LHC design:**

**No major CE modification on machine tunnel and caverns**

- Similar geometry and layout as LHC machine and experiments
- Due to 16 T dipole field and increased cryogenic load, magnet cryostat and cryo distribution line (QRL) larger than for LHC.
- Challenges for tunnel integration and QRL & 16 T cryostat design.
- **Maximum magnet cryostat external diameter compatible with LHC tunnel: 1200 -1250 mm**
- **Classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!**




Slide from Michael Benedikt

# 16 T cryo-dipole approach

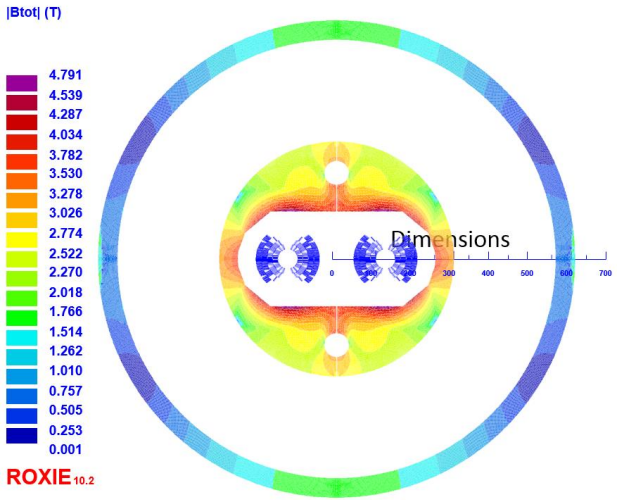
**Design strategy: develop a single 16 T magnet, compatible with both HE LHC and FCC-hh requirements:**

- Goal is reduction of external diameter to ~1200 mm
- Options und consideration:
  - Allow stray-field and/or cryostat as (partial) return-yoke
  - Active compensation with (simple) shielding coils
  - Optimization of inter-beam distance (compactness of coils)
  - *(QRL integrated in magnets, → negative impact on integral field because of longitudinal space required for service module (5%))*

**→ Smaller diam. also relevant for FCC-hh cost optimization**

**→ Design optimization for specific project after decision**

## Example magnetic cryostat coldmass 40t, total mass 62t




Only magnetic elements shown

Slide from Michael Benedikt

# HE-LHC session



## Thursday, 1 June, afternoon

| | | |
|---|---|---|
| **15:30-17:00** | **HE-LHC design, chair Andrei Seryi, Oxford U./JAI** | |
| | | |
| 15:30-15:45 | **Frank Zimmermann, CERN** | **HE-LHC Baseline Parameters** |
| 15:45-16:05 | **Yuri Nosochkov, SLAC** | **Optics Development for HE-LHC** |
| 16:05-16:25 | **Leon van Riesen-Haupt, JAI** | **HE-LHC Triplet** |
| 16:25-16:40 | **Demin Zhou, KEK** | **Nonlinear Analysis and Dynamic Aperture** |
| 16:40-17:00 | **Lotta Mether, EPFL** | **HE-LHC photon flux & electron cloud** |

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# Collider optics - criteria

## ❑ HE-LHC Requires stronger magnets

- Present LHC magnets → 8.33 T dipole, 223 T/m arc quadrupole, 4430 T/m$^2$ sextupole, 56 mm aperture
- For HE-LHC → FCC technology: 16 T dipole, 400 T/m quad, 7800 T/m$^2$ sextupole, 50 mm aperture
- Dipole field must increase with energy to fit the ring → ~16 T
- Scaling LHC optics to 13.5 TeV: arc quadrupoles would slightly exceed 400 T/m; sextupoles at 7800 T/m$^2$ may be limiting collision $\beta^*$ (M.P. Crouch)

➢ **Study lattices with reduced quadrupole and sextupole strengths**

## ❑ Field quality of dipoles for the HE-LHC energy range is not yet defined → assume pessimistic scenario with larger errors, particularly at injection energy → affects dynamic aperture, depends on injection energy (1.3 TeV proposed for HE-LHC)

➢ **Design lattice with reduced sensitivity to field errors**

Yuri Nosochkov, Demin Zhou

# Making ring optics – step 1

**Reduce arc FODO cell phase advance μ and / or increase cell length $L_c$**

| 90 deg → 60 deg | Longer cell $L_c$ |
|---|---|
| Weaker quads → factor of √2 (~sin(μ/2)) | Weaker quads ~$1/L_c$ |
| Weaker sextupoles → factor of 3 (for arcs correction) | Weaker sextupoles ~$1/L_c^3$ |
| Lower cell chromaticity → factor of √3 (~tan(μ/2)) | Same cell chromaticity |
| Similar peak β-functions | Larger peak β ~ $L_c$ |
| Larger dispersion → factor of 2 | Larger dispersion ~ $L_c^2$ |

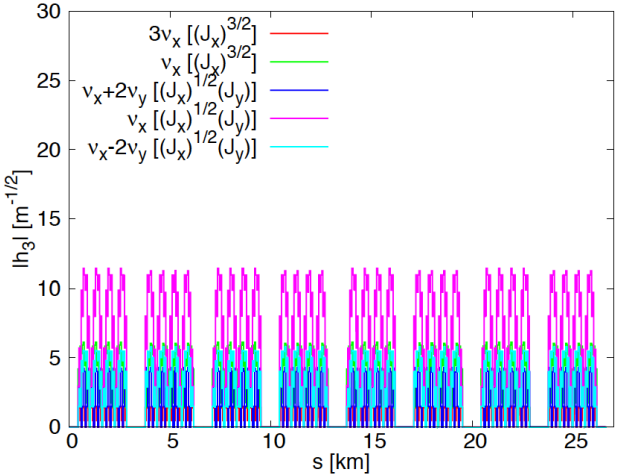
Yuri Nosochkov, Demin Zhou

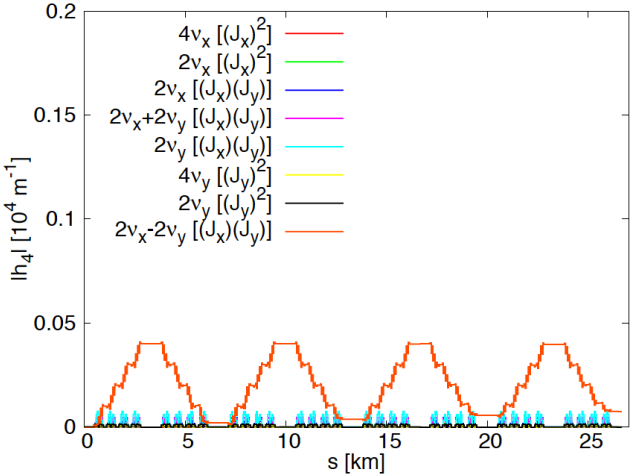
# Making ring optics – step 2

**Design arc lattice with reduced sensitivity to systematic non-linear field**

- Choose cell phase advance and number of cells $N_c$ per arc such that $N_c\mu_c = 2\pi k$
  - $\mu_c = 60$ deg → $N_c = 24, 18, \ldots$ ; $\mu_c = 90$ deg → $N_c = 24, 20, \ldots$
- Cancellation of many non-linear resonances from systematic non-linear field in periodic arc (*A. Verdier, PAC'99; Y. Cai, NIM, A645:168–174, 2011*)

➢ **Potential improvement of dynamic aperture**



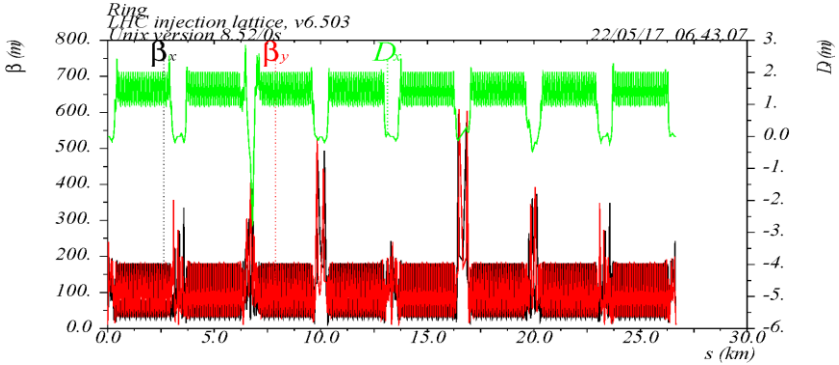




3rd and 4th order RDT from sextupoles in 60° arcs

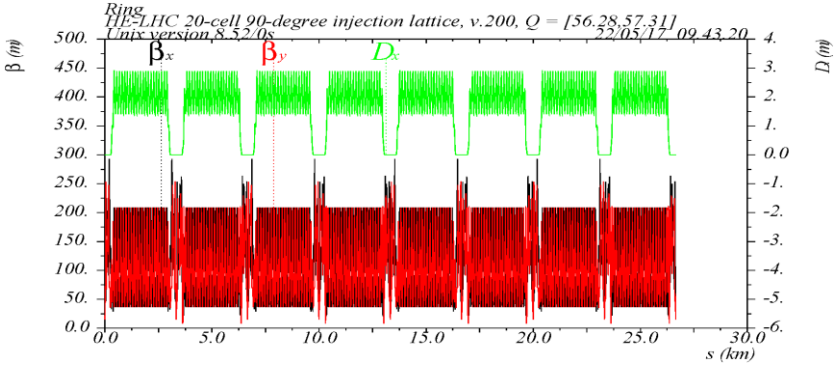
Yuri Nosochkov, Demin Zhou

# Optics: LHC & 3 models

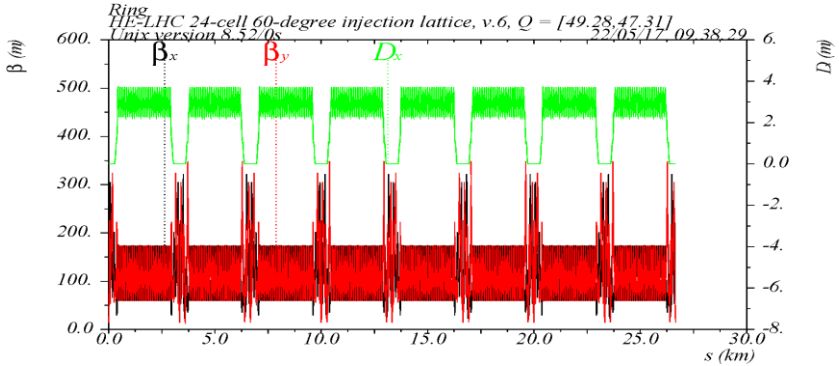
LHC V6.503, 23 x 90° arc, Q = 64.28, 59.31



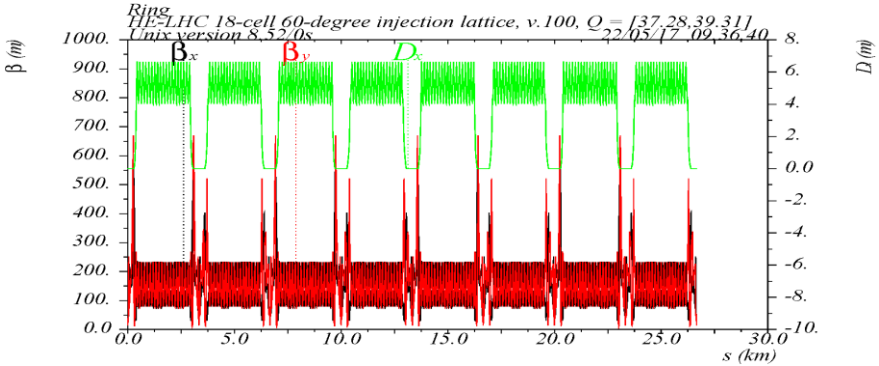

Model, 20 x 90° arc, Q = 56.28, 57.31




Model, 24 x 60° arc, Q = 49.28, 47.31




Model, 18 x 60° arc, Q = 37.28, 39.31



# Optics parameters

| | LHC V6.503 23 x 90 deg | Model 24 x 60 deg | Model 18 x 60 deg | Model 20 x 90 deg | SLHCV3.1a 24 x 60 deg |
|---|---|---|---|---|---|
| Cell length, m | 106.90 | 102.45 | 136.59 | 122.94 | 102.89 |
| Dipole length, m | 14.3 | 13.56 (1) | 14.1 (1) | 12.39 (1) | 13.56 |
| Number of dipoles | 1232 | 1280 | 1280 | 1424 (2) | 1280 |
| Dipole B, T | 16.06 | 16.30 (1) | 15.68 (1) | 16.04 (1) | 16.30 |
| Cell quad B′, T/m | 404.8 | 289.5 | 215.9 | 340.0 | 288.2 |
| Sextupole B′′, T/m$^2$ (3) | 4883 | 2057 | 1103 | 3366 | 1891 |
| Max/Min arc $\beta$, m | 184 / 29 | 177 / 60 | 236 / 79 | 209 / 36 | 178 / 60 |
| Max/Min arc $\eta$, m | 2.03 / 0.96 | 3.75 / 2.26 | 6.67 / 4.02 | 2.92 / 1.41 | 3.78 / 2.28 |
| Tune, x/y | 64.28 / 59.31 | 49.28 / 47.31 | 37.28 / 39.31 | 56.28 / 57.31 | 46.28 / 45.31 |
| Momentum compaction | 3.22 $10^{-4}$ | 6.41 $10^{-4}$ | 1.13 $10^{-3}$ | 4.57 $10^{-4}$ | 6.50 $10^{-4}$ |
| Natural chromaticity | -86 / -82 | -63 / -63 | -53 / -63 | -78 / -80 | -58 / -59 |

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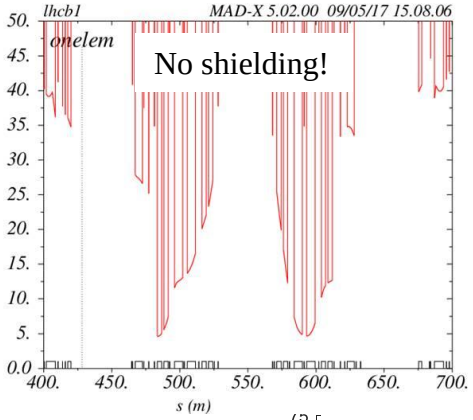
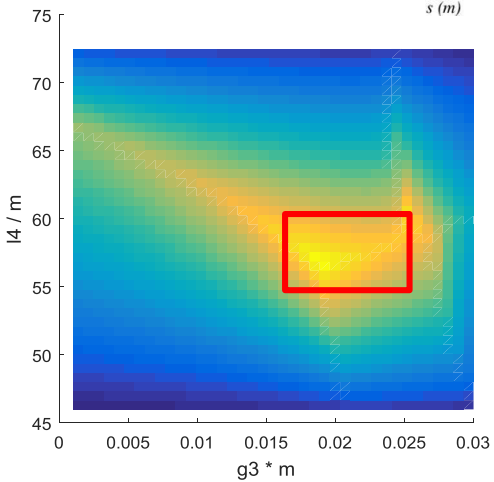
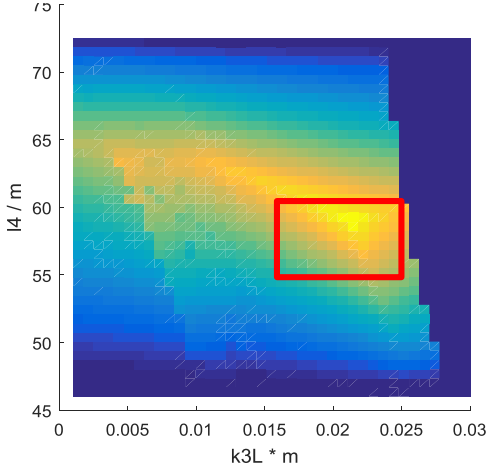
# Interaction region optics

- **High Luminosity LHC triplet would not have enough acceptance**
- **Ran first iteration of triplet optimization**
  - **Same tools as FCC**
  - **Triplet code to find optimum triplet**
  - **Initial 10 mm shielding**

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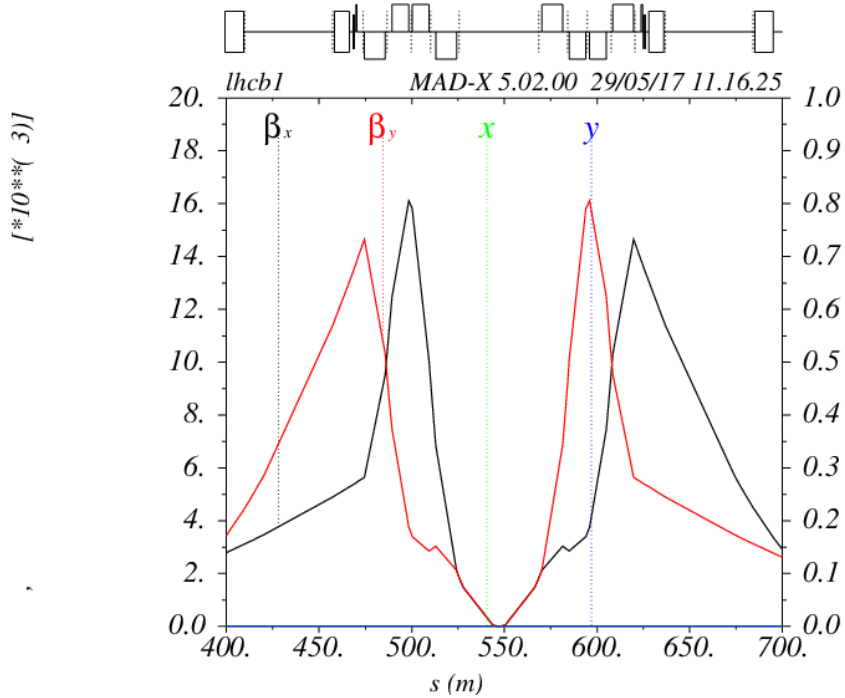
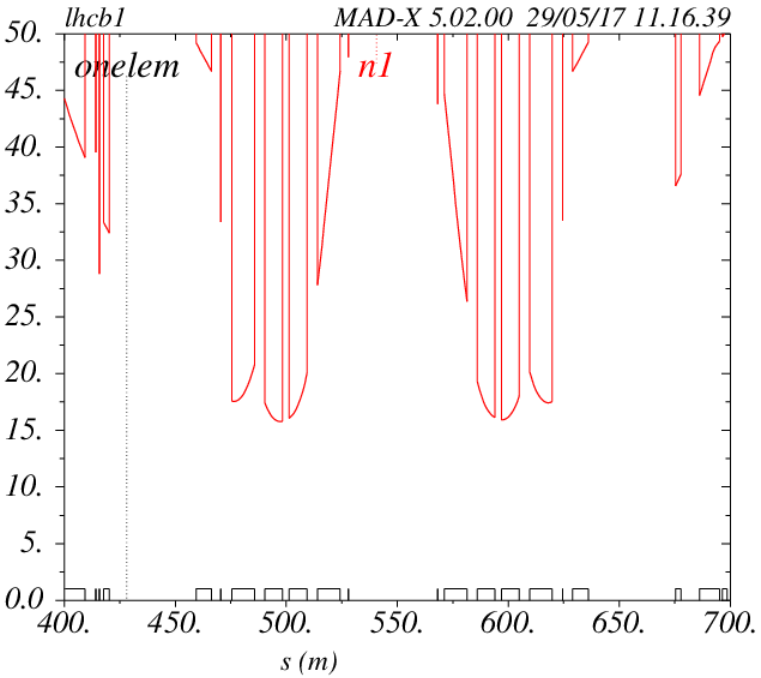
Jose Abelleira-Fernandez

# Interaction region optics

- **New HE-LHC triplet integrated into EIR optics**

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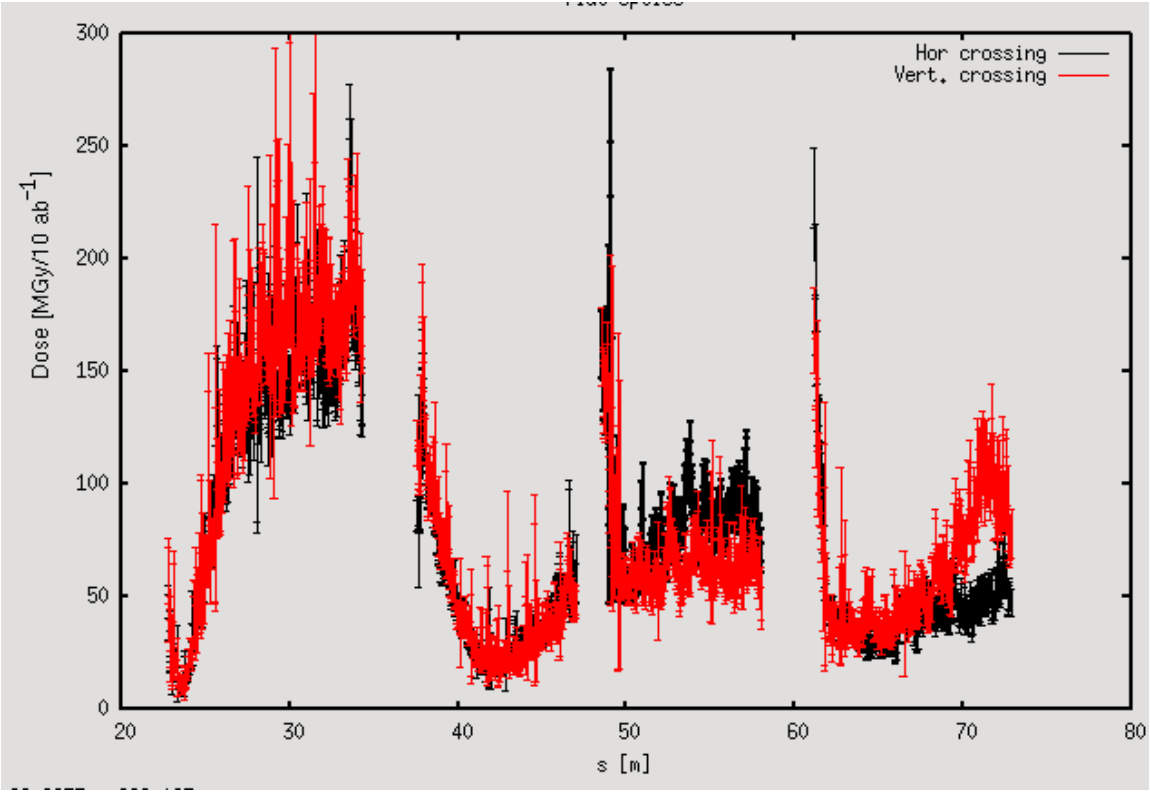
# Interaction region optics

- **Performed energy deposition studies**
  - **Dose too high**
  - **Further iterations of optimisation needed**
  - **Need more shielding**
  - **Further design iterations will be done**

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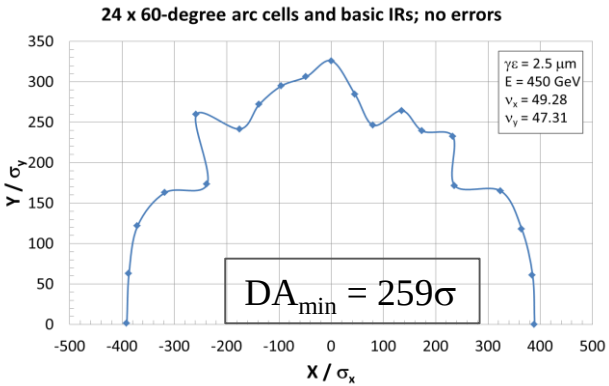
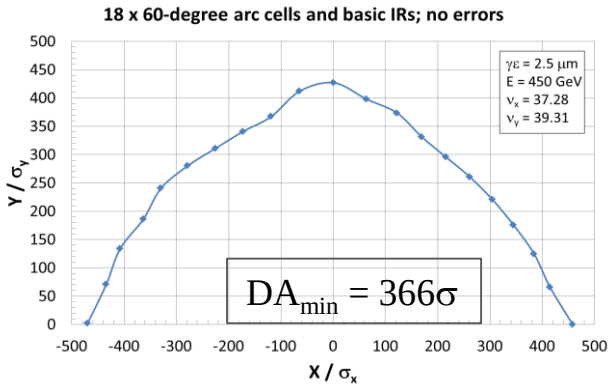
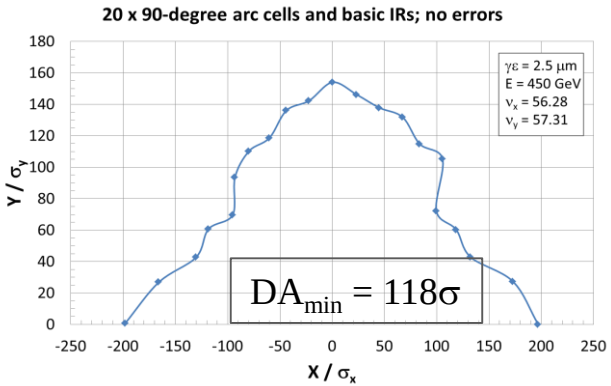
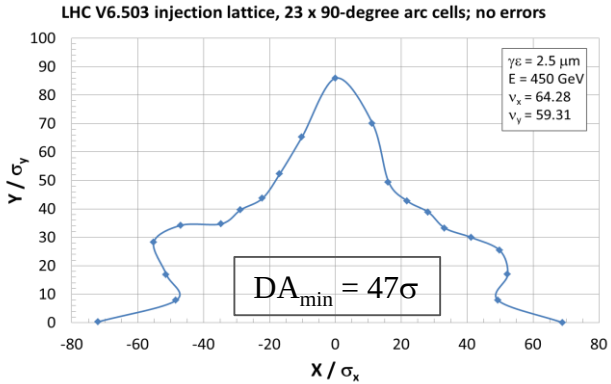
# DA w/o errors

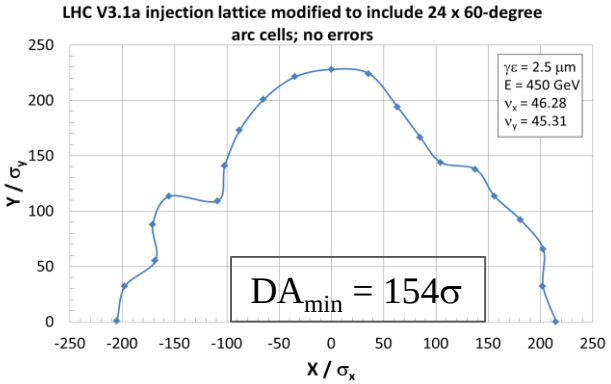



- **Huge DA of model lattices due to built-in arc non-linear compensation (cancellation of sextupole effects), but also due to 4-fold periodicity**
- **Larger DA of realistic SLHCV3.1a model compared to LHC V6.503, due to 60 deg arcs with weaker sextupoles**

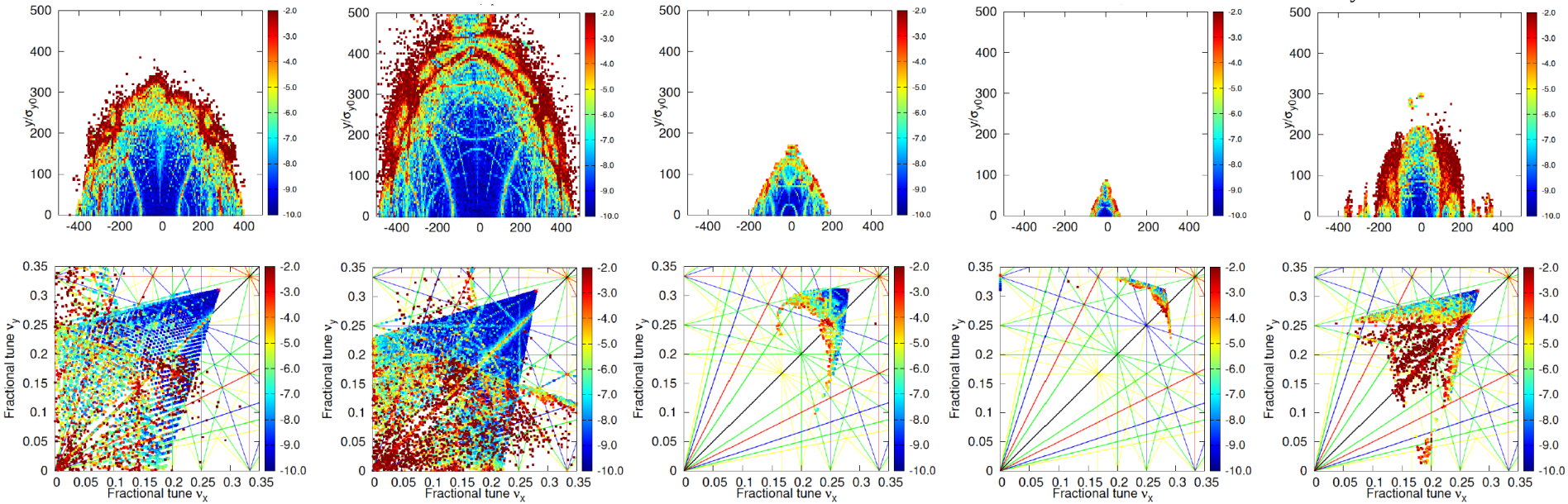


# Dynamic aperture

- **Short-term DA for injection lattice w/o errors**

24x 60-deg+Basic IRs | 18x 60-deg+Basic IRs | 20x 90-deg+Basic IRs | LHC injection optics V6.503 | 24x 60-deg arcs & IRs of SLHCV3.1a By T. Risselada

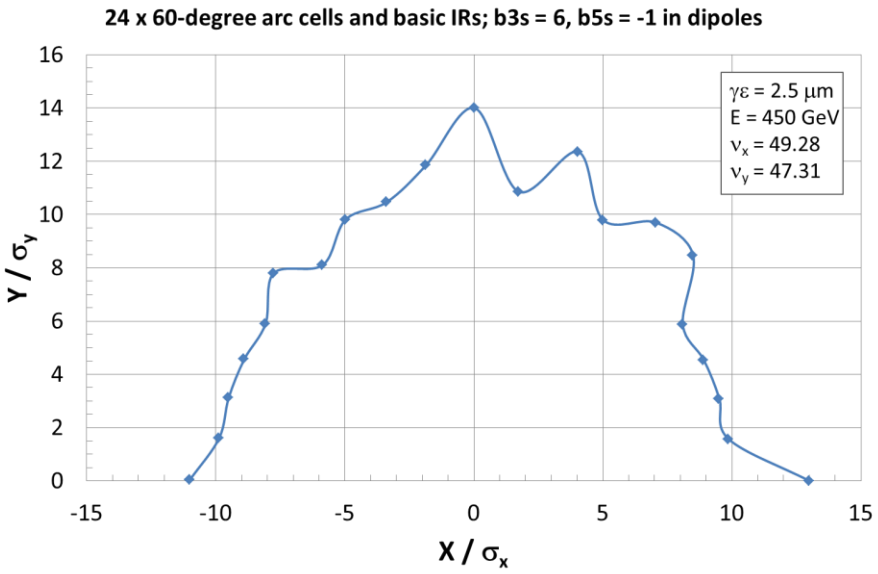



Demin Zhou, Yuri Nosochkov

# Dynamic aperture

- **DA for injection lattice with errors – started studies**

Example:
DA for b3s = +6 and b5s = -1 in dipoles




- **Promising results**
- **Systematic studies of DA with errors – to be continued**

Yuri Nosochkov

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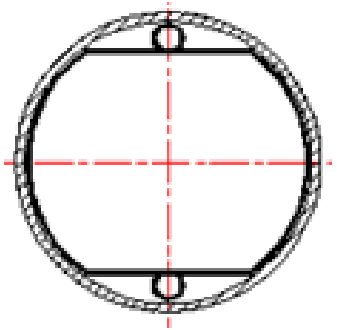
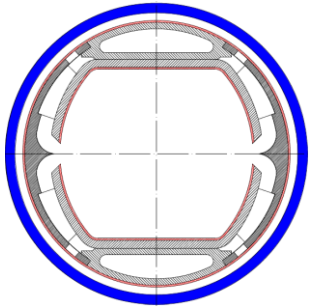
# Photon flux & e-cloud

## Beam screen options for HE-LHC



Scaled LHC beam screen

- Pumping slots in main chamber
- Saw-tooth structure at impact of synchrotron radiation fan



FCC beam screen

- Shielded pumping slots
- Minimized photon absorption in main chamber

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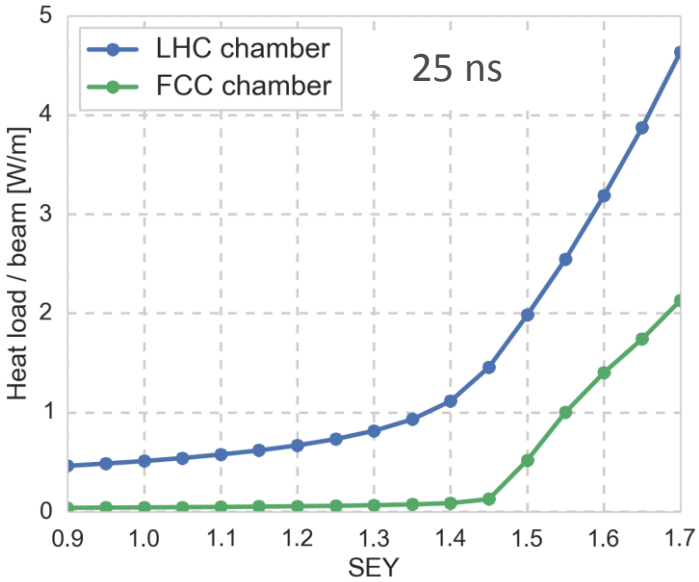
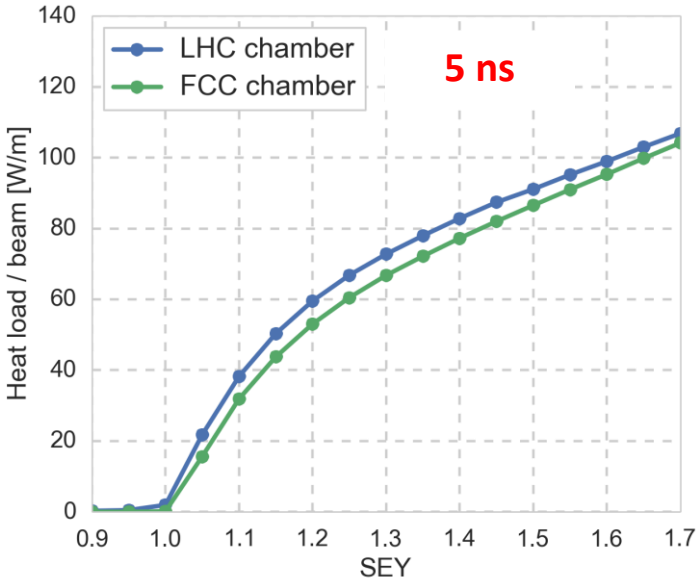
# Photon flux & e-cloud

**Heat load of SR ~ 4.6 W/m/beam**




Multipacting threshold around SEY ~ 1.45
Higher heat load for scaled LHC chamber
(more photoelectrons)

Multipacting threshold around SEY ~ 1
Similar heat load for both chambers
Very high heat load

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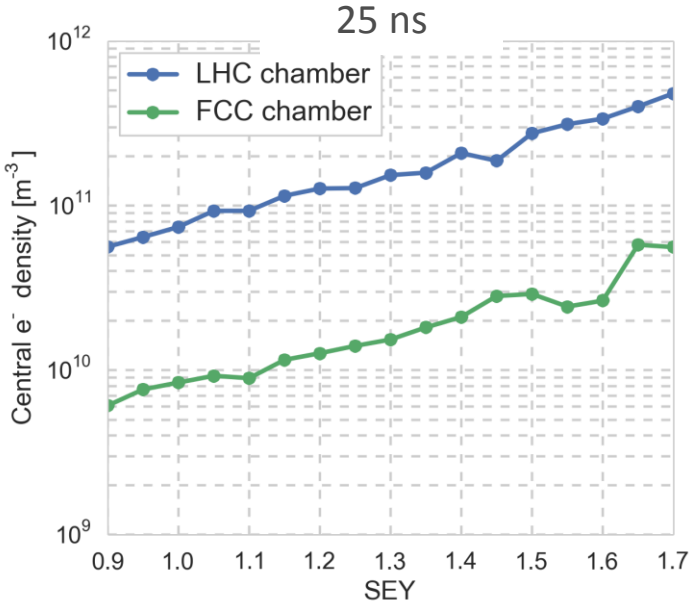
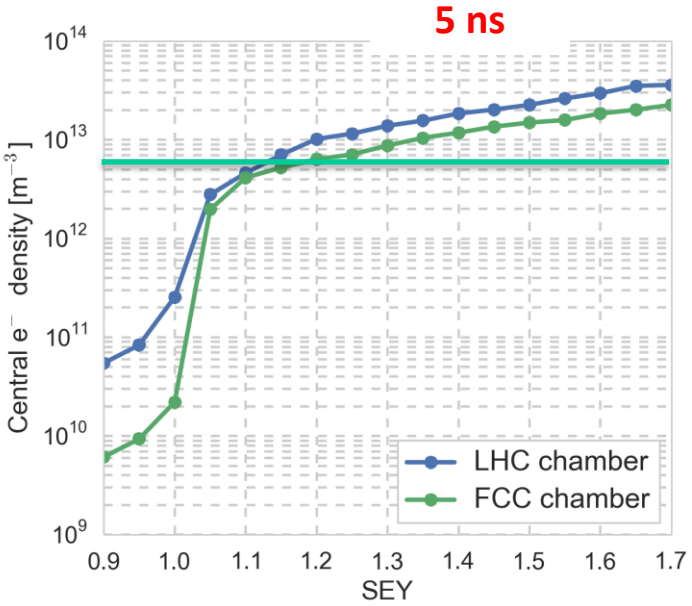
# Photon flux & e-cloud

## Threshold electron density for single bunch instability

- Central density below threshold for 25 ns beam
- For 5 ns density below threshold for SEY < 1.1

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# Conclusions

- **HE-LHC ring optics**
  - Developed models that fit to FCC magnet technology
  - Due to selected design approach dynamic aperture considerably increased
- **Experimental Interaction Region**
  - First optics created and integrated
- **Electron cloud studies performed**
  - 5 ns case require attention

- **Great progress, a lot of studies to be done further**