2025 Workshop on Fixed Field Alternating Gradient Accelerators (FFA25)

Design and study of a spiral focusing structure for the FFA at CSNS

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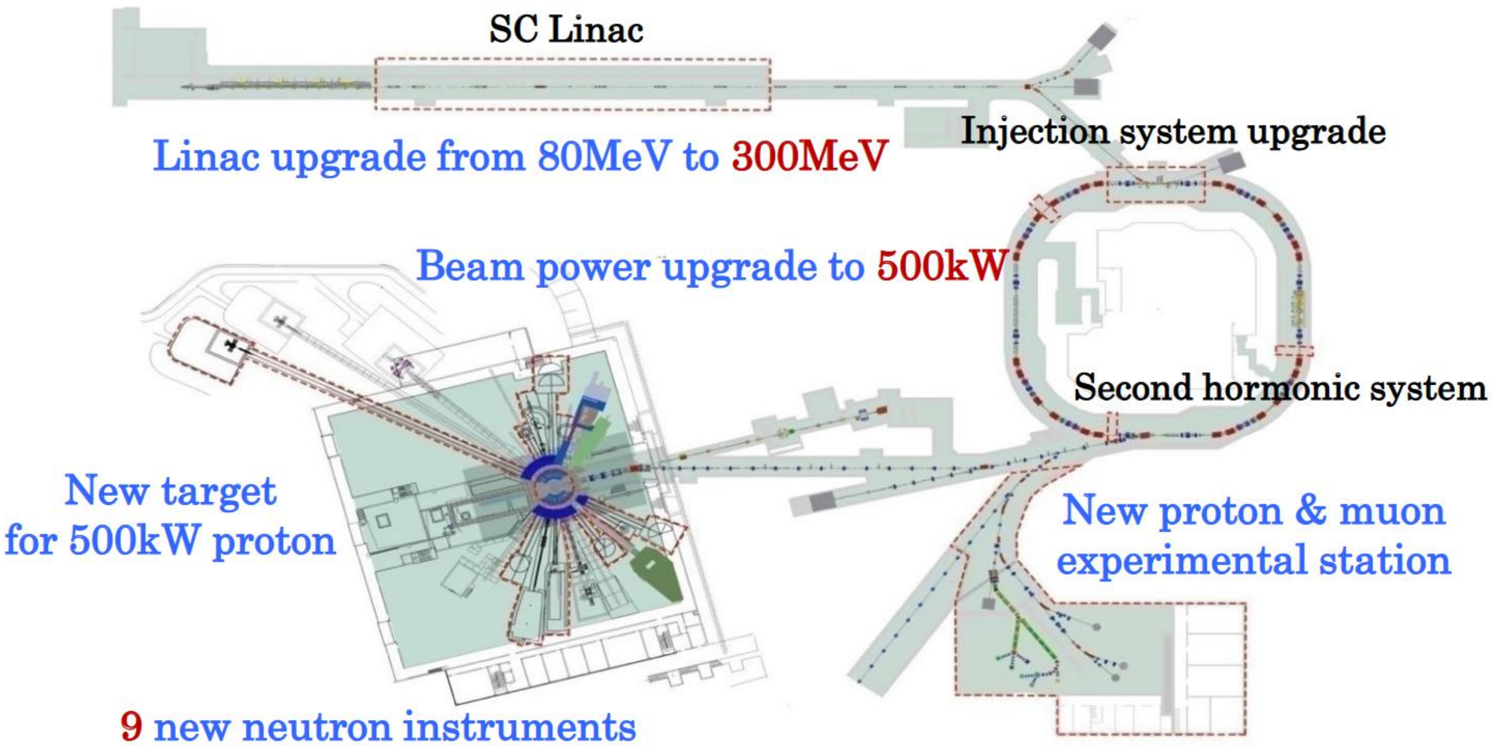
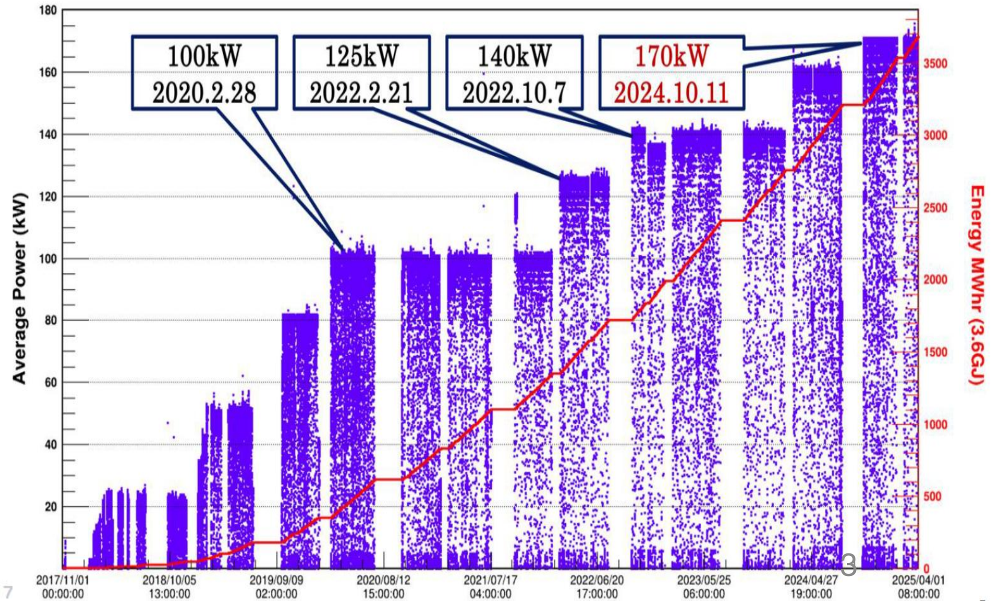
China Spallation Neutron Source (CSNS)

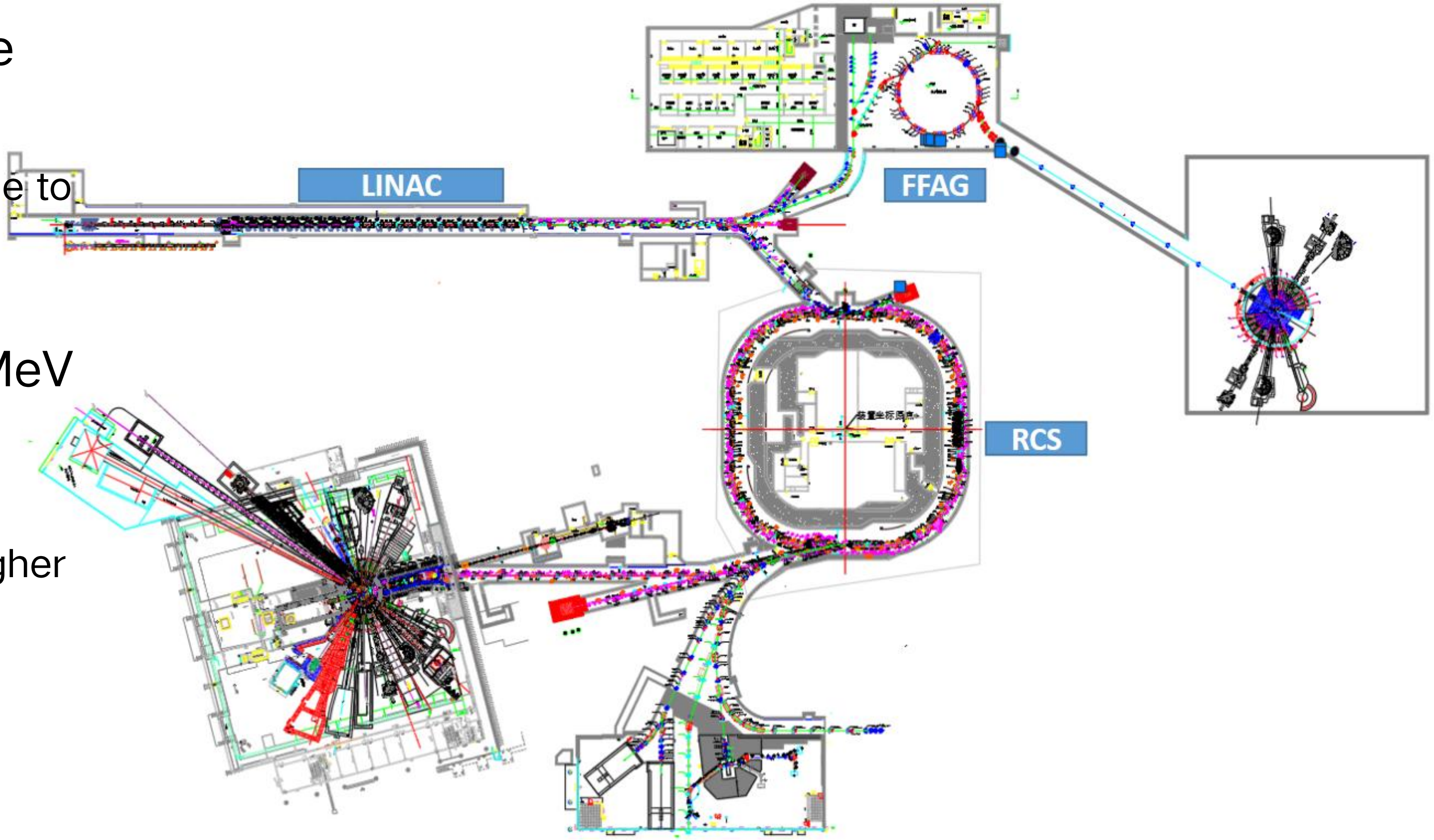
- Located in southern China, Guangdong Province
- The beam power has been increased to 170 kW
- Beam power will be achieved to 500 kW in CSNS-II
- Linac energy upgrade from 80 MeV to 300 MeV





A High-Intensity Proton FFA:

- Injector: 300 MeV beam from the upgraded CSNS Linac
  - The repetition rate of linac will upgrade to 50 Hz
  - 25 Hz for RCS and 25 Hz for other applications
- Extraction energy of FFAG 600 MeV
- Repetition rate of FFAG 25 Hz
  - Limited by the repetition rate of linac
  - Capable of operating at 200 Hz or higher
- Average beam power 50 kW
  Average beam current 83.4 uA



Multi-application:

- **White Neutron Source/High Repetition Rate Muon Source /The production of alfa medical isotopes/Preliminary technical research for CSNS-III**

Key Design Requirements & Constraints

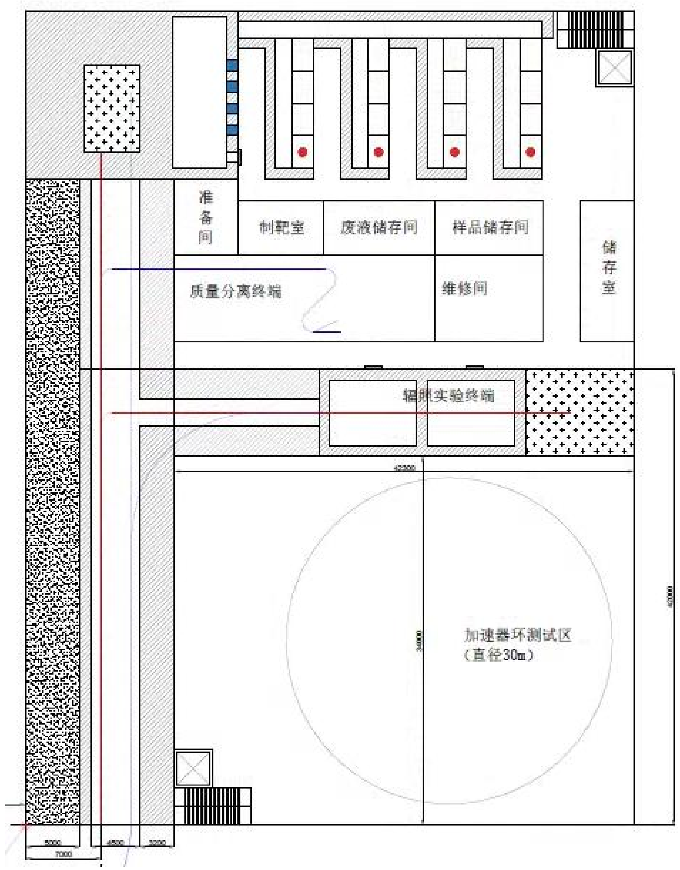
Basic Requirements

- **300 MeV to 600MeV** at injection and extraction
- FFAG type: Scaling
- Limited space for accelerator <Ø24m
- Normal-conducting magnet with variable air gap
  - Magnetic fields: B < 1.66 [T]
  - Beam excursion (△R) < 0.8 [m]

$$B(r) = B_0 \left(\frac{r}{r_0}\right)^k$$

- Enough space for Injection/Extraction and RF cavity
  - Drift space> 1.8 [m]
- Physical dynamic aperture: DA > 800 $[\pi\, mm.mrad]$

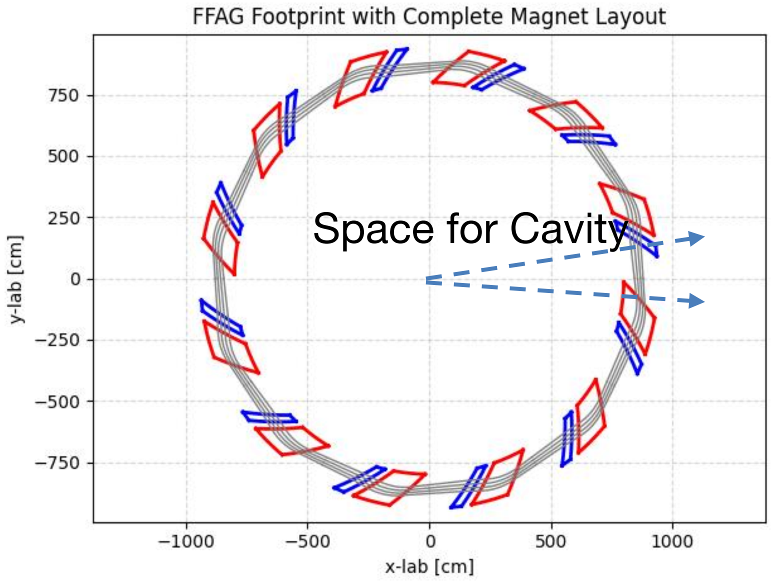
  (Experience from CSNS/RCS)



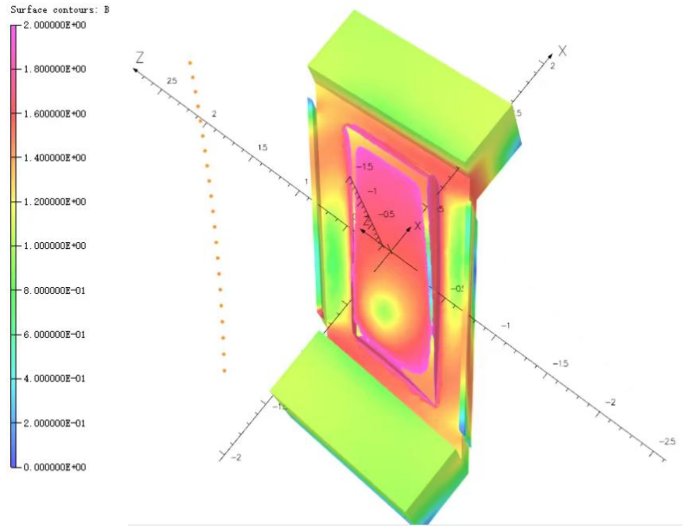
CSNS Linac End Experimental Hall (Under Construction)

Initial Lattice Design & Challenges

Spiral Magnet Parameters	
Particle Type	Proton
Injection Energy (MeV)	300
Extraction Energy (MeV)	600
Super periodicity N	12
Peak Magnetic Field in F (T)	1.66
Peak Magnetic Field in D（T)	0.67
R_{ms1}	0.282
R_{ms2}	0.280
Spiral Angle (°)	43.563
Filling Factor P_f	0.485
Field Index K_i	5.449
F Magnet Width (°)	9.314
D Magnet Width (°)	2.627
F-D Magnet Gap (°)	2.608
Straight Section Width (°)	13.129
Cell tunes （υ_r/υ_z）	0.233/0.14



3D magnets model

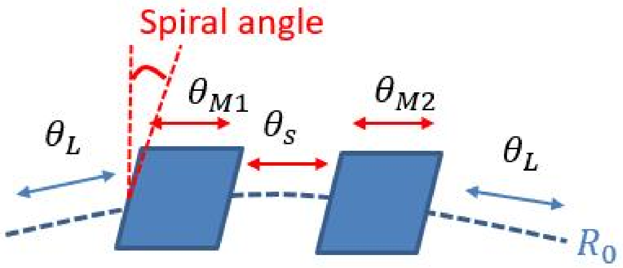


- Advantage: Provided a long drift space
- Disadvantage
  1. Small Vertical Tune: This leads to a large vertical beta function (βz), complicating beam injection.
  2. Large F-Magnet Size: The focusing magnets were over 2 meters wide, making them excessively heavy and creating significant manufacturing challenges for the vacuum chamber.
- Conclusion: A more advacned, optimized lattice structure is required
  1. 16-cell FD or 12-cell FDF
  2. Lattice parameters need to be optimized for larger DA, smaller βz, B_max and longer drift space

Multi-Objective Optimization problem

- Goal: Find an optimal lattice design that satisfies all competing requirements simultaneously

	parameters	Search range
1	Spiral angle	[20°~60°]
2	Filling factor	[0.4~0.58]
3	D magnets Width θ_{M2}	[0.8~1]
4	F/D gap θ_s	[0.38~0.5]
5	Ki	[4~12]
6	B_d/B_f	[0.35~1.2]

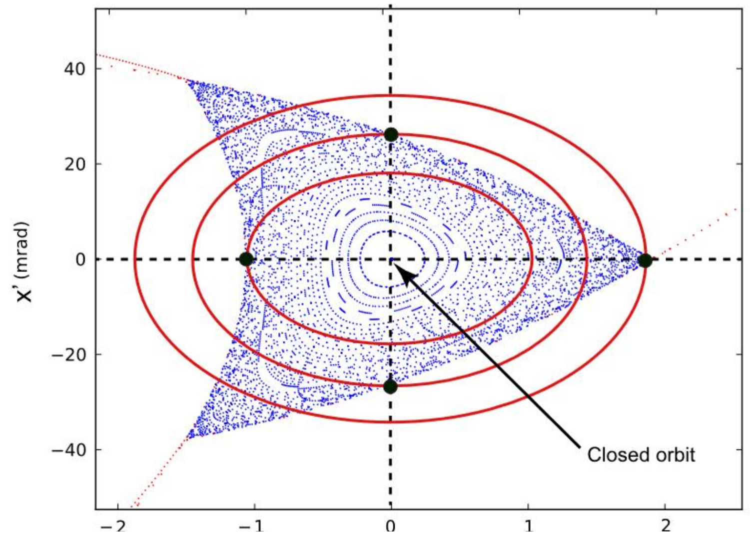


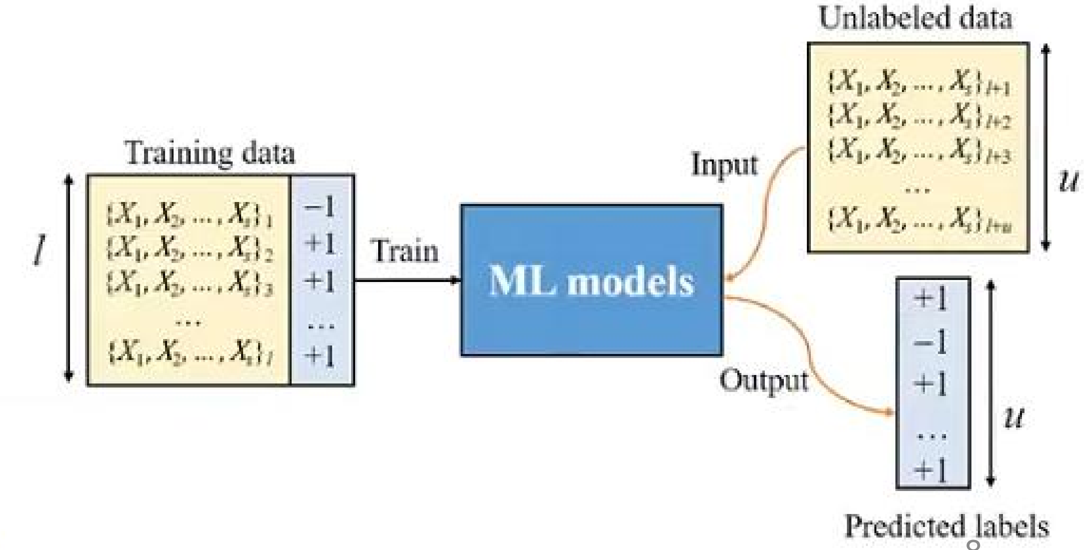
	Objectives	Description	Direction	Purpose
1	L_{drift}	Drift space	Maximize	>1.8m
2	B_m	Maximum magnetic field	Minimize	<1.66T
3	ΔR	Beam excursion	Minimize	<0.8m
4	β_{z0}	Beta functions at straight section center	Minimize	$\beta z < 8$m
5	β_{z-max}	Beta functions in cells	Minimize	Reduce bunch envelope
6	DA	Particle stability	Maximize	Increasing beam intensity
Supporting role for DA fast optimization				
7	Q_z_shift	Vertical tune shift in DA	Minimize	Increase large amplitude particle stability
8	$Tune\_Diffsion$	Tune diffusion rates	Minimize	

- Method: Multi-Objective Genetic Algorithm (NSGA-II).

Chanlleges and Solutions

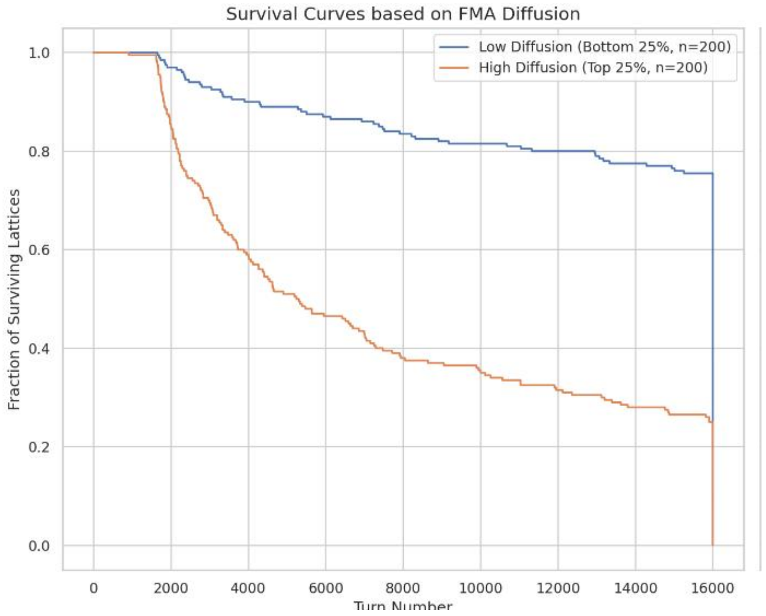
- Key Optimization Challenges:
  - High Computational Cost: Accurate Dynamic Aperture (DA) calculation requires multi-turn tracking and iteration (Binary serach), which is extremely time-consuming for an population-based optimization algorithm.
  - Finding the Global Optimum: Genetic algorithms may get trapped in local optima.
- Our Solution:
  - DA calculation with few turns.
  - Employ a surrogate model to learn the system dynamics, allowing for rapid and exhaustive exploration of the parameter space to predict the true global optimum.

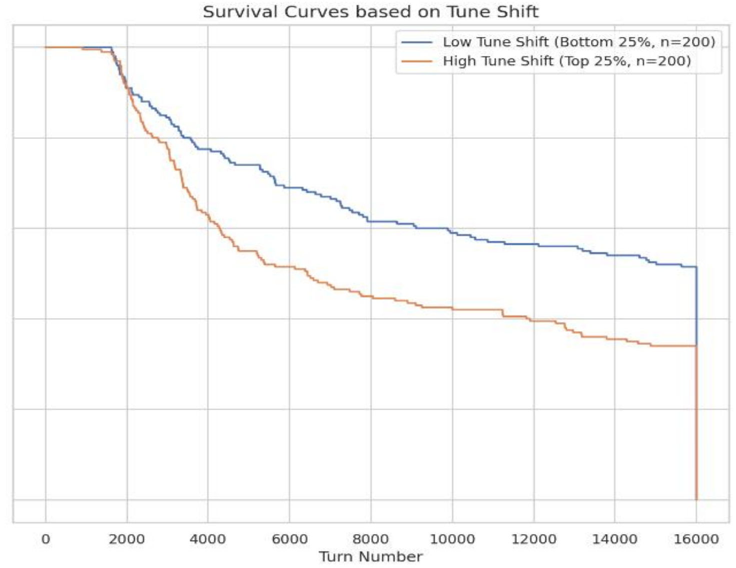




Predicting Long-Term Stability

- Problem: Short-term tracking (~100 turns) does not guarantee long-term stability.
- Solution: Use Frequency Map Analysis (FMA) metrics as reliable indicators
  - Tune Shift: frequency (tune) change with amplitude.
  - Tune Diffusion: the rate of frequency change, indicating chaos.
- Experiment:
  - We took 800 lattice samples, all with good short-term DA
  - We tracked them in short-term DA for 1000 turns.
- Result:
  - Lattices with low tune diffusion and low tune shift showed significantly higher survival rates.
  - This confirms these metrics are good proxies for long-term stability and can be used to accelerate optimization.





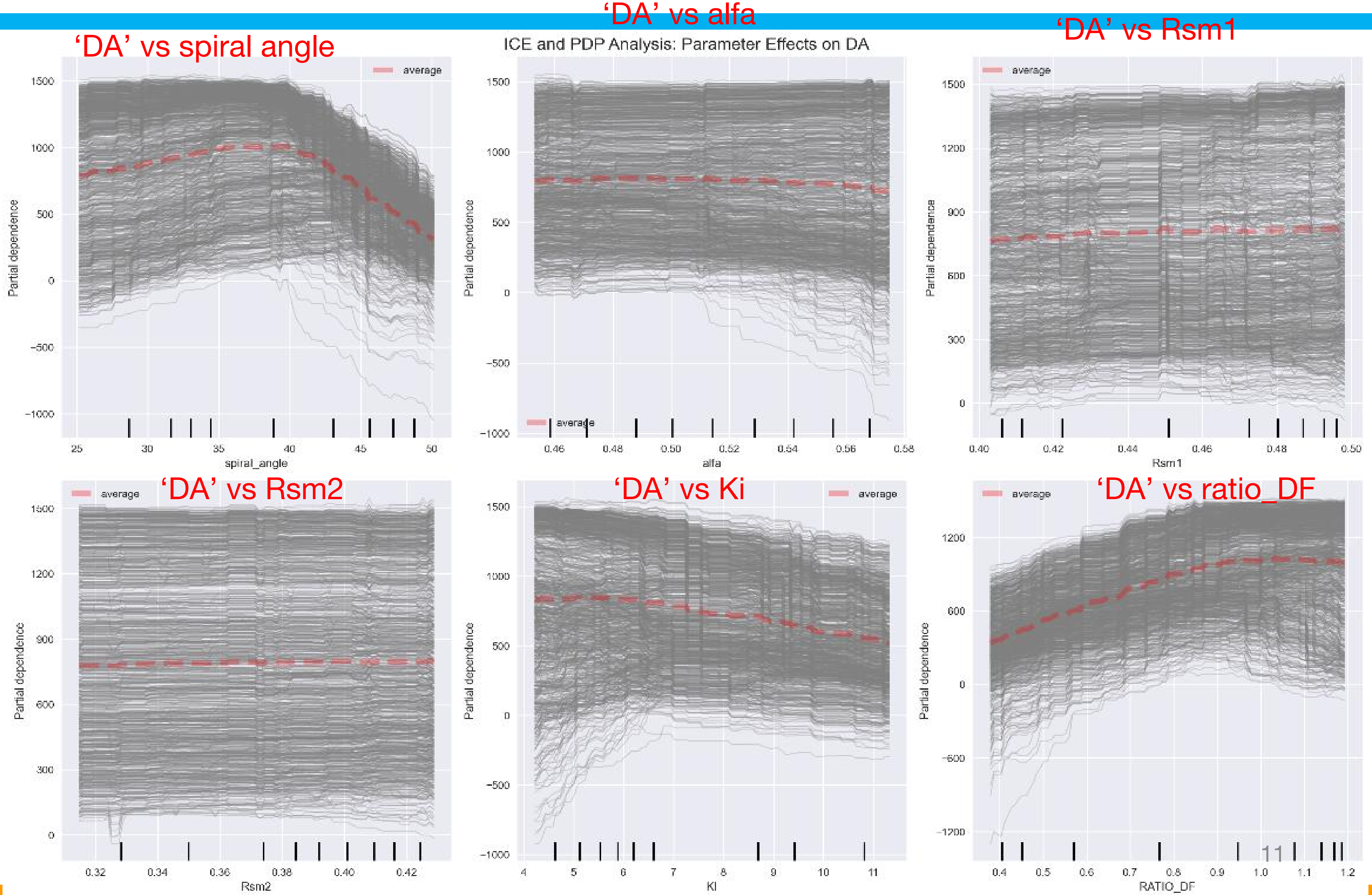
Finding the global optimum

- Developing a surrogate model to understand the complex, non-linear system dynamics of the scaling FFA, rapidly identify the region of the global optimum
- Method:
  - Initial Sampling: Generate ~1000 diverse lattice configurations using Latin Hypercube Sampling
  - Simulation: Run tracking code for this initial dataset.
  - Train Surrogate Model: Develop an XGBoost model, which offers good **interpretability**, to learn the mapping from lattice parameters to performance objectives (e.g., DA)
- Key Advantage: Speed
  - This trained model can predict the performance for thousands of parameter combinations in few seconds

Surrogate Model for Rapid System Analysis

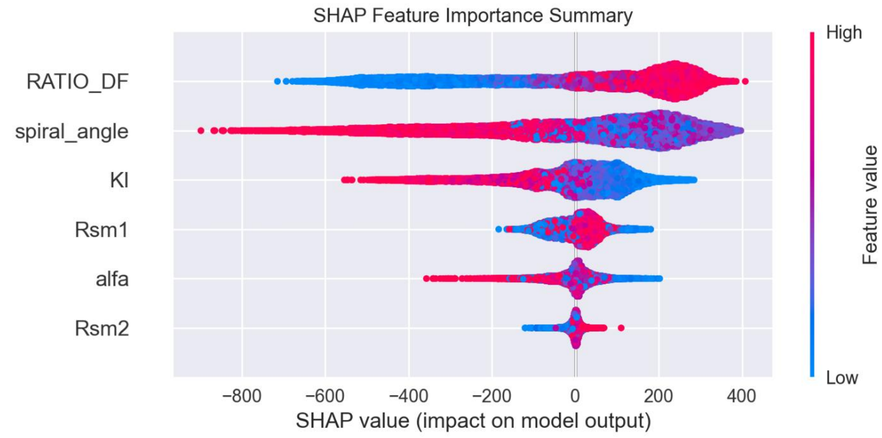
- Experiment:
- Taking 16-cell FD for example
- Lattice Parameters effects on DA

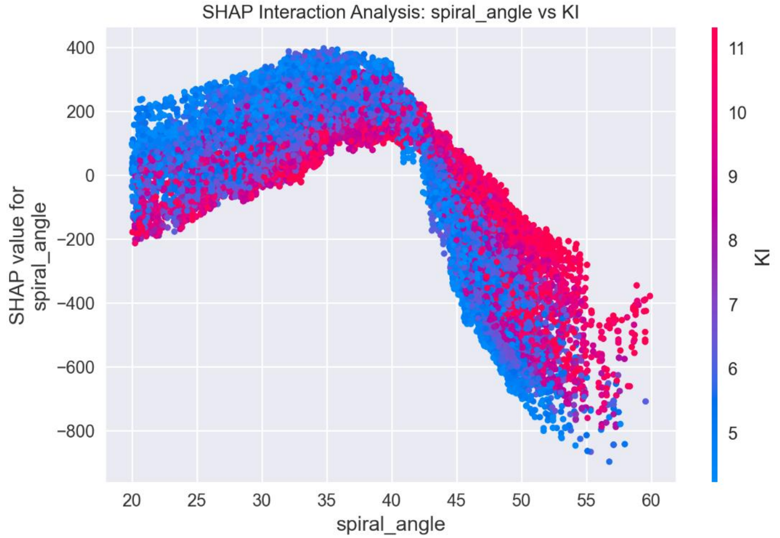
- Initial Finding:
    - The model predicted that the optimal solutions for DA would be found when the spiral angle is near 40 degrees

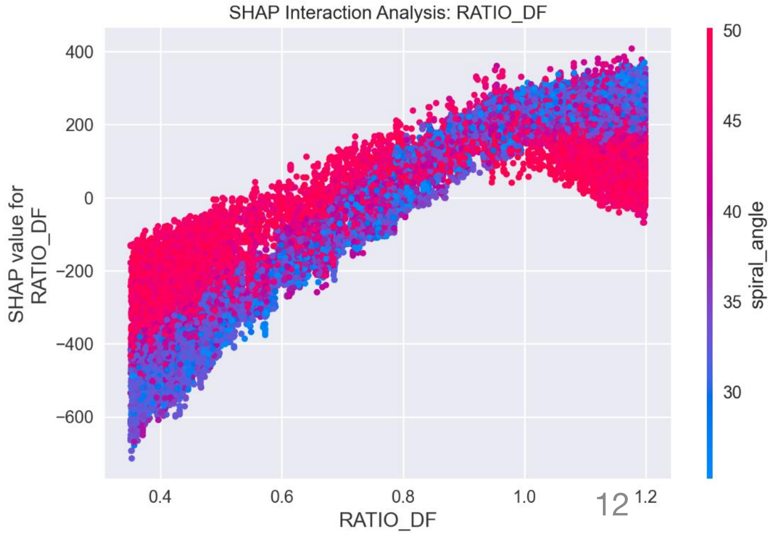


Model Interpretability: Understanding the Physics

- Beyond Prediction: Gaining Physical Insight
  - Our model is not a "black box." We use SHAP (SHapley Additive exPlanations) to understand why the model makes its predictions.
  - This allows us to analyze the complex, non-linear interactions between parameters.
- Example Insights:
  - Feature Importance: Confirms that spiral_angle, RATIO_DF (F/D magnet strength ratio), and Ki (field index) have the most significant impact on the dynamic aperture.
  - Parameter Interaction : We can visualize how two parameters interact. For example, the contribution of the spiral angle to DA peaks around 40 degrees. When the RATIO_DF is high, a slightly smaller spiral angle is needed to maintain a large DA.

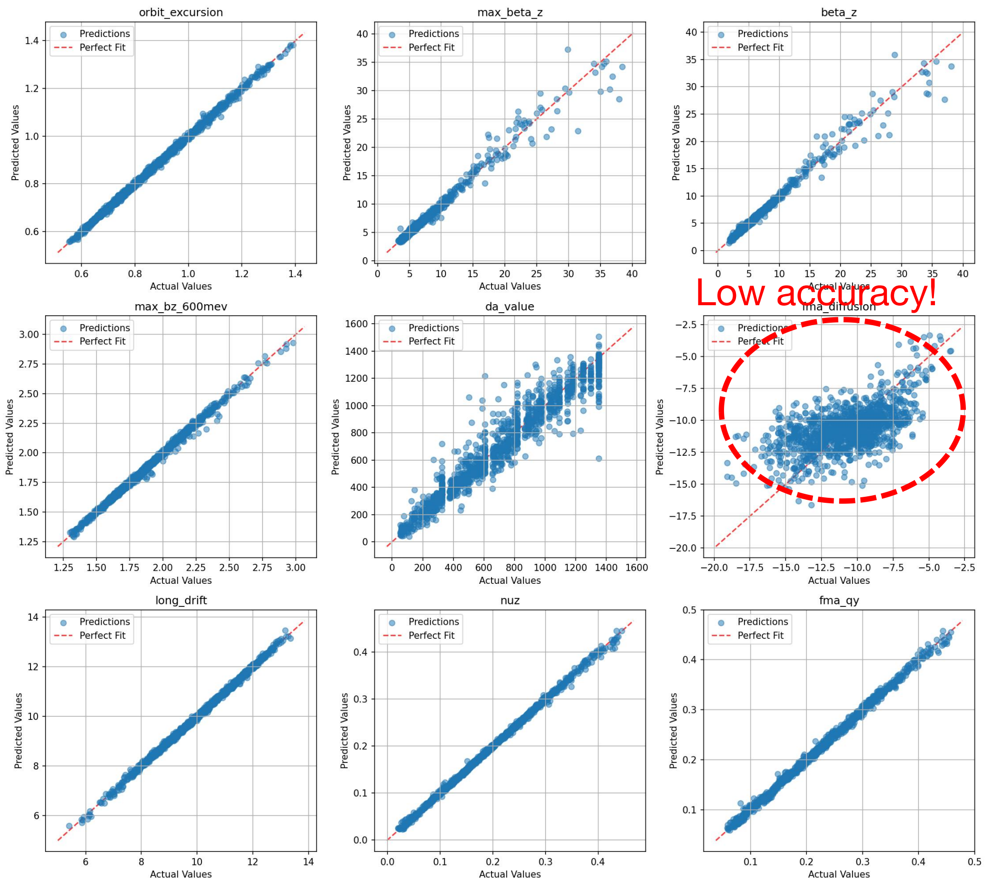






Optimization Algorithm

- Using real tracking code (Not surrogate model) to calculate the objectives (DA calcultaed with 100-turns)
- Tracking code: Fixfield (Thanks to J.B's help) with 6 orders magnetic expansion precision for nonlinearity
- Developing a python script to interface with Fixfield (C/C++), facilitating its integration with model optimization frameworks or Machine Learnig (works done like PyZgoubi)




```
bz_f = B_f
bz_d = B_f * ratio_D_F
latt_gen = LatticeFileGenerator(periodicity=int(Ncells), filepath=lattice_filepath)
cell1 = Cell(cell_id=1, cell_type="ffag-spi-enge", step_size=0.001, collimators=(10, 13, 0.25),
            opening_angle_deg=angle)
magnet1 = Magnet(r_center=(long_drift + theta_f / 2), r0=rm, b0=-bz_f, k=Ki, spiral_deg=spiral_angle,
                 fringe_en_angle_deg=-omega1, fringe_en_A=0.14, fringe_en_order=6.0, fringe_en_c1=c1_param,
                 fringe_ex_angle_deg=omega1, fringe_ex_A=0.07, fringe_ex_order=6.0, fringe_ex_c1=c1_param)
cell1.add_magnet(magnet1)
magnet2 = Magnet(r_center=(long_drift + theta_f + theta_s + theta_d / 2), r0=rm, b0=bz_d, k=Ki,
                 spiral_deg=spiral_angle, fringe_en_angle_deg=-omega2, fringe_en_A=0.07,
                 fringe_en_order=6.0, fringe_en_c1=c1_param, fringe_ex_angle_deg=omega2,
                 fringe_ex_A=0.14, fringe_ex_order=6.0, fringe_ex_c1=c1_param)
cell1.add_magnet(magnet2)
magnet3 = Magnet(r_center=(long_drift + theta_f + theta_s + theta_d + theta_s + theta_f / 2), r0=rm, b0=-bz_f, k=Ki,
                 spiral_deg=spiral_angle, fringe_en_angle_deg=-omega3, fringe_en_A=0.07,
                 fringe_en_order=6.0, fringe_en_c1=c1_param, fringe_ex_angle_deg=omega2,
                 fringe_ex_A=0.14, fringe_ex_order=6.0, fringe_ex_c1=c1_param)
cell1.add_magnet(magnet3)
latt_gen.add_cell(cell1)
latt_gen.generate_file()
```

FFA magnets defination: User-friendly interface for interacting with Fixfield

Optimization Results of 16-cell FD and 12-cell FDF

- Two structure have the same fringe field coefficients for a fair comparison
- Generation=200， Pareto solution sets filtered by B_max<1.66T, β_z_0<8m,△R<0.8m

Fig.1 Spiral angle Vs DA

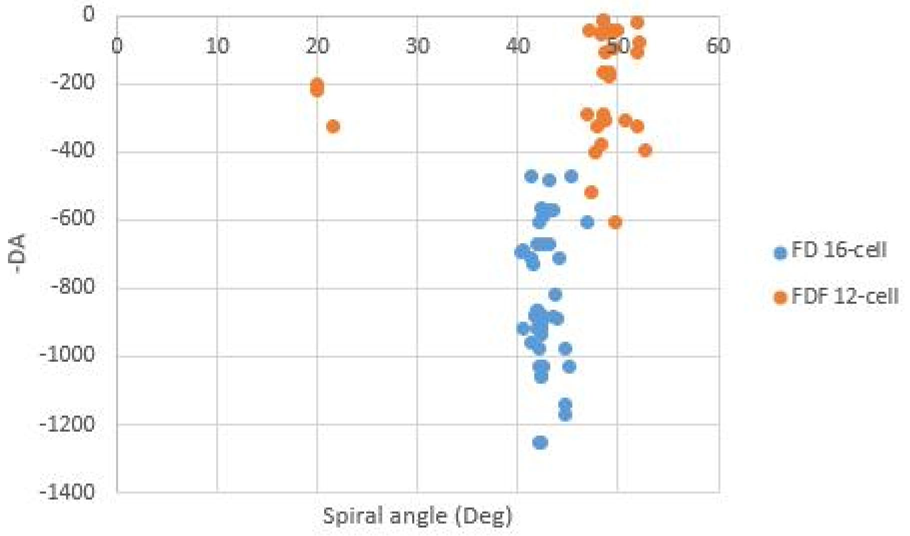


Fig.2 B_max Vs DA

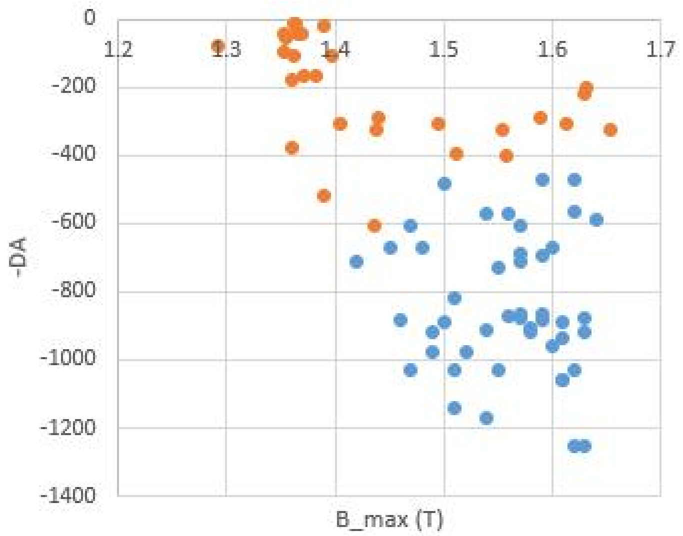
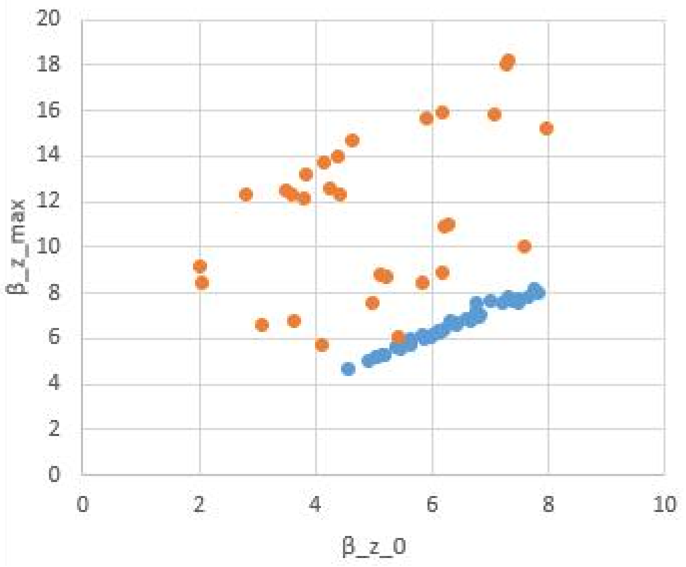


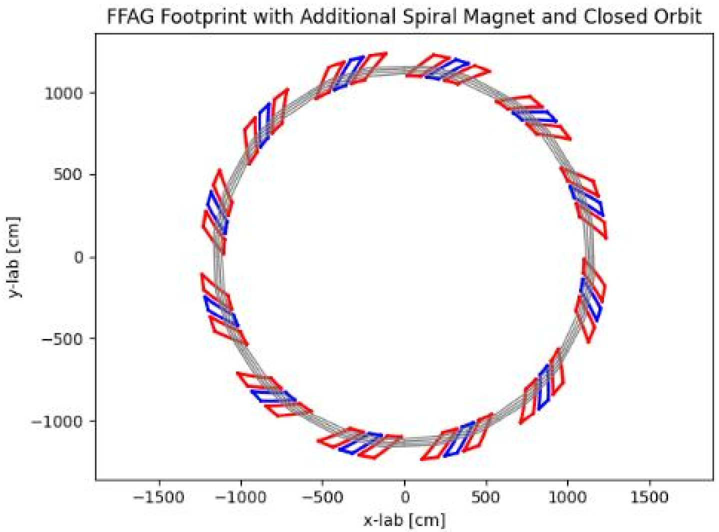
Fig.3 β_z_0 Vs β_z_max

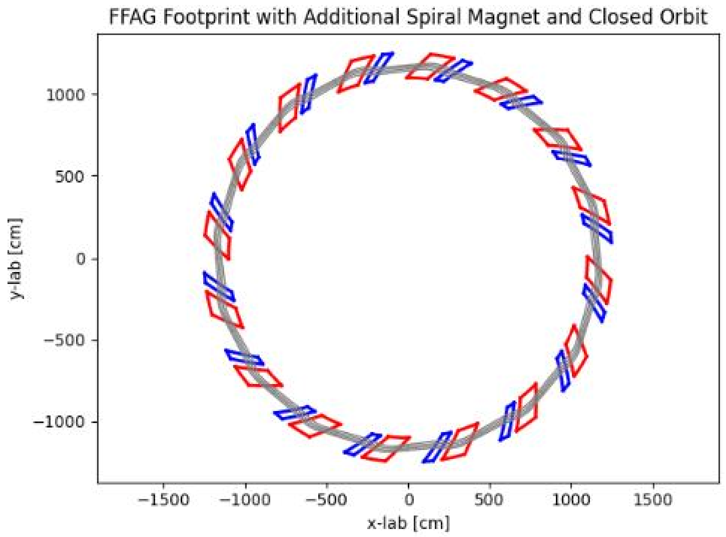


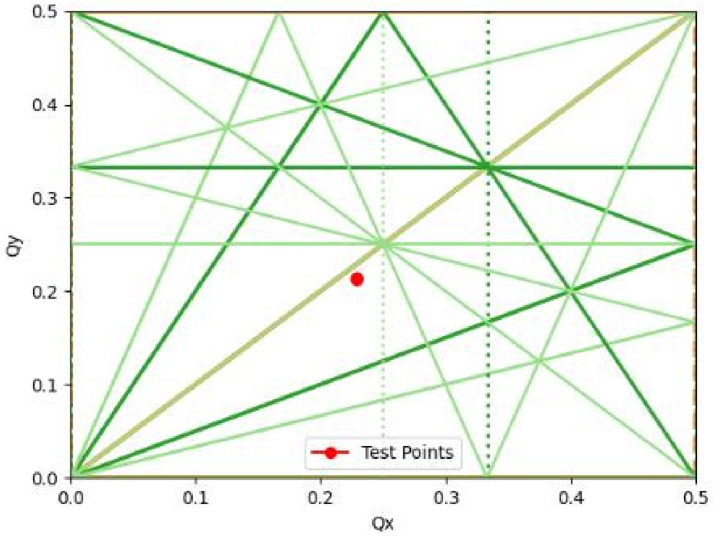
- Validation of the Surrogate Model:
  - The highest-performing solutions for the FD structure (in blue) are tightly clustered with a spiral angle around 42 degrees.
  - This results matche the optimal region predicted by the surrogate model analysis.

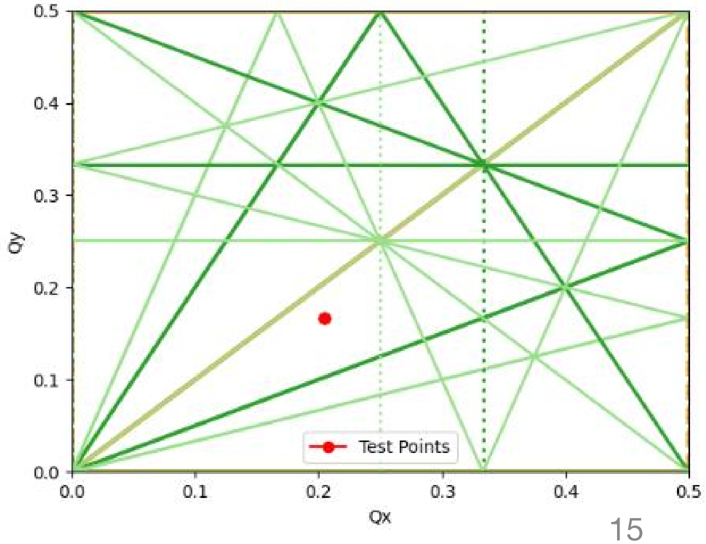
Final Design Parameters: 16-Cell FD Lattice

	FDF 12-cell	FD 16-cell
Spi_angle	47.272	42.343
Alfa	0.55	0.523
Rsm1	0.83	0.406
Rsm2	0.458	0.387
Ki	6.054	7.678
Bd/Bf	0.357	0.762
DA	520.912	936.401
△R (m)	0.761	0.784
B_max(T)	1.389	1.608
β_z_0(m)	5.046	5.609
β_z_max(m)	6.097	5.982
Drift (m)	1.986	1.872
Qx	2.743	3.28
Qz	2.475	2.572









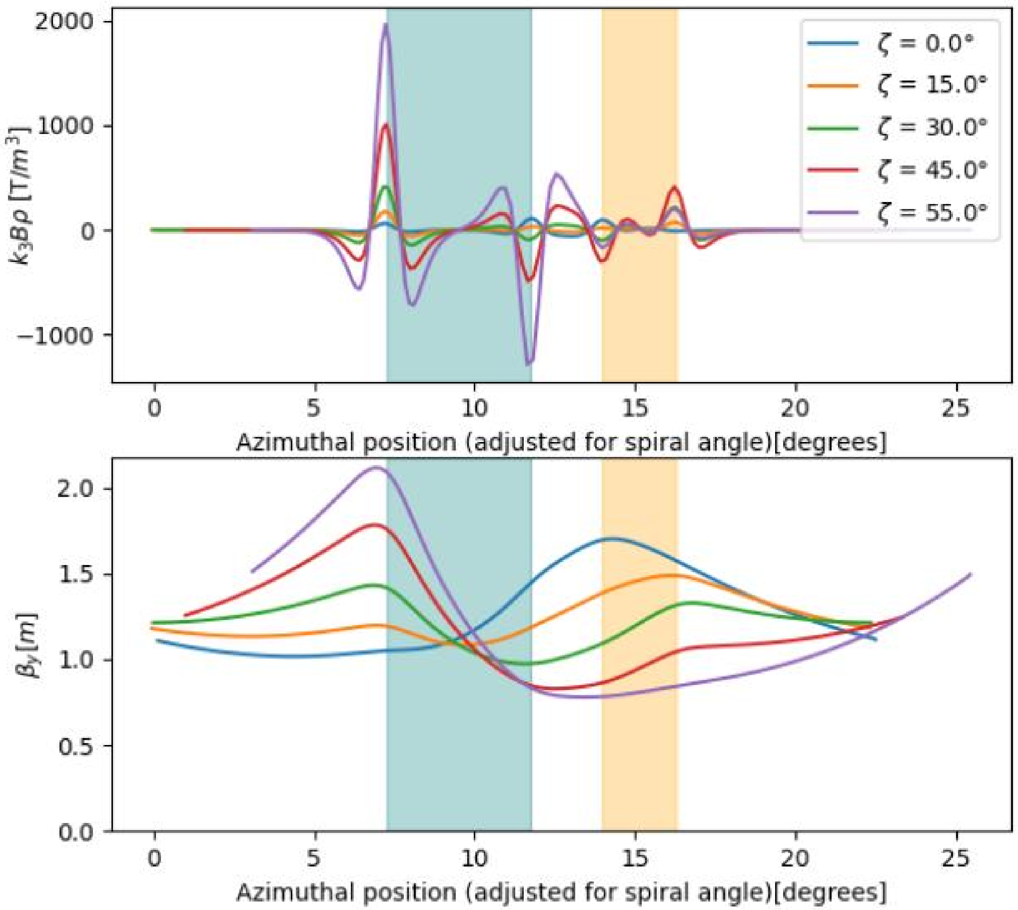
Summary

- A compact, high-intensity FFAG accelerator at CSNS, but initial lattice designs were unfeasible.
- Method: We developed an efficient optimization workflow by enhancing a genetic algorithm with machine learning.
  - This approach overcomes the extreme computational cost of traditional methods.
  - It allowed us to confidently identify a global optimum solution.
- Result: A 16-cell spiral FD lattice is a good choice
  - The design meets all strict physical and beam dynamics requirements.
  - It demonstrates superior stability and a larger dynamic aperture compared 12-cell FDF structures.
- However, as the injection scheme is closely coupled with the lattice design, the final parameters will require further fine-tuning.

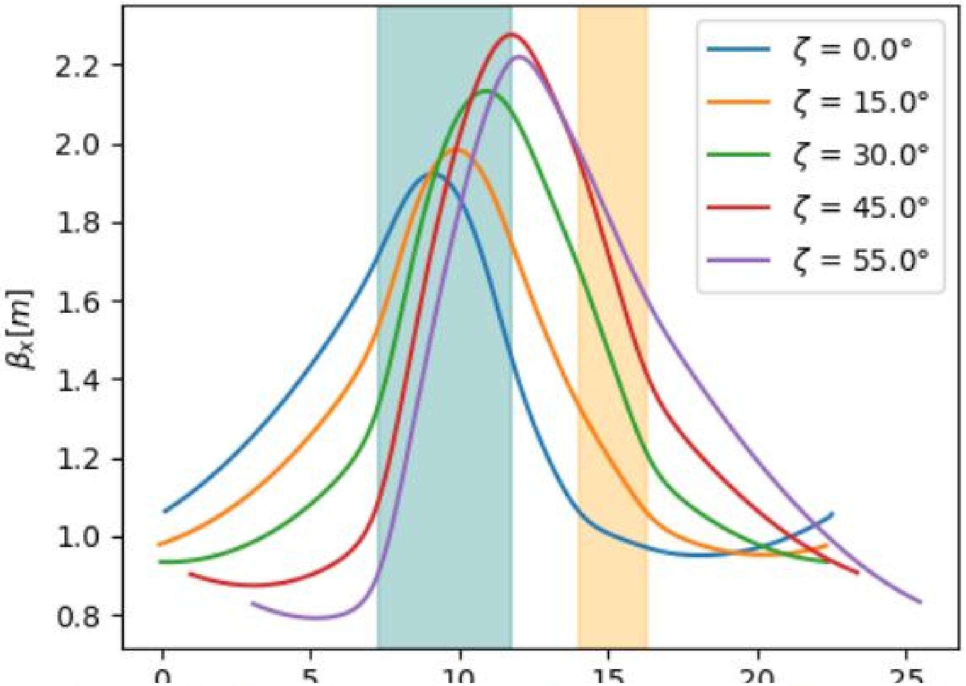
Thank you for your attention

Back up

- **Octuple component in fringe field is the limited source for DA，How to reduce the impact of Octuple component to tune shift requires the cooperation of the spiral angle**



M. Topp-Mugglestone. Nonlinear Dynamics of Scaling FFAs. IPAC 2023

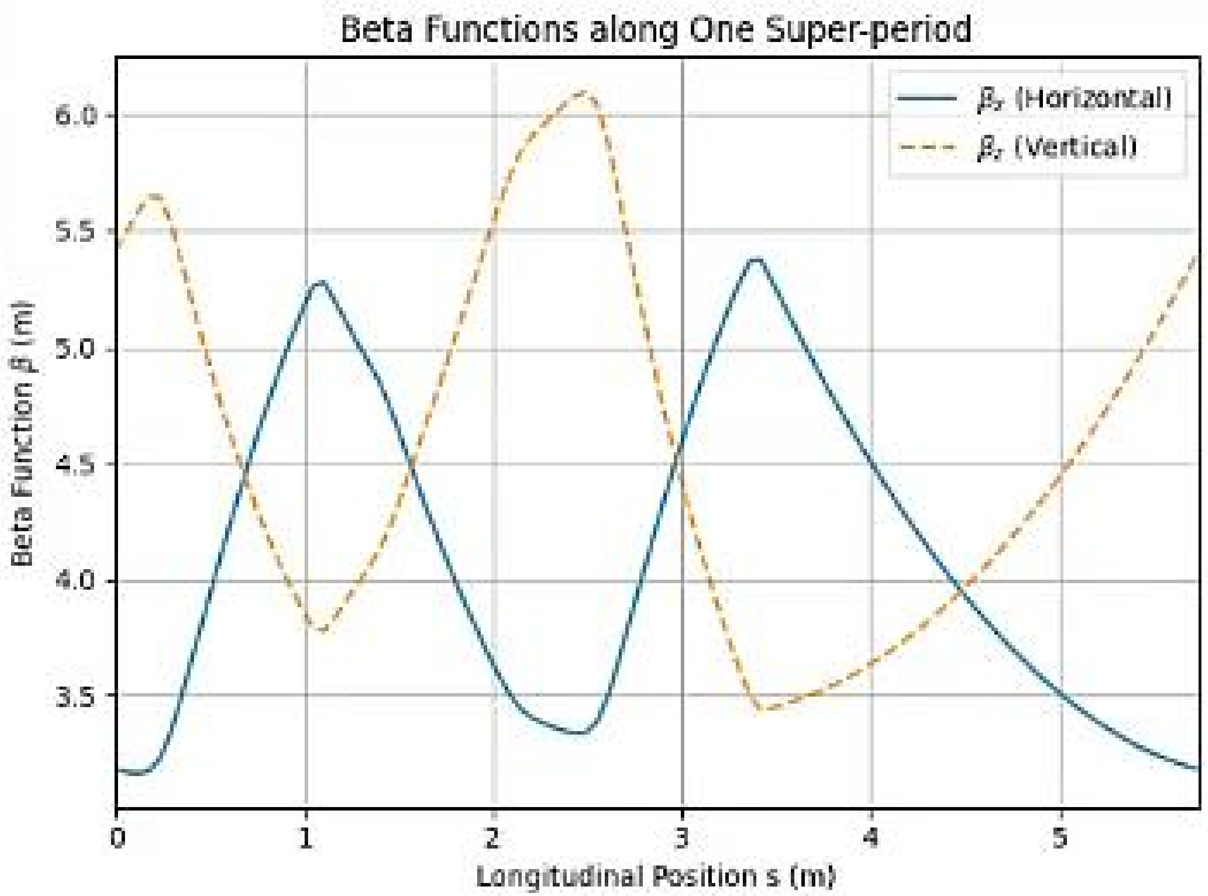


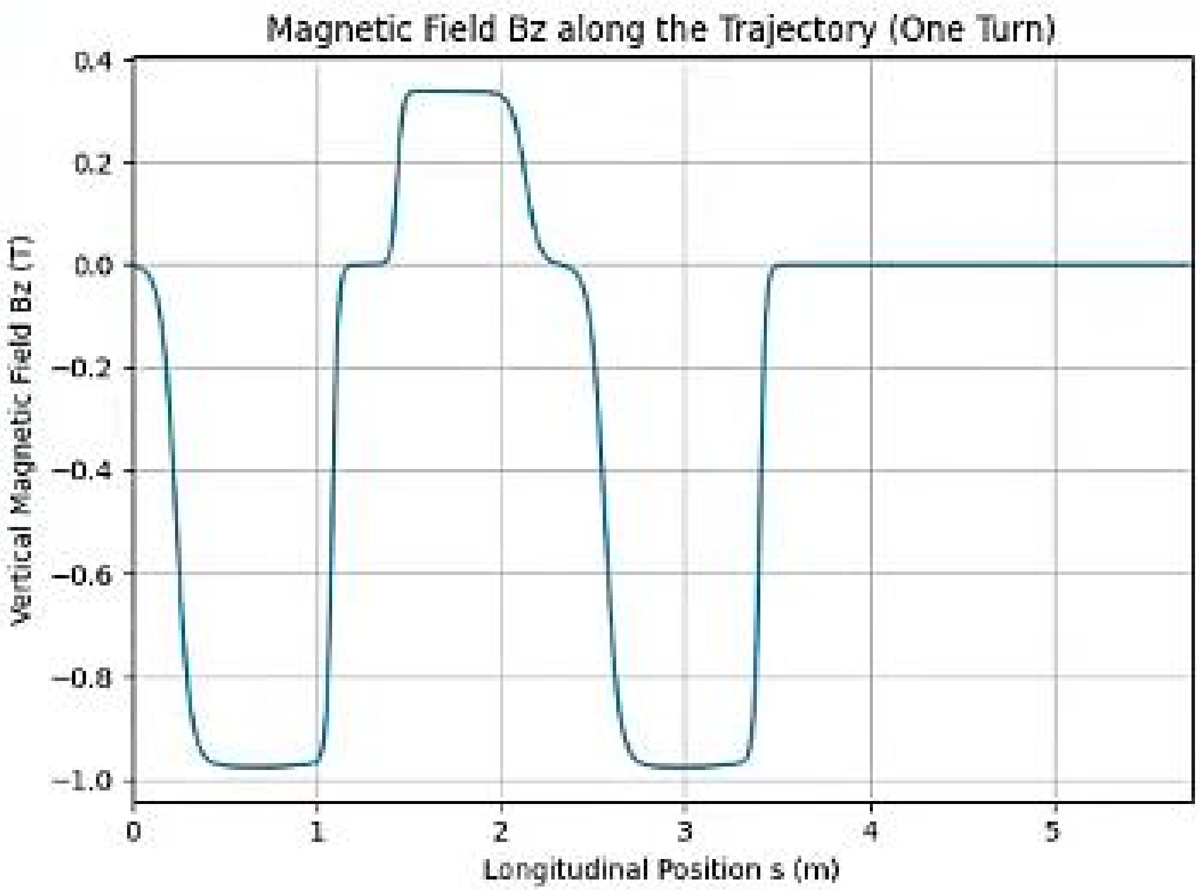
Tune shift with octupole B4 and amplitude Jx,y.

$$\Delta Q_y = \frac{q}{p}\frac{3B_4}{8\pi}\left(\beta_y^2 J_y - 2\beta_y\beta_x J_x\right)$$

Back up

- FDF, linear optics results（Fixfield code simulation）





Back up

- FD, linear optics results（Fixfield code simulation）