FCC-ee Dynamic Aperture @ 175 GeV

Luis MEDINA

UNIVERSIDAD DE GUANAJUATO
División de Ciencias e Ingenierías
Mexico

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Thanks to A. Bogomyagkov, K. Oide, P. Piminov, and F. Zimmermann

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1 Introduction

2 Dynamic Aperture Results
   4D DA Comparison
   A. Bogomyagkov’s FCC-ee V9-PS2 lattice
   K. Oide’s FCC-ee V74-11 lattice

3 Conclusions
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3 Conclusions
• **Review** of DA results.
• Two FCC-ee crab-waist (175 GeV) lattices with asymmetric IRs under study [1].

**AB**
FCC-ee V9-PS2, 26 mrad, developed by A. Bogomyagkov and optimized by P. Piminov [4].

**KO**
FCC-ee and V74-11, 30 mrad (asymmetric $L^*$), developed by K. Oide [5].
IR optics

Left side

AB

Right side

KO

Conclusions
Parameters and Simulations

- Dynamic Aperture (DA): Limit on the **amplitude** of oscillations beyond which motion is unstable. It is usually found by particle tracking.

Studies to be presented:
- **4D DA** by tracking with **PTC** on AB V9-PS2-1 and KO V74-11.
- Observation @ IP.
- **6D DA** for the latest lattices, taking into account several **effects**:
  - RF, damping by SR, tapering, crab waist...

<table>
<thead>
<tr>
<th>Energy</th>
<th>$\beta_x^*$</th>
<th>$\beta_y^*$</th>
<th>$\epsilon_y / \epsilon_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>175 GeV</td>
<td>50 cm</td>
<td>1 mm</td>
<td>0.2 %</td>
</tr>
</tbody>
</table>
One year ago...

Since then...
Adjustments to fulfill geometric constrains, reduction of SR in the IR, optimization of momentum acceptance and DA, etc.
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**4D DA Comparison**

**AB FCC-ee V9-PS2-1**

\[ \Delta p/p = -1.8\% \]

**KO FCC-ee V74-11**

Minimum DA

<table>
<thead>
<tr>
<th>30.0</th>
<th>25.0</th>
<th>20.0</th>
<th>15.0</th>
<th>10.0</th>
<th>5.0</th>
<th>0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.0</td>
<td>-1.5</td>
<td>-1.0</td>
<td>-0.5</td>
<td>0.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

FCC-ee Dynamic Aperture @ 175 GeV

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Introduction

Dynamic Aperture Results

4D DA Comparison

AB’s FCC-ee lattice

KO’s FCC-ee lattice

Conclusions
Dynamic Aperture Results

4D DA Comparison

AB's FCC-ee lattice
KO's FCC-ee lattice

Conclusions
4D DA Comparison

**AB** FCC-ee V9-PS2-1

\[ \Delta p/p = -1.2\% \]

**KO** FCC-ee V74-11

Minimum DA
4D DA Comparison

**AB** FCC-ee V9-PS2-1

\[ \Delta \frac{p}{p} = -0.9\% \]

**KO** FCC-ee V74-11

\[ \Delta \frac{p}{p} = -0.9\% \]
4D DA Comparison

**AB FCC-ee V9-PS2-1**

\[ \Delta \rho / \rho = -0.6\% \]

**KO FCC-ee V74-11**

Minimum DA

\[ \text{Minimum DA} \]
4D DA Comparison

AB FCC-ee V9-PS2-1

\[ \Delta p/p = -0.3\% \]

KO FCC-ee V74-11

Minimum DA
4D DA Comparison

**AB FCC-ee V9-PS2-1**

- $\Delta p/p = 0.0\%$

**KO FCC-ee V74-11**

- $\Delta p/p = 0.0\%$

Minimum DA

- FCCee-AB-V9-PS2-1 ($\sigma_x = 2.64\times10^{-5}\text{ m}$, $\sigma_y = 5.28\times10^{-8}\text{ m}$, $\sigma_y/\sigma_x = 0.2\%$)
- FCCee-KO-V74-11 ($\sigma_x = 2.59\times10^{-5}\text{ m}$, $\sigma_y = 5.18\times10^{-8}\text{ m}$, $\sigma_y/\sigma_x = 0.2\%$)
4D DA Comparison

**AB FCC-ee V9-PS2-1**

\[ \Delta p/p = +0.3\% \]

**KO FCC-ee V74-11**

Minimum DA
4D DA Comparison

**AB FCC-ee V9-PS2-1**

\[ \Delta p/p = +0.6\% \]

**KO FCC-ee V74-11**

Minimum DA
4D DA Comparison

**AB FCC-ee V9-PS2-1**

Δp/p = +0.9%

**KO FCC-ee V74-11**

Minimum DA

![Graphs showing dynamic aperture comparison between AB and KO FCC-ee lattices.](image)
4D DA Comparison

**AB FCC-ee V9-PS2-1**

Δp/p = +1.2%

**KO FCC-ee V74-11**

Minimum DA

<table>
<thead>
<tr>
<th>Δp/p [%]</th>
<th>Minimum DA [σ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>2.64e-05 m</td>
</tr>
<tr>
<td>5.0</td>
<td>5.28e-08 m</td>
</tr>
<tr>
<td>10.0</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

FCCee-AB-V9-PS2-1 (σx = 2.64e-05 m, σy = 5.28e-08 m, σy/σx = 0.2%)

FCCee-KO-V74-11 (σx = 2.59e-05 m, σy = 5.18e-08 m, σy/σx = 0.2%)
4D DA Comparison

**AB FCC-ee V9-PS2-1**

\[ \Delta \rho/\rho = +1.5\% \]

**KO FCC-ee V74-11**

Minimum DA
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**AB: 4D DA revisited**

**Crab off**, 50 turns, $\epsilon_x = 1.4\,\text{nm} \cdot \text{rad}$, 

$\nu_{x,y,s} = 395.10, 297.16, 0.0807$, $\tau_x = 44$ turns, 

$U_0 = 7.97\,\text{GeV}$, $U_{rf} = 11\,\text{GV}$. 
Nonlinear chromaticity from tracking with 1024 turns. Small betatron amplitudes. Initial transverse coordinates are changed according to product of energy deviation and nonlinear dispersion. RF is off.
Betatron tunes dependence on energy deviation obtained from tracking with 1024 turns. Initial transverse coordinates are zero, but betatron amplitudes depend on growing energy deviation. RF is on.
AB: No damping nor tapering

Crab off, 50 turns, $\epsilon_x = 1.4 \text{ nm} \cdot \text{rad}$,

$\nu_{x,y,s} = 395.10, 297.16, 0.0807$, $\tau_x = 44$ turns,

$U_0 = 7.97 \text{ GeV}$, $U_{rf} = 11 \text{ GV}$. 
AB: No damping nor tapering

\[ \nu_{x,y,s} = 395.10, 297.16, 0.0807, \tau_x = 44 \text{ turns}, \]
\[ U_0 = 7.97 \text{ GeV}, \quad U_{rf} = 11 \text{ GV}. \]
Crab off, 50 turns, $\epsilon_x = 1.4$ nm $\cdot$ rad, RF on, $\nu_x, y, s = 395.10, 297.16, 0.0807$, $\tau_x = 44$ turns, $U_0 = 7.97$ GeV, $U_{rf} = 11$ GV.
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KO: Effect of RF and radiation

RF off, radiation off

Crab on, 50 turns, $\epsilon_x = 1.34 \text{ nm} \cdot \text{rad}$, $\sigma_E = 0.144 \%$, $\sigma_z = 2.4 \text{ mm}$, $\nu_{x,y,z} = 387.0800, 387.1400, -0.0686$. $U_0 = 7.74 \text{ GeV}$. 
KO: Effect of RF and radiation

**RF on, radiation off**

Crab on, 50 turns, $\epsilon_x = 1.34$ nm $\cdot$ rad, $\sigma_E = 0.144\%$, $\sigma_z = 2.4$ mm, 
$v_x, y, z = 387.0800, 387.1400, -0.0686$. $U_0 = 7.74$ GeV.
KO: Effect of RF and radiation

RF on, radiation on (damping each turn)

Crab on, 50 turns, $\epsilon_x = 1.34 \text{ nm} \cdot \text{rad}$, $\sigma_E = 0.144 \%$, $\sigma_z = 2.4 \text{ mm}$, $\nu_x, y, z = 387.0800, 387.1400, -0.0686$. $U_0 = 7.74 \text{ GeV}$. 
KO: Effect of RF and radiation

RF on, radiation on (each element)

Crab on, 50 turns, $\epsilon_x = 1.34 \text{ nm} \cdot \text{rad}$, $\sigma_E = 0.144 \%$, $\sigma_z = 2.4 \text{ mm}$, $\nu_{x,y,z} = 387.0800, 387.1400, -0.0686$. $U_0 = 7.74 \text{ GeV}$. 
KO: Effect of larger $\beta_{x,y}^*$

$\beta_{x,y}^* = 0.5 \text{ m, } 1 \text{ mm}$

Horizontal plane:

Crab on, 50 turns, $\epsilon_x = 1.34 \text{ nm \cdot rad}$, $\sigma_E = 0.144 \%$, $\sigma_z = 2.4 \text{ mm}$, $\nu_{x,y,z} = 387.0800, 387.1400, -0.0686$. $U_0 = 7.74 \text{ GeV}$. 
KO: Effect of larger $\beta^*_{x,y}$

$\beta^*_{x,y} = 1.0 \text{ m, } 2 \text{ mm}$

Horizontal plane:

Crab on, 50 turns, $\epsilon_x = 1.34 \text{ nm} \cdot \text{rad}$, $\sigma_E = 0.144 \%$, $\sigma_z = 2.4 \text{ mm}$, $\nu_{x,y,z} = 387.0800, 387.1400, -0.0686$. $U_0 = 7.74 \text{ GeV}$. 
KO: Effect of larger $\beta_{x,y}^*$

$\beta_{x,y}^* = 0.5 \text{ m, 1 mm}$

Vertical plane:

Crab on, 50 turns, $\epsilon_x = 1.34 \text{ nm} \cdot \text{rad}$, $\sigma_E = 0.144 \%$, $\sigma_z = 2.4 \text{ mm}$, $\nu_{x,y,z} = 387.0800, 387.1400, -0.0686$. $U_0 = 7.74 \text{ GeV}$. 
KO: Effect of larger $\beta_{x,y}^*$

$\beta_{x,y}^* = 1.0 \text{ m, 2 mm}$

Vertical plane:

Crab on, 50 turns, $\epsilon_x = 1.34 \text{ nm} \cdot \text{rad}$, $\sigma_E = 0.144 \%$, $\sigma_z = 2.4 \text{ mm}$, $\nu_{x,y,z} = 387.0800, 387.1400, -0.0686$. $U_0 = 7.74 \text{ GeV}$. 

K. Oide
Summary: **KO FCCee-V74-11**

**Effect of RF and radiation**

- **RF off, radiation off**
- **RF on, radiation off**
- **RF on, radiation on (damping each turn)**
- **RF on, radiation on (each element)**

**Crab on**, 50 turns, $\epsilon_x = 1.34 \text{ nm} \cdot \text{rad}$,
\[ \nu_{x,y,z} = 387.0800, 387.1400, -0.0686. \]
\[ \sigma_E = 0.144 \%, \sigma_z = 2.4 \text{ mm}, U_0 = 7.74 \text{ GeV}. \]
Summary: KO FCCee-V74-11

Effect of larger $\beta^{*}_{x,y}$

$\beta^{*}_{x,y} = 0.5 \text{ m, } 1 \text{ mm}$

$\beta^{*}_{x,y} = 1.0 \text{ m, } 2 \text{ mm}$

Crab on, 50 turns, $\epsilon_{x} = 1.34 \text{ nm} \cdot \text{ rad}$,
$\nu_{x,y,z} = 387.0800, 387.1400, -0.0686$.
$\sigma_{E} = 0.144 \text{ %}, \sigma_{z} = 2.4 \text{ mm}, U_{0} = 7.74 \text{ GeV}$.

The reduction of the vertical aperture for $\beta^{*}_{y} = 1 \text{ mm}$ is due to synchrotron radiation in the final quadrupoles.
## Effects included in KO studies

<table>
<thead>
<tr>
<th>Effects</th>
<th>Included?</th>
<th>Significance for DA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchrotron motion</td>
<td>✓</td>
<td>Essential</td>
</tr>
<tr>
<td>Radiation damping (turn-by-turn)</td>
<td>✓</td>
<td>Essential, increases DA</td>
</tr>
<tr>
<td>Radiation damping (each element)*</td>
<td>✓</td>
<td>Essential, decreases DA</td>
</tr>
<tr>
<td>Tapering</td>
<td>✓</td>
<td>Essential</td>
</tr>
<tr>
<td>Crab-waist</td>
<td>✓</td>
<td>Essential, decreases DA,</td>
</tr>
<tr>
<td>Solenoids</td>
<td>✓</td>
<td>Minimal, if locally compensated</td>
</tr>
<tr>
<td>Maxwellian fringe fields</td>
<td>✓</td>
<td>Small</td>
</tr>
<tr>
<td>Kinetic terms</td>
<td>✓</td>
<td>Small</td>
</tr>
<tr>
<td>Errors / misalignments</td>
<td>✗</td>
<td>Essential, correction schemes must be developed</td>
</tr>
</tbody>
</table>

* No fluctuations yet.

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Effects Included? Significance for DA

- **Synchrotron motion**: ✓ Essential
- **Radiation damping (turn-by-turn)**: ✓ Essential, increases DA
- **Radiation damping (each element)**: ✓ Essential, decreases DA
- **Tapering**: ✓ Essential
- **Crab-waist**: ✓ Essential, decreases DA,
- **Solenoids**: ✓ Minimal, if locally compensated
- **Maxwellian fringe fields**: ✓ Small
- **Kinetic terms**: ✓ Small
- **Errors / misalignments**: ✗ Essential, correction schemes must be developed

* K. Oide

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**Dynamic Aperture Results**

AB's FCC-ee lattice

KO's FCC-ee lattice

**Conclusions**
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- Significant **progress** has been done in both AB and KO optics.
- Lattice optimizations have lead to increased DAs.
- Several **effects** have been simulated, and their impact on the 6D DA has been observed.
- Minimum DA (on-momentum): $20\sigma$ for AB, and $28\sigma$ for KO.
- DA almost **satisfy** the requirement of $15\sigma / 5\sigma$ for on-energy / 2% off-energy. [6].

Outlook

- Continue with **optimization**...
- **Statistical** approach for DA with **radiation**.
- Estimation of DA with **errors** and **misalignments**.
References


