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Field Quality at injection for FCC-hh

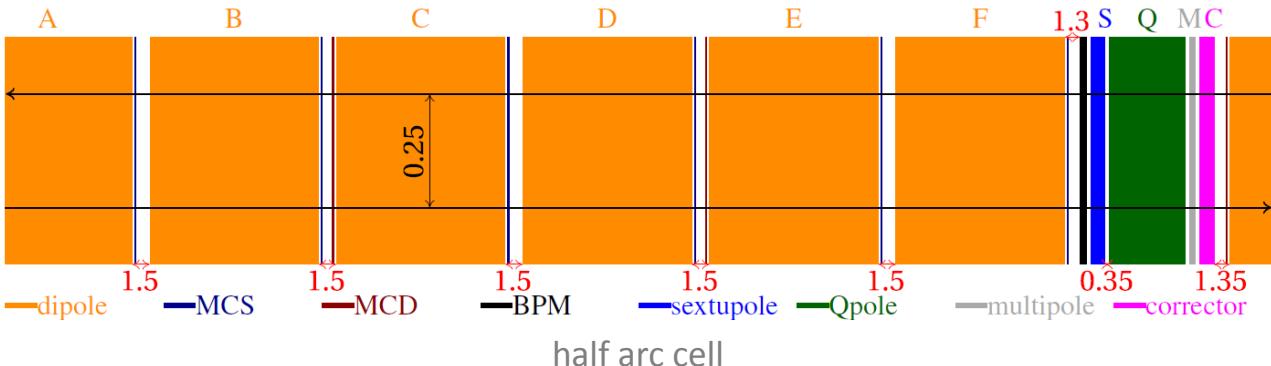
B. Dalena

D. Boutin, A. Chance, E. Cruz, R. De Maria, S. Izquierdo
Bermudez, E. Maclean, R. Martin, A. Mereghetti, J. Molson,
T. Persson, D. Schoerling, D. Schulte, R. Tomas

Outline

- Motivation
- Main Dipole Field Quality and non linear correction schemes
 - Sextupole and Decapole errors
- Dynamic Aperture at injection (3.3 TeV)
 - With and without sextupole and decapole correction
 - Landau Octupoles
 - RF acceptance
- Conclusion and perspectives

Motivation



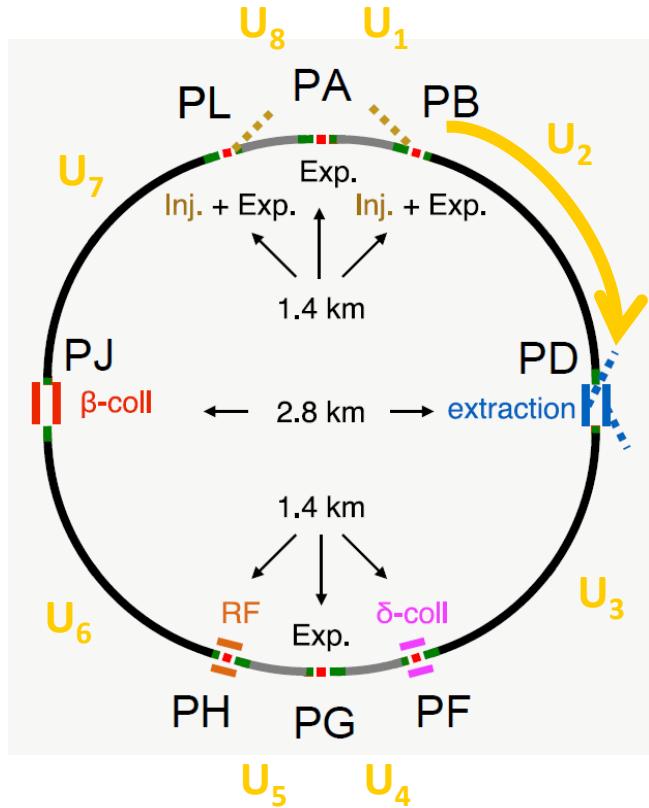
- Design correction schemes for non-linear errors of main magnets of the arcs
- Provide tolerances for the main high order multipoles components of magnets of the arcs
- Key issues:
 - Reserve space for correctors in the arc cells
 - Get order of magnitude of correctors strengths to identify possible R&D needed
 - Define tolerances on main fields errors
 - Define tolerances on arcs magnets field quality to ensure $DA > 12 \sigma$ at injection and more at collision

Main Dipoles Field Quality

$$b_n = b_{n_S} + \frac{\xi_U}{1.5} b_{n_U} + \xi_R \sigma_{b_n} \quad (1)$$

- b_{n_S} systematic error component
- b_{n_U} uncertainty error component:
8 different sectors as in LHC
- σ_{b_n} random error component:
different seeds for each dipole
- Even normal error components change sign between inner and outer chamber*
- Odd skew error components change sign between inner and outer chamber*

*NB. this is not true for the common coil design of the main dipoles...



(1) S. Fartoukh and O. Bruning LHC Project Report 501
LHC Design Report

Main Dipoles Field Quality tables

WP2

1st table: **max systematic sextupole error** can be corrected/tolerated **at collision** ⇒

2nd table: **max value of random skew quadrupole error** can be tolerate ⇒

3rd and **4th** tables: **limit for systematic quadrupole error** ⇒

4th table: **limit for systematic and random sextupole and decapole error at injection** ⇒

5th table: **decapole correction at injection** ⇒

WP5

⇐ 5 Field Quality tables

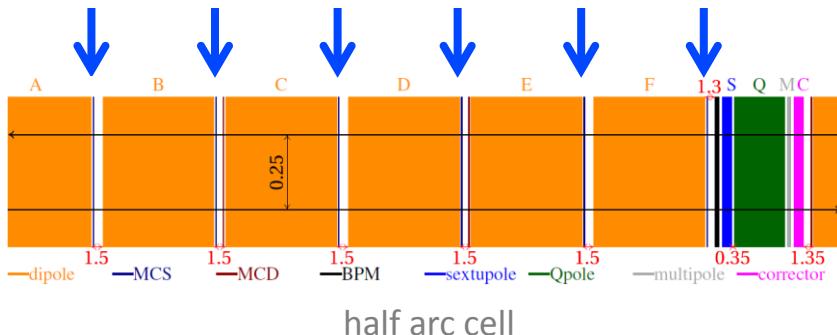
⇐ max correctors Gradients feasible with NbTi technology

⇐ new asymmetric coil design (INFN-LASA & INFN GENOVA)

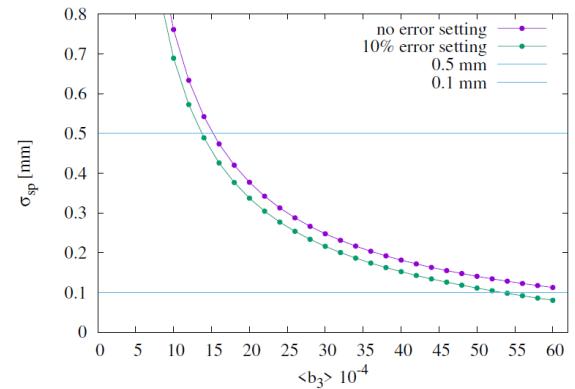
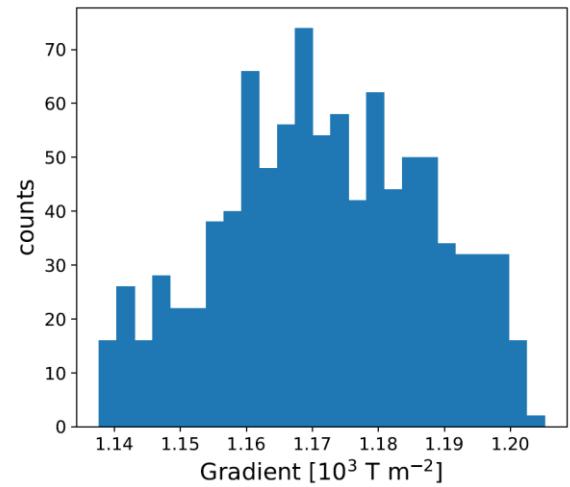
⇐ new strand magnetization for persistent current effects*

*T. Spina, A. Ballarino, L. Bottura et al., "Artificial pinning in Nb₃Sn wires", IEEE Transactions on Applied Superconductivity, vol. 27, pp. 1-5, 2017

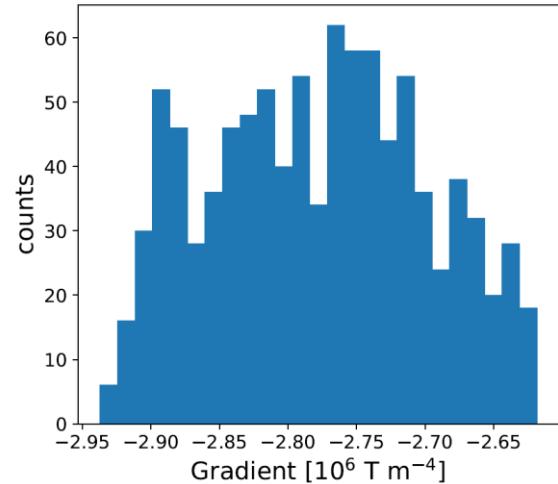
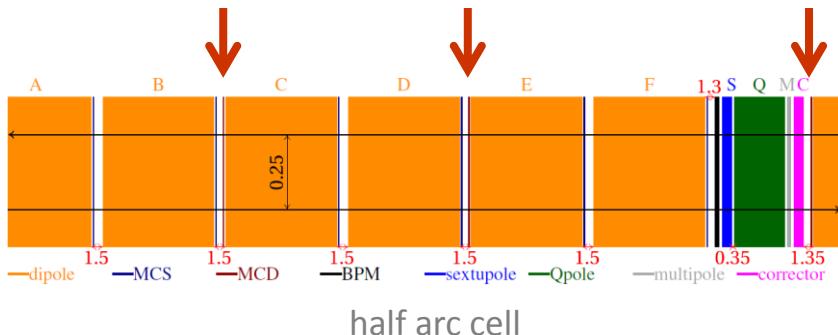
Sextupole corrector and tolerance



- One corrector at each dipole powered in series for each of the arc
- Max feasible gradient 3000 T/m^2 and 0.11 m long (NbTi technology)
- Can correct systematic up to 6 (60) units of systematic b_3 at collision (injection)
- Max used gradient for last table is 1205 T/m^2
- To reduce β -beating from feed-down, MCS relative alignment to the main dipole has to be controlled



Decapole corrector and tolerance



- One corrector every other dipole powered in series for each of the arcs
- Max feasible gradient $4.3(2.8) \times 10^6 \text{ T/m}^4$ and 0.066 m long, aperture $53(68) \text{ mm}$
- Can correct a systematic component of b_5 up to $0.53(8)$ units at collision (injection 3.3 TeV)
- Max used gradient at injection is $2.94 \times 10^6 \text{ T/m}^4$

Dynamic Aperture (DA)

defined as: initial amplitude of particle losses at 10^5 turns

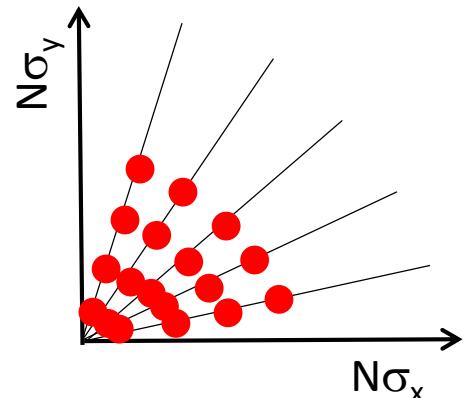
computed with SixTrack (<http://sixtrack.web.cern.ch/SixTrack>)

Initial conditions for long-term DA study:

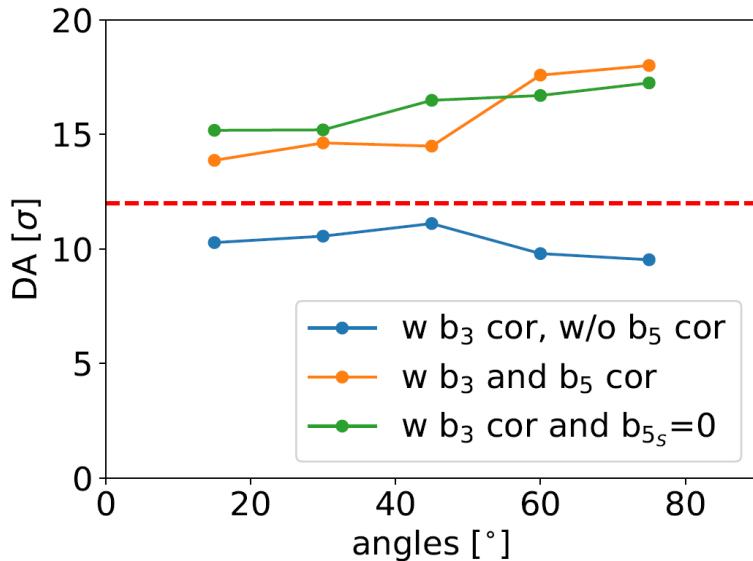
- 60 seeds
- 30 particle pairs
- Emit norm $2.2\text{e-}6 \text{ m.rad}$
- $E_0 = 3.3 \text{ TeV}$
- $Q' = 2$
- $\text{dp/p} = 0.00032$
- $\sigma \text{ step} = 2, \sigma \in [0:-]$
- $5 \text{ angles } \in [0,90^\circ]$

Fractional part of tunes:

$Q_x = .28, Q_y = .31$ injection



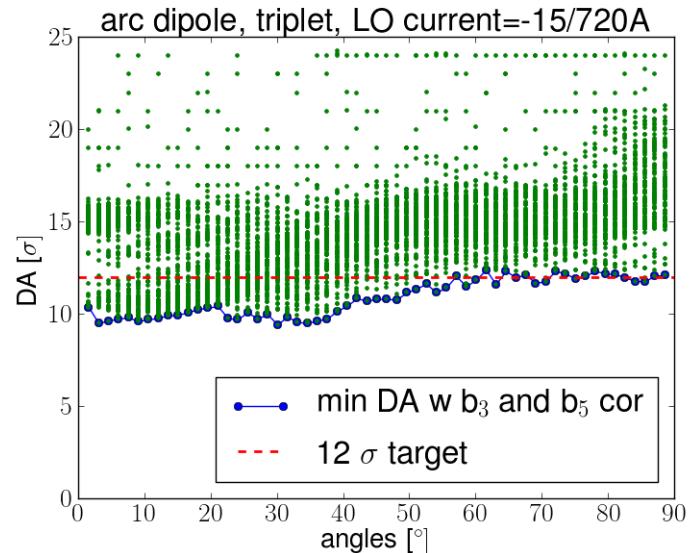
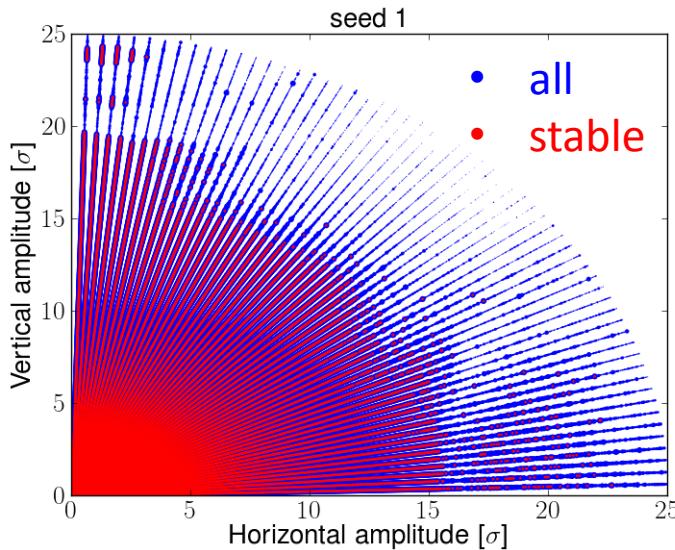
DA results at injection



- Sextupole and decapole corrections required to have minimum DA above the target of 12σ
- Negligible impact of Experimental Insertion Regions (EIR) on DA
- Minimum DA $\sim 8.3 \sigma$ at injection energy of 1.3 TeV

Effect of Landau Damping octupoles at injection

- Minimum DA below target with LO (like for LHC)
- Minimum above the collimation settings \Rightarrow is not considered a big issue
- DA is dominated by multipoles random components with sextupole and decapole correction
- DA seeds distribution is non Gaussian

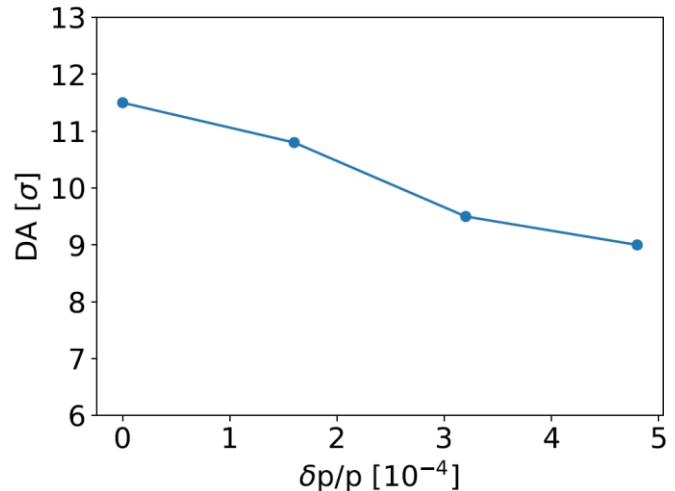


RF bucket size

$$\left(\frac{\Delta p}{p_0}\right)_{max} = \sqrt{\frac{2V_{RF}}{\pi h |\eta| c p_0}}$$

	V _{RF} [MV]	P ₀ [TeV]	Δp/p max 10 ⁻⁴
FCC	16	3.3	4.8
	32	50	1.7
LHC	8	0.45	9.6
	16	7	3.4

- A current of -15/720 A in all the Landau damping octupoles of the ring at injection
- Minimum DA reduces to 9.4 σ for an initial momentum offset of the particles at 2/3 of RF bucket size
- Minimum DA reduction of 2.5 σ inside the RF bucket



Conclusions

- Main Dipole Field Quality at injection provide DA above the 12σ target if sextupole and decapole systematic errors are corrected
- LHC non-linear correction schemes and NbTi technology can be used
- Landau Damping Octupoles reduced DA below the target value, but still above collimation settings
- RF bucket account for $\sim 2.5\sigma$ reduction

Perspectives

- Impact of main quadrupoles on DA
- Impact of linear imperfection on DA
- Working point at injection
- Impact of Dynamic errors
- Application of AI techniques to predict DA

Additional slides

Field Quality table

	<i>FCC Dipole field quality version 5 - 28 Sep 2018- $R_{ref}=16.7\text{ mm}$. $1.3\text{ TeV Injection (Binj} = 0.42\text{ T})$; $\text{Deff} = 20\text{ }\mu\text{m}$, Half artificial pinning</i>								
	Systematic					Uncertainty		Random	
Normal	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field
2	3,680	-3,655	3,650	7,329	0,025	0,929	0,929	0,929	0,929
3	-2,364	2,470	-43,659	-46,024	0,106	0,668	0,668	0,668	0,668
4	0,952	-0,639	-0,244	0,708	0,313	0,467	0,467	0,467	0,467
5	0,296	-0,113	12,268	12,564	0,182	0,283	0,283	0,283	0,283
6	0,345	0,002	0,688	1,033	0,347	0,187	0,187	0,187	0,187
7	0,170	0,014	-3,781	-3,611	0,184	0,109	0,109	0,109	0,109
8	0,346	0,028	0,253	0,600	0,375	0,072	0,072	0,072	0,072
9	0,525	0,043	3,625	4,150	0,568	0,047	0,047	0,047	0,047
10	0,120	0,010	0,236	0,356	0,130	0,028	0,028	0,028	0,028
11	1,021	0,083	-0,014	1,007	1,105	0,015	0,015	0,015	0,015
12	0,081	0,007	0,000	0,081	0,088	0,010	0,010	0,010	0,010
13	-0,227	-0,019	0,000	-0,227	-0,245	0,005	0,005	0,005	0,005
14	0,026	0,002	0,000	0,026	0,028	0,003	0,003	0,003	0,003
15	-0,020	-0,002	0,000	-0,020	-0,022	0,002	0,002	0,002	0,002
Skew									
2	0,000	0,000	0,000	0,000	0,000	1,103	1,103	1,103	1,103
3	0,000	0,000	0,000	0,000	0,000	0,754	0,754	0,754	0,754
4	0,000	0,000	0,000	0,000	0,000	0,473	0,473	0,473	0,473
5	0,000	0,000	0,000	0,000	0,000	0,329	0,329	0,329	0,329
6	0,000	0,000	0,000	0,000	0,000	0,205	0,205	0,205	0,205
7	0,000	0,000	0,000	0,000	0,000	0,114	0,114	0,114	0,114
8	0,000	0,000	0,000	0,000	0,000	0,069	0,069	0,069	0,069
9	0,000	0,000	0,000	0,000	0,000	0,038	0,038	0,038	0,038
10	0,000	0,000	0,000	0,000	0,000	0,023	0,023	0,023	0,023
11	0,000	0,000	0,000	0,000	0,000	0,015	0,015	0,015	0,015
12	0,000	0,000	0,000	0,000	0,000	0,008	0,008	0,008	0,008
13	0,000	0,000	0,000	0,000	0,000	0,005	0,005	0,005	0,005
14	0,000	0,000	0,000	0,000	0,000	0,003	0,003	0,003	0,003
15	0,000	0,000	0,000	0,000	0,000	0,002	0,002	0,002	0,002

Field Quality table

	<i>FCC Dipole field quality version 5 - 28 Sep 2018 - R_{ref}=16.7 mm.</i> <i>3.3 TeV Injection (Binj = 1.06 T); Deff = 20 μm , Half artificial pinning</i>									
	Systematic					Uncertainty		Random		
Normal	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field	
2	3,680	-3,655	1,954	5,634	0,025	0,929	0,929	0,929	0,929	
3	-2,364	2,470	-22,757	-25,121	0,106	0,668	0,668	0,668	0,668	
4	0,952	-0,639	-0,157	0,795	0,313	0,467	0,467	0,467	0,467	
5	0,296	-0,113	4,874	5,170	0,182	0,283	0,283	0,283	0,283	
6	0,345	0,002	0,329	0,673	0,347	0,187	0,187	0,187	0,187	
7	0,170	0,014	-1,500	-1,330	0,184	0,109	0,109	0,109	0,109	
8	0,346	0,028	0,116	0,463	0,375	0,072	0,072	0,072	0,072	
9	0,525	0,043	1,530	2,055	0,568	0,047	0,047	0,047	0,047	
10	0,120	0,010	0,101	0,221	0,130	0,028	0,028	0,028	0,028	
11	1,021	0,083	0,026	1,048	1,105	0,015	0,015	0,015	0,015	
12	0,081	0,007	0,000	0,081	0,088	0,010	0,010	0,010	0,010	
13	-0,227	-0,019	0,000	-0,227	-0,245	0,005	0,005	0,005	0,005	
14	0,026	0,002	0,000	0,026	0,028	0,003	0,003	0,003	0,003	
15	-0,020	-0,002	0,000	-0,020	-0,022	0,002	0,002	0,002	0,002	
Skew										
2	0,000	0,000	0,000	0,000	0,000	1,103	1,103	1,103	1,103	
3	0,000	0,000	0,000	0,000	0,000	0,754	0,754	0,754	0,754	
4	0,000	0,000	0,000	0,000	0,000	0,473	0,473	0,473	0,473	
5	0,000	0,000	0,000	0,000	0,000	0,329	0,329	0,329	0,329	
6	0,000	0,000	0,000	0,000	0,000	0,205	0,205	0,205	0,205	
7	0,000	0,000	0,000	0,000	0,000	0,114	0,114	0,114	0,114	
8	0,000	0,000	0,000	0,000	0,000	0,069	0,069	0,069	0,069	
9	0,000	0,000	0,000	0,000	0,000	0,038	0,038	0,038	0,038	
10	0,000	0,000	0,000	0,000	0,000	0,023	0,023	0,023	0,023	
11	0,000	0,000	0,000	0,000	0,000	0,015	0,015	0,015	0,015	
12	0,000	0,000	0,000	0,000	0,000	0,008	0,008	0,008	0,008	
13	0,000	0,000	0,000	0,000	0,000	0,005	0,005	0,005	0,005	
14	0,000	0,000	0,000	0,000	0,000	0,003	0,003	0,003	0,003	
15	0,000	0,000	0,000	0,000	0,000	0,002	0,002	0,002	0,002	

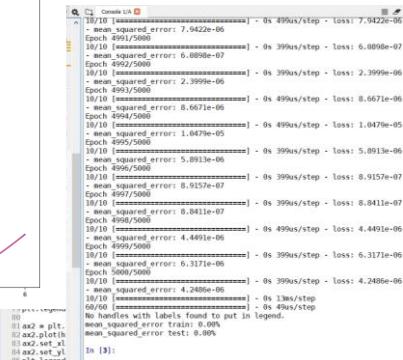
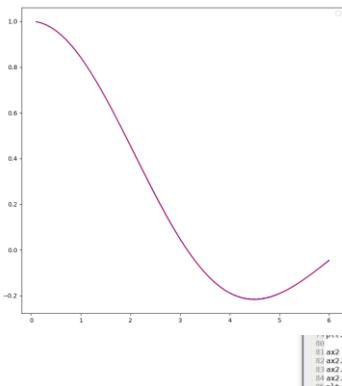
Perspectives: application of AI techniques to DA evaluation



InTheArt: discussion group about *Artificial Intelligence*

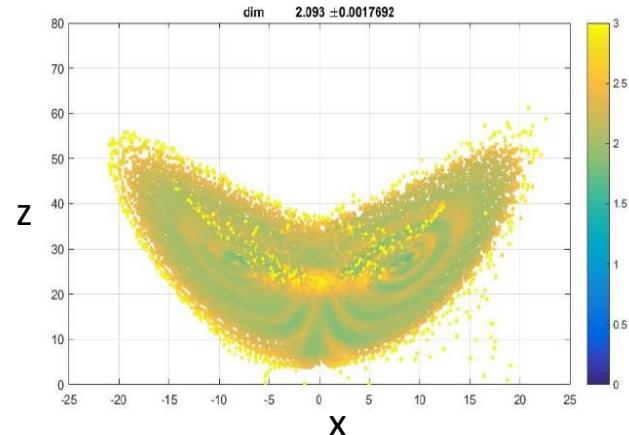


Using neural network to find interpolating function of DA as a function of multipole errors.



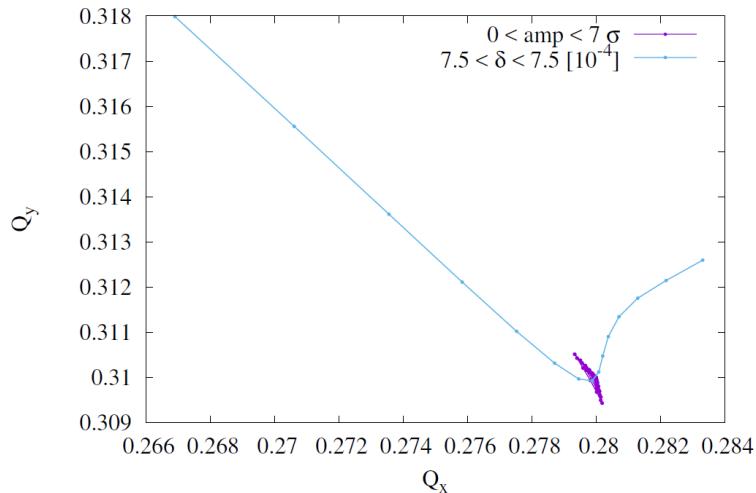
G. Daniel, B.D.

Model chaotic dynamical systems using reservoir computing methods, in order to predict long term behavior.



A. Hamid, D. Faranda, V. Gautard

Detuning 4th table



- ⇒ Detuning is larger with momentum!
- ⇒ Qx''' seems to dominate (b5 correctors required)

Detuning with momentum table v3

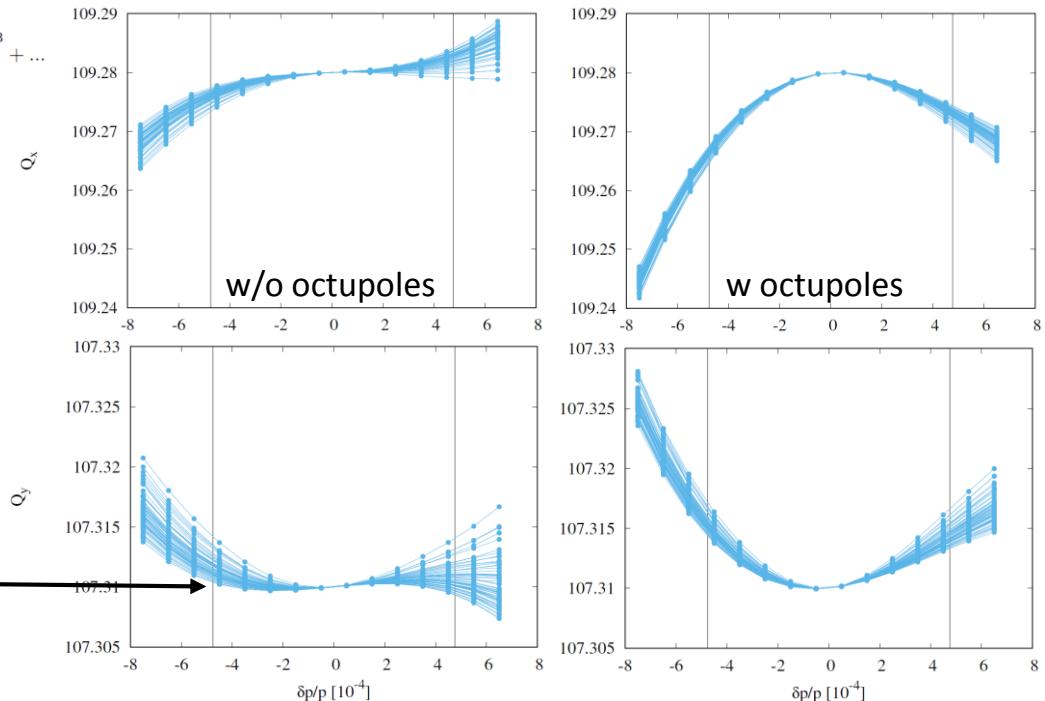
$$Q_z \left(\frac{\delta p}{p_0} \right) = Q_{z0} + Q'_z \left(\frac{\delta p}{p_0} \right) + \frac{1}{2!} Q''_z \left(\frac{\delta p}{p_0} \right)^2 + \frac{1}{3!} Q'''_z \left(\frac{\delta p}{p_0} \right)^3 + \dots$$

$$Q''_z \propto 3\beta b_4 + \dots$$

$$Q'''_z \propto 12\beta b_5 + \dots$$

Fitting with a 3rd order polynomial
for seed giving minimum DA
 $\Rightarrow Q'''$ is stronger than Q''

With Octupoles ON Q'' dominates and
out of the **RF acceptance** the
octupoles reduce the tune spread due
to different seeds of main dipole
errors

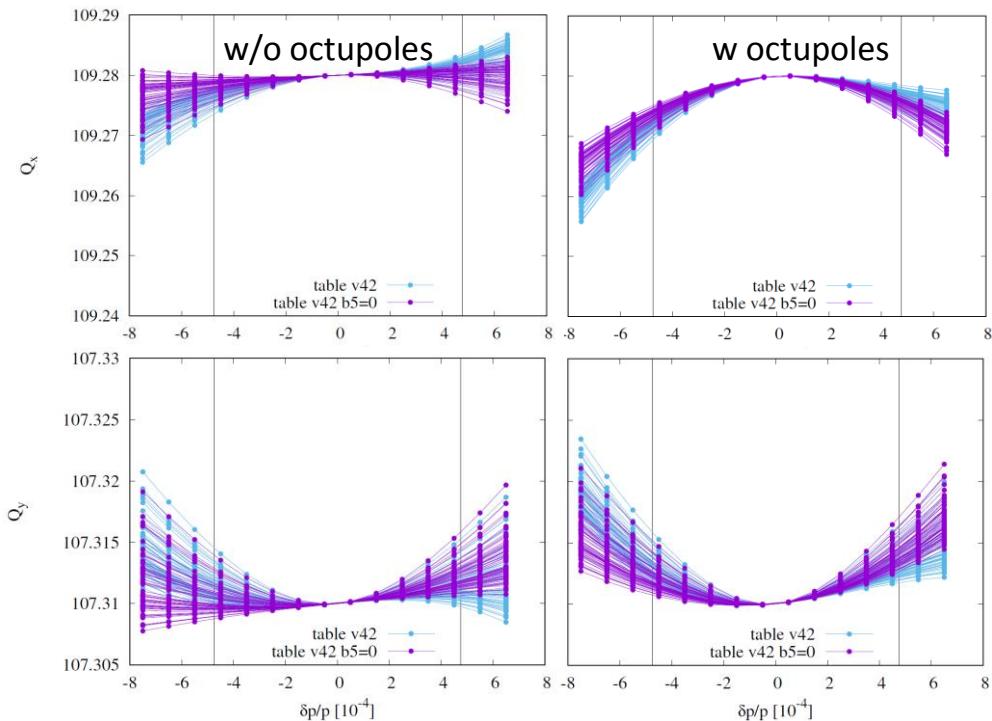


Detuning with momentum w and w/o b_5 (table v42)

$$Q_z \left(\frac{\delta p}{p_0} \right) = Q_{z0} + Q'_z \left(\frac{\delta p}{p_0} \right) + \frac{1}{2!} Q''_z \left(\frac{\delta p}{p_0} \right)^2 + \frac{1}{3!} Q'''_z \left(\frac{\delta p}{p_0} \right)^3 + \dots$$

With $b_{55} = 0$ we have only Q'' left and both w and w/o octupole max detuning is < 0.01 @ $3.2e^{-4}$ dp/p

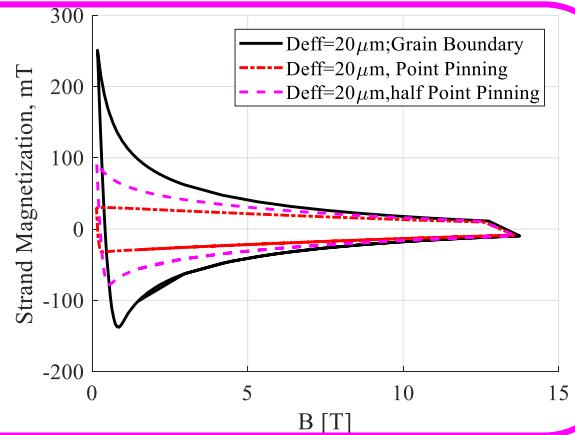
\Rightarrow Correction of b_4 from Table v42 not required



Tables v42 (half artificial pinning)

- New asymmetric coil design (INFN-LASA & INFN GENOVA)
- New strand magnetization for persistent current effects

Susana Izquierdo Bermudez, Davide Tommasini
01-10-2018

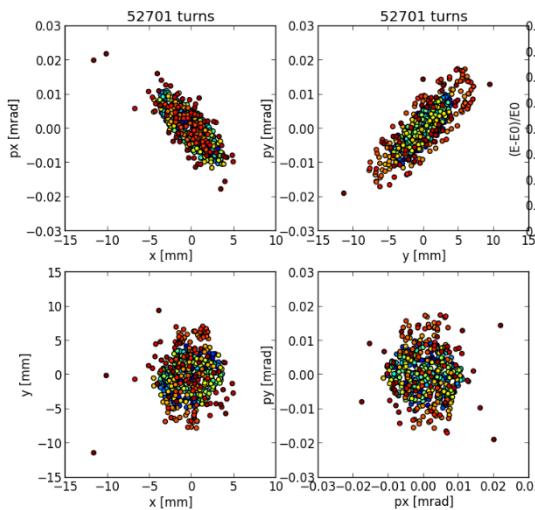


- Initial amplitude of particles lost used to evaluate DA (alost2)
- Energy corresponding to 2/3 of the max RF acceptance considered
- Main Octupoles current of -15A @ injection (Sergey ARSENYEV communication)

	Min DA [σ] $\Delta p/p=0$	Min DA [σ] $\Delta p/p=3.2e^{-4}$
arc	16.21	9.4
arc+triplet	~16.21	~9.4
arc+triplet+oct = -15 A	10.55	6.3

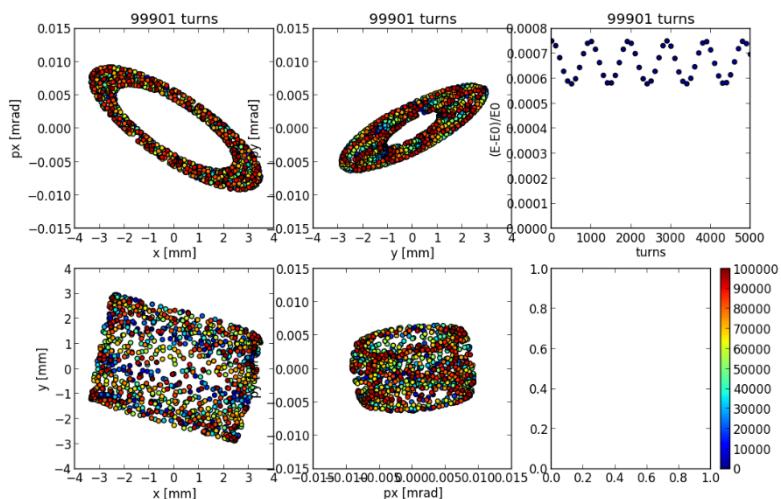
Effect of octupoles for $\delta p/p = 7.5e^{-4}$

Arc errors only



Lost

Arc, IRs errors and octupoles $I=-30$ A



Stable

Effect of octupoles for $\delta p/p = 7.5e-4$

