

FCC Arc Alignment Requirements

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FCC IS Workshop
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FCC-ee Arc Alignment Challenges

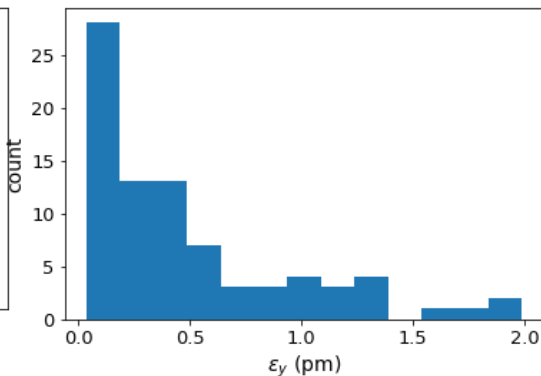
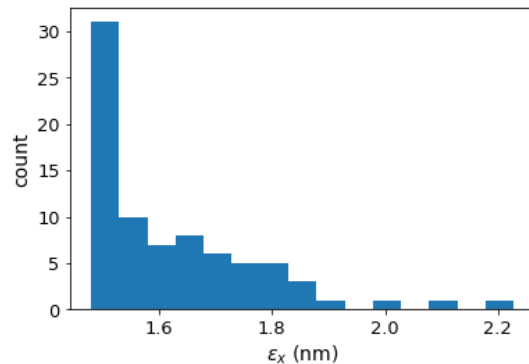
- **Outline**

- Challenges
- Ground motion models
- Beam-Based Alignment approaches
- Movers versus correctors
- Diagnostic requirements

FCC-ee Arc Tuning and Correction

- **Extensive studies on emittance tuning and dynamic aperture**
 - Emittance tuning looks good given a ‘reasonable’ set of errors
 - Working to develop beam-based alignment models to combine with mechanical alignment specifications
 - Sets requirements on diagnostics but eases installation and stability requirements

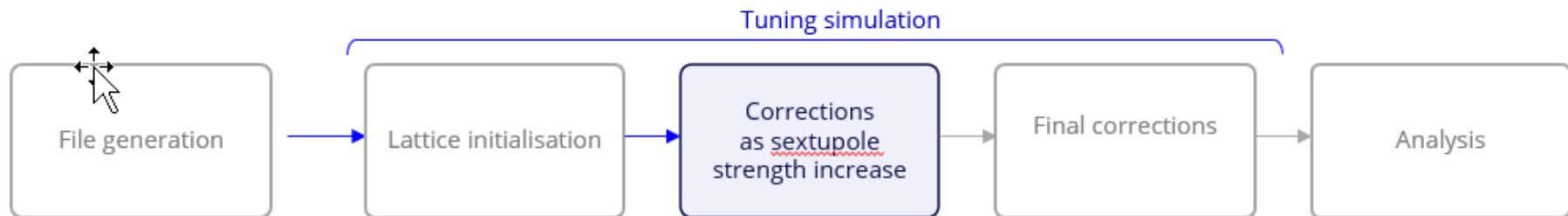
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔDPHI (μrad)	Field Errors
Arc quadrupole*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	1000	1000	300	1000	0	0	$\Delta B/B = 1 \times 10^{-4}$
Girders	150	150	-	1000	-	-	-
IR quadrupole	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	100	100	250	250	100	100	$\Delta k/k = 2 \times 10^{-4}$



T. Charles

FCC-ee Arc Tuning Approach

- Sensitivities mainly due to sextupoles require iterative approach which does not always converge



Sextupoles set to 10% of their design strength

- Orbit correction
- Combined coupling and dispersion correction (Python)
- Beta-beating correction applied (Python)
- Sextupole strengths increased by 10%

} Iterated over many times.

Constant checking of the tunes and orbit avoids running into resonances, or failure to find the closed orbit.

T. Charles

FCC-ee Dynamic Aperture Tol. (May 2022)

- The baseline values for misalignments (sigma): D. Shatilov, FCC-ee Tuning Workshop, May 2022
 - Quads, DX and DY: 50 microns
 - Sextupoles, DX and DY: 50 microns
 - Dipoles, DX and DY: 1000 microns
- The previous examples have shown that dynamic aperture and momentum acceptance drop off significantly at these misalignments.
- To continue beam-beam simulations, we reduced the misalignments to the following values:
 - Quads, DX and DY: 11.5 microns
 - Sextupoles, DX and DY: 13.6 microns
 - Dipoles, DX and DY: 76.7 microns
- So far, such examples have been made only for high energy (\sqrt{s}), the last version of the lattice. The corrections were made by Tessa, then I converted all the MADX data to my format and continued modeling with Lifetrac.

FCC-ee Tolerance Length Scales

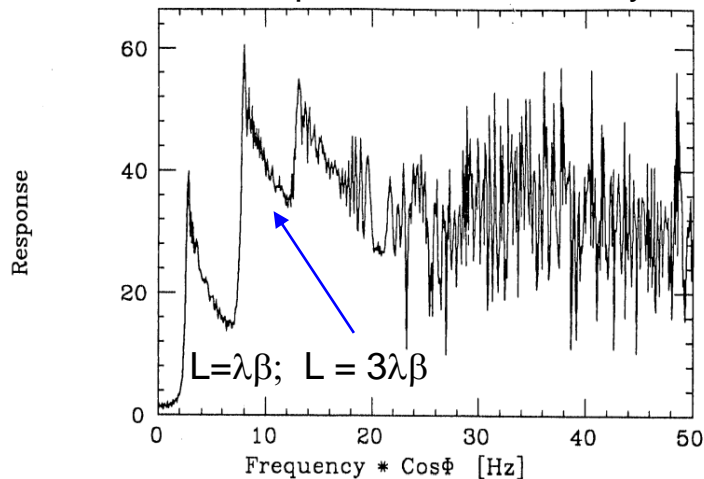
- The length scale for the tolerances are set by the betatron wavelength

- Long wavelength misalignments have minimal effect

$$\begin{aligned} \Delta y^* &= \sum_n \sqrt{\beta^* \beta_q} \exp(-nT_0/\tau_y + i\omega_q nT_0) \sin(\phi_q + n\mu_y) k_q \Delta y_q && \text{K. Oide} \\ &= \sum_n \sqrt{\beta^* \beta_q} \exp(-n\alpha_y + in\mu_q) \sin(\phi_q + n\mu_y) k_q \Delta y_q, && (1) \end{aligned}$$

- If static $\rightarrow n=0$ and resonant at betatron wavelength or harmonics
- FCC-ee betatron wavelength is 400-m at Z & W operation

Example from a linac study

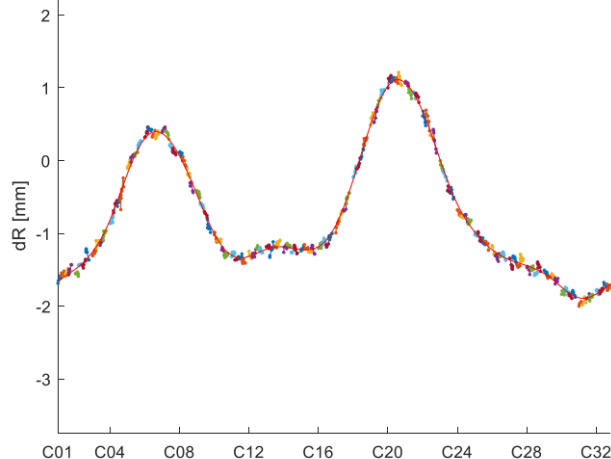


Alignment Length scales – Example from ESRF

- **ESRF achieved excellent performance**
 - Long wavelength misalignments have minimal effect

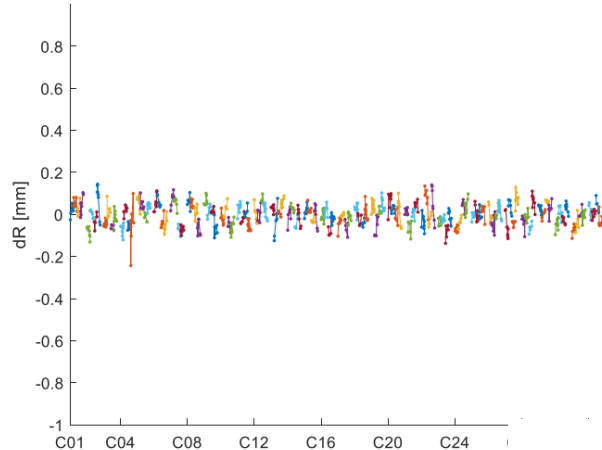
NOVEMBER 2019 – AFTER FINAL ALIG

dR magnet center errors with respect to EBS nominal values



NOVEMBER 2019 – AFTER FINAL ALIG

dR magnet center residuals with respect to a smooth curve



ESRF upgrade
Circ ~ 850 meters
X tunes ~ 70

D. Martin on behalf of the
ESRF Survey and Alignment Group

Mechanical Alignment Challenges

- **Alignment of 100 μm over 100-m or 1 cm over 10 km is SOA**
 - Scales with length (although at short distances limited by fiducialization).

Alignment tolerances: LHC

- All components pre-aligned w.r.t. geodetic network to achieve a relative accuracy of 0.2 mm at 1σ , at the level of the fiducials (not integrating the fiducialisation)
- Smoothing: deviation w.r.t a smooth line: 0.20 mm at 1σ in a 150 m long sliding window (main components)



5 December 2022

H. Mainaud Durand | FCC-ee tuning & alignment mini-workshop


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- Field alignment tolerances (20m):
 - Local alignment relative to the network 100 μm
- Network
 - Mid range (200m) 0.3mm
 - Long range (1km) 2-3mm

G. Gassner, SLAC Alignment Network,
FCC-ee Tuning and Alignment Workshop
May, 2022

Long-term Stability

- **Even if you get it, can you keep it?**

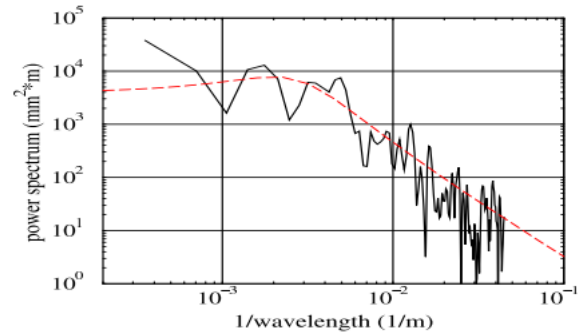
-  Accumulation of alignment errors along the tunnel may be inevitable.
 - Even water levels or GPS cannot detect such kind of large scale errors.
 - Similar misalignments have been reported by S. Liuzzo in this workshop, in the ESRF accelerator hall.
- Here we assume $\langle \Delta y^2 \rangle = a \Delta s$, where Δs is the difference of s between two components.
 - Let us use a number $a = 10^{-10}$ m, or $\langle \Delta y^2 \rangle = (100 \mu\text{m})^2 / (100 \text{ m})$.
 - This has a similarity with the ATL Law (V. Shiltsev, *Phys.Rev.Lett.* 104 (2010) 238501).
 - LEP: $A = (3 \pm 0.6) \times 10^{-18}$ m/s . The a above corresponds to about 1 year change at LEP.

K. Oide

Stability: long-term, mid-term, high frequency

- Incoherent, Diffusion, & Waves**

- V. Shiltsev proposed ATL-law
- During linear collider program we spent years (not hours) arguing about details
- Many measurements of wave coherence, slow motion, etc
- Many models but ATL is pretty good for long-term motion



A. Seryi & T. Raub... 2000

Figure 4: Spatial power spectrum of vertical displacements of the SLAC tunnel for 1966 to 1983.

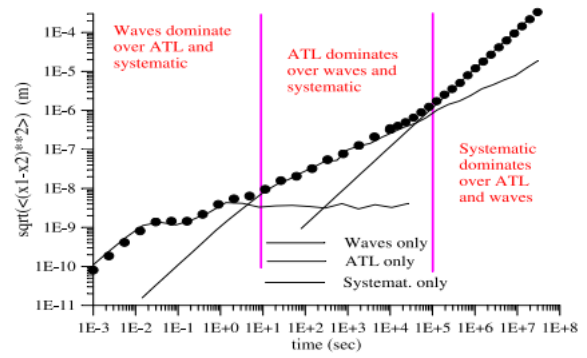


Figure 5: Rms relative motion versus time for $L = 30$ m for the 2 a.m. SLAC site ground motion model.

Arc Beam-Based Alignment

- **Two challenges: absolute alignment and long-term stability**
 - Large separation between magnets makes mechanical alignment more challenging. 100 μm over 100 meters is SOA
 - Mechanical alignment over 90 km will be time consuming
- **Use BBA to relax mechanical requirements**
 - Transfer mechanical alignment challenge into a beam diagnostic challenge and sets requirements on diagnostic resolution, magnetic center variation and temperature stability
- **Many approaches dating back to 1980's including quadrupole dithering, dispersion-free steering, LOCO, FICO, RCDS, PBBA, ...**
 - Need also to determine timescales and how to establish alignment, e.g. trims, movers, or correctors. Track changes \rightarrow Hourly? Daily? Monthly?

Beam-Based Alignment Concept – Quadrupoles

- **Quadrupole Arc BBA techniques can have very high resolution**
 - LOCO can be used with high precision diagnostics but not clear how errors scale with problem size and fluctuations may prevent convergence
 - Quad dithering \rightarrow 10 μm with 1 μm BPM resolution at low current beam
 - \rightarrow Requires quadrupole center does not vary with excitation \leftarrow
 - LEP achieved quadrupole alignment about 4x BPM resolution while about 5x BPM resolution was measured in SPEAR
 - Roughly 6000 arc quads and sextupoles, dithering 10 to 20 per arc paired to cancel tune and beta beating \rightarrow hour per cycle
 - Dipole correctors correcting for 100 μm errors will require $<10^{-4}$ trim PS stability to limit $\Delta Y/\sigma_y < 10\%$

Beam-Based Alignment Concept – Sextupoles

- **Sextupole Arc BBA has had poorer accuracy but may be possible with higher current stored beam**
 - Sextupole correction has been studied looking at tune shifts (horizontal position), phase shifts, and orbit shifts
 - Resolution in past studies is typically 5~10x worse than quadrupole alignment but it should be possible to get 10 μm effective alignment with stored beam
 - Also might be possible to use quadrupole trim winding on sextupoles to get linear orbit response as was done at ATF and KEKB if magnetic centers stable
- Need to understand how to reference quadrupole to sextupole to BPM
- If BBA is repeated often enough \rightarrow no need for external tracking but

Trim Windings

- **Trim windings can be used to correct for mechanical misalignments**
 - X/Y Dipole correctors on quads plus Quad and Skew quad windings on sextupoles for effective alignment
 - FCC-ee effectively has independent sextupole PS (need to verify whether strings are necessary) but quadrupoles are on strings
 - Also need Quadrupole trims on quads for tapering (and BBA)
 - Skew quadrupole trims needed on sextupoles correct for quadrupole rolls
→ can these also be used for quadrupole excitation?
- **Depending on required strength, (dipole) trim PS may require high stability**

Proposed Alignment and Ground Motion model I

- **Develop a model that is easy to implement in MAD-X**
 - Mechanical misalignments as a function of length scale
 - Slow ATL-type motion combined with waves and incoherent vibration
 - Include response functions for girders and supports
 - Use this to test BBA and feedback concepts and specify diagnostic and hardware req.

Initial Mechanical alignment		
Length scale	tolerance	
6	20 to 50 um	mechanical installation tolerance of components on quad/sext girder - main issue is corrector and f
50	200 um	mechanical installation and alignment of girder to girder - need to be able to transport first beam
200	500 um	mechanical installation
1000	2 mm	mechanical installation smoothed around the ring
10000	5 mm	Installation tolerance based on surface alignment network and GPS

Proposed Alignment and Ground Motion model II

- **Dynamic variation**
 - **Some combination of incoherent waves, plane waves, systematic variation, and ATL-type diffusion**
 - **Verify feedback, feed-forward, and BBA timescales**

Timescale	tolerance	Correlation		https://cds.cern.ch/record/554622/files/woab009.pdf	
f > 100 Hz	1 nm	none		https://www.slac.stanford.edu/cgi-bin/getdoc/slac-pub-8595.pdf	
100 > f > 10 Hz	5 nm	none			
10 > f > 1 Hz	20 nm	none			
1 > f > 0.01	100 nm	none			
1 > f > 0.01	1 um	10 km			
tidal	1 mm	1000 km		systematic horizontal motion across the ring	
diurnal	??				
Seasonal	100 um	around lake region		systematic vertical deformation	
ATL		1x10 ⁻⁵ um ² /m/s		PRL 104, 238501 (2010)	

• **Expectation for BBA**

BBA alignment requirements									
Length scale	tolerance								
6	10 um	BBA alignment of quadrupole to sextupole to bpm	How do we reference long girder to BPM?						
50	20 um	BBA alignment of quadrupoles to BPM using dither and smoothing with steering							
200	20 um								
1000	100 um	BBA alignment of trajectory							
10000	1 mm	BBA alignment from circumference and trajectory							

• **Requirements**

- **0.1 um BPM resolution at high current for stored multi-bunch beam**
- **Trims on quadrupoles and sextupoles without coupling to magnetic center**
- **Clarification on location of dipole and skew correctors is required**
- **Correctors or movers to implement corrections (dipoles for quads and maybe quad/skew quad trims on the sextupoles)**
- **Timescale for correction faster than degradation**

Proposal for BBA

- **Develop model for results from mechanical alignment**
 - Starting point for any BBA approach
- **Develop ground motion and orbit feedback model**
 - ‘Fast’ motion drives orbit stability
 - Mid and Slow motion to understand BBA stability
- **Study Dithering, PBBA, and LOCO as approaches**
 - Develop BBA system that can be automated for rapidly check of alignment status – is hourly possible? If not, what are stability requirements.
 - Specify diagnostics (BPMs are already more than sufficient) and correctors



Thank you
for your attention.