The Diamond-II Booster Design

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On behalf of the Diamond-II Injector Design Team

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Talk Outline

Diamond-II Lattice and New Booster Requirements

Booster Design Details

- Booster optics and main parameters
- Engineering details (RF / Diagnostics / Vacuum chamber)
- Injection and extraction schemes
- Orbit / Optics control

Booster Performance

- Dipole magnet modelling
- Impedance database
- Beam parameters during the ramp
- Single / coupled bunch thresholds

Diamond-II Lattice

Modified Hybrid 6-Bend Achromat (M-H6BA) for low emittance

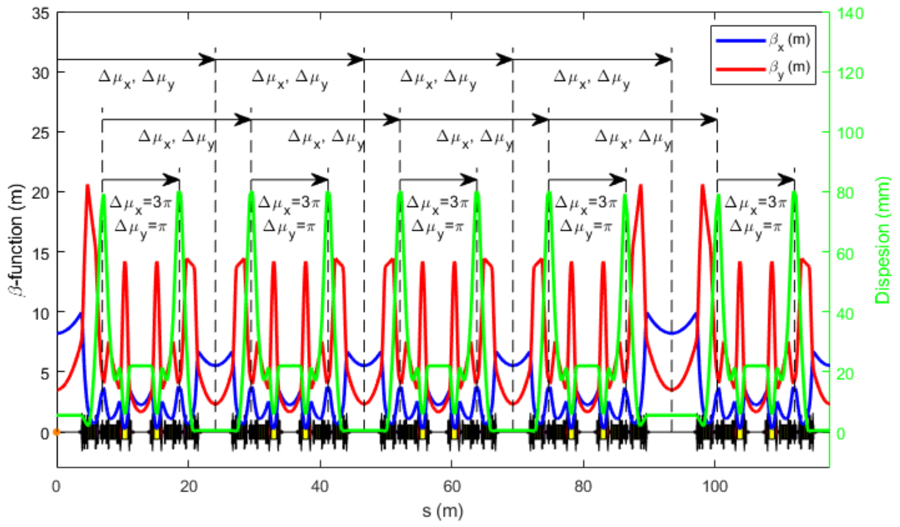
Number of insertion straights increased from 24 to 48

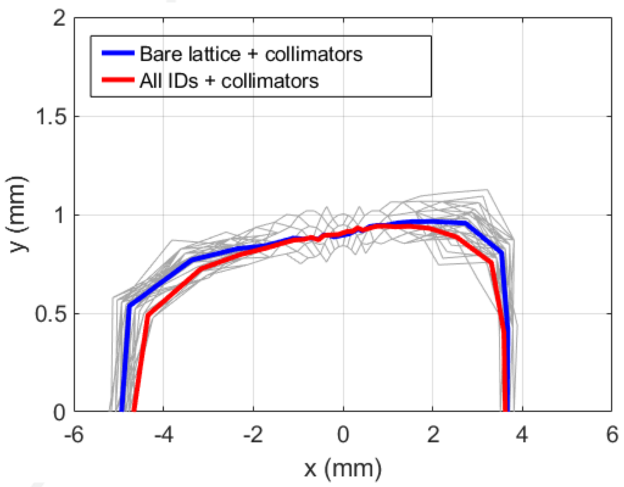
- Long straights: 7.54 m
- Standard straights: 5.06 m
- Mid straights: 2.92 m

Off-axis injection for beam accumulation

'-I' transformer plus const. cell phase for nonlinear dynamics

Passive SC harmonic cavity for lifetime / beam stability / IBS





Parameter	Units	Diamond	Diamond-II
Energy	**GeV**	**3.0**	**3.5**
Circumference	m	560.6	560.560944
Harmonic Number	-	936	934
RF Frequency	MHz	499.654	499.511
Positive Bending Angle	deg	360.0	374.4
Reverse Bending Angle	deg	0.0	14.4
Total Bending Angle	deg	360.0	388.8
Betatron Tunes	-	[27.21, 12.36]	[54.14, 20.24]
Natural Chromaticity	-	[-79.0, -35.6]	[-68.2, -89.1]
Corrected Chromaticity	-	[1.7, 2.2]	[2.6, 2.6]
Mom. Compaction Factor	$\times10^{-4}$	1.70	1.03
Natural Emittance	**pm.rad**	**2729**	**162**
Energy Spread	%	0.096	0.094
Energy Loss per Turn	MeV	1.01	0.724
Natural Bunch Length	ps	11.4@2.4 MV	12.4@1.4 MV
Horizontal Damping Partition	-	1.00	1.88
Horizontal Damping Time	ms	11.1	9.4
Vertical Damping Time	ms	11.2	18.1
Longitudinal Damping Time	ms	5.6	16.1

Booster-II Requirements

D-II storage ring injection requirements:

- Extraction energy increased to 3.5 GeV
- Lower emittance
- Shorter bunch length
- Increased charge per shot (SB and MB)

Other considerations:

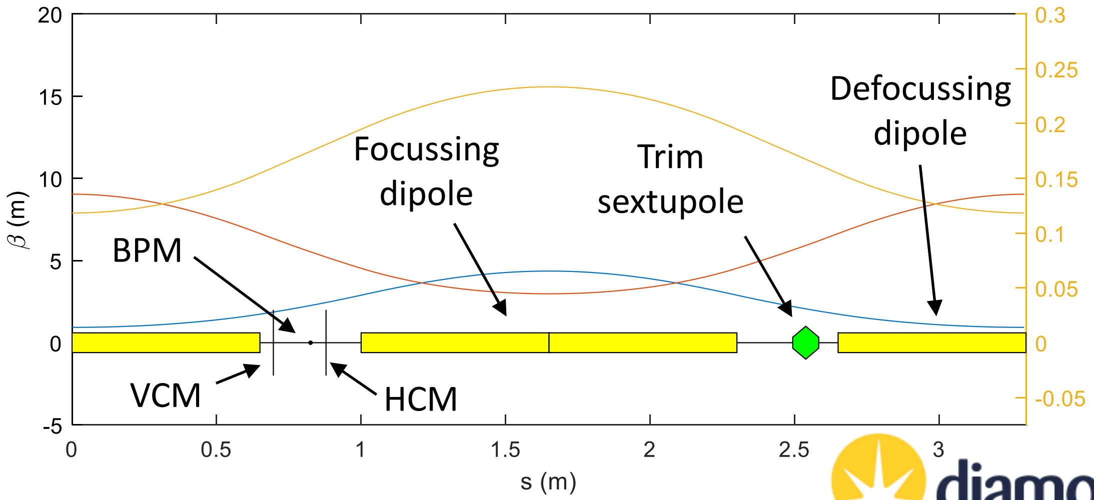
- Must fit in existing tunnel (racetrack)
- High transfer efficiency
- Low impedance for high-current bunches
- Robust performance / low error sensitivity
- Long-term reliability

=> Unit cells built from combined-function dipoles

	Existing booster	Target
Energy	0.1 - 3.0 GeV	0.1 - 3.5 GeV
Emittance	134 nm.rad	<30 nm.rad#
Bunch length	100 ps	<40 ps*
Max. SB charge	~0.2-0.4 nC	~5 nC+
Max. MB charge	~1-2 nC	~15 nC+

#defined by storage ring dynamic aperture
*defined by storage ring momentum aperture
+for future-proofing, robustness and fast fill times

Booster-II Unit Cell



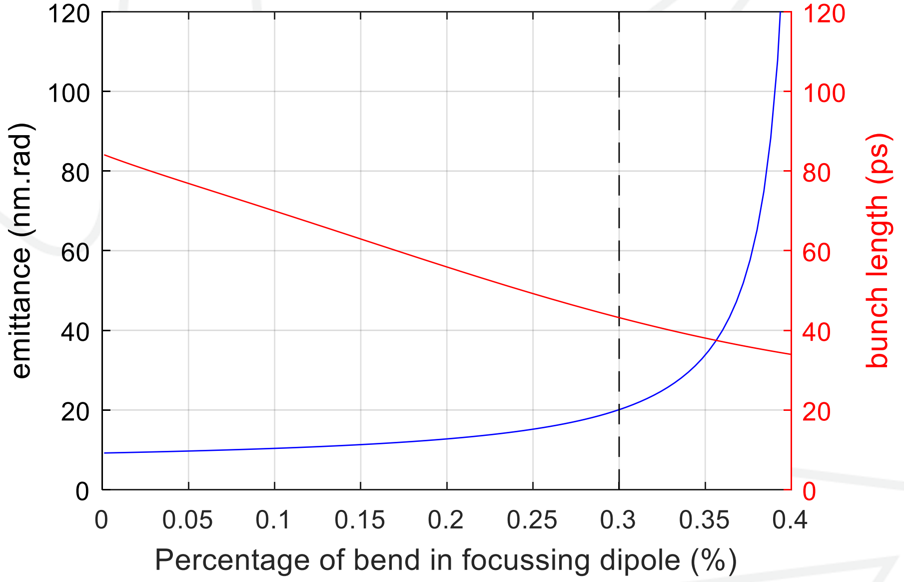
Unit Cell Optimisation

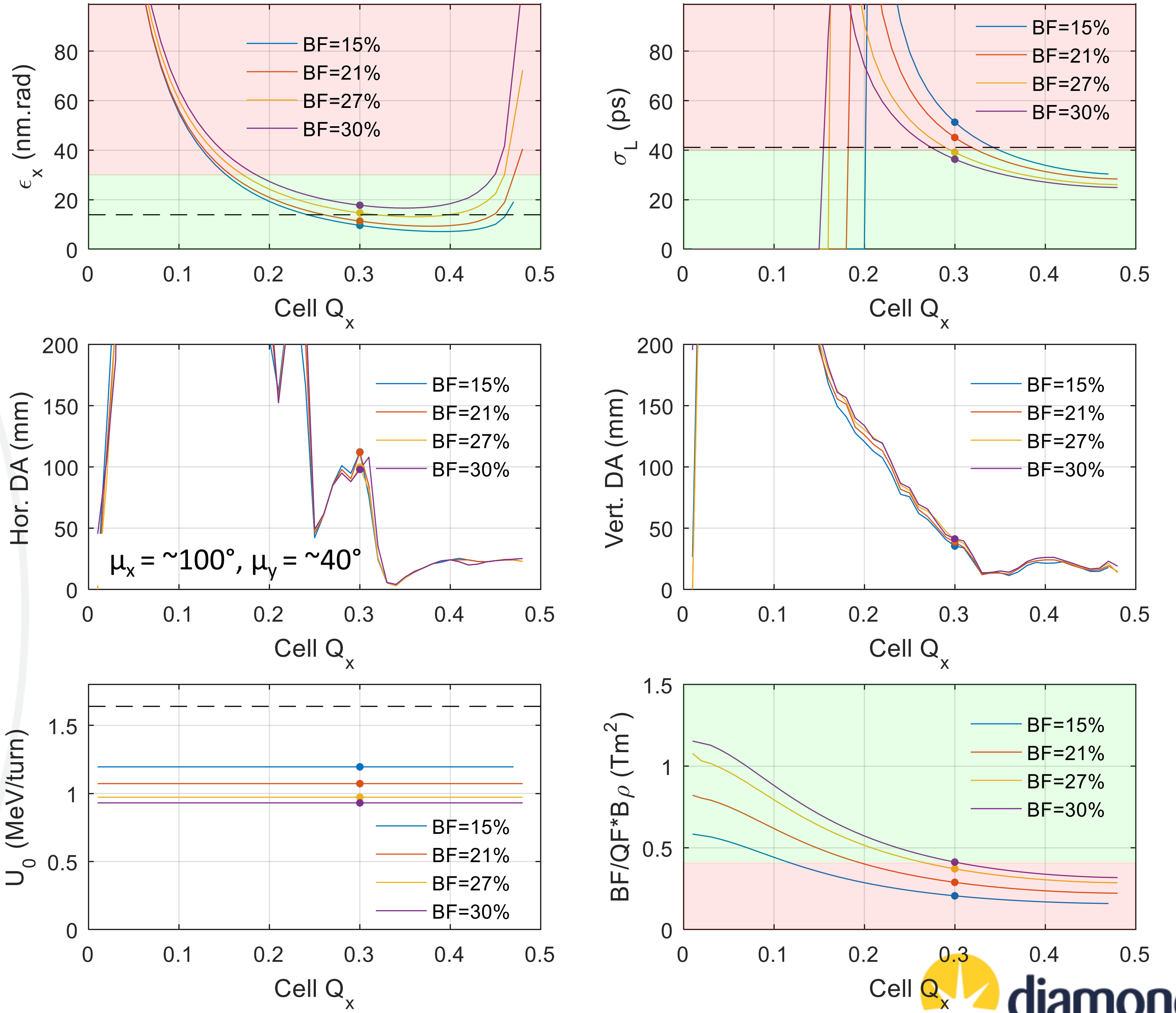
<u>Systematic scan:</u>

- Number of unit cells
- Dipole lengths / field components

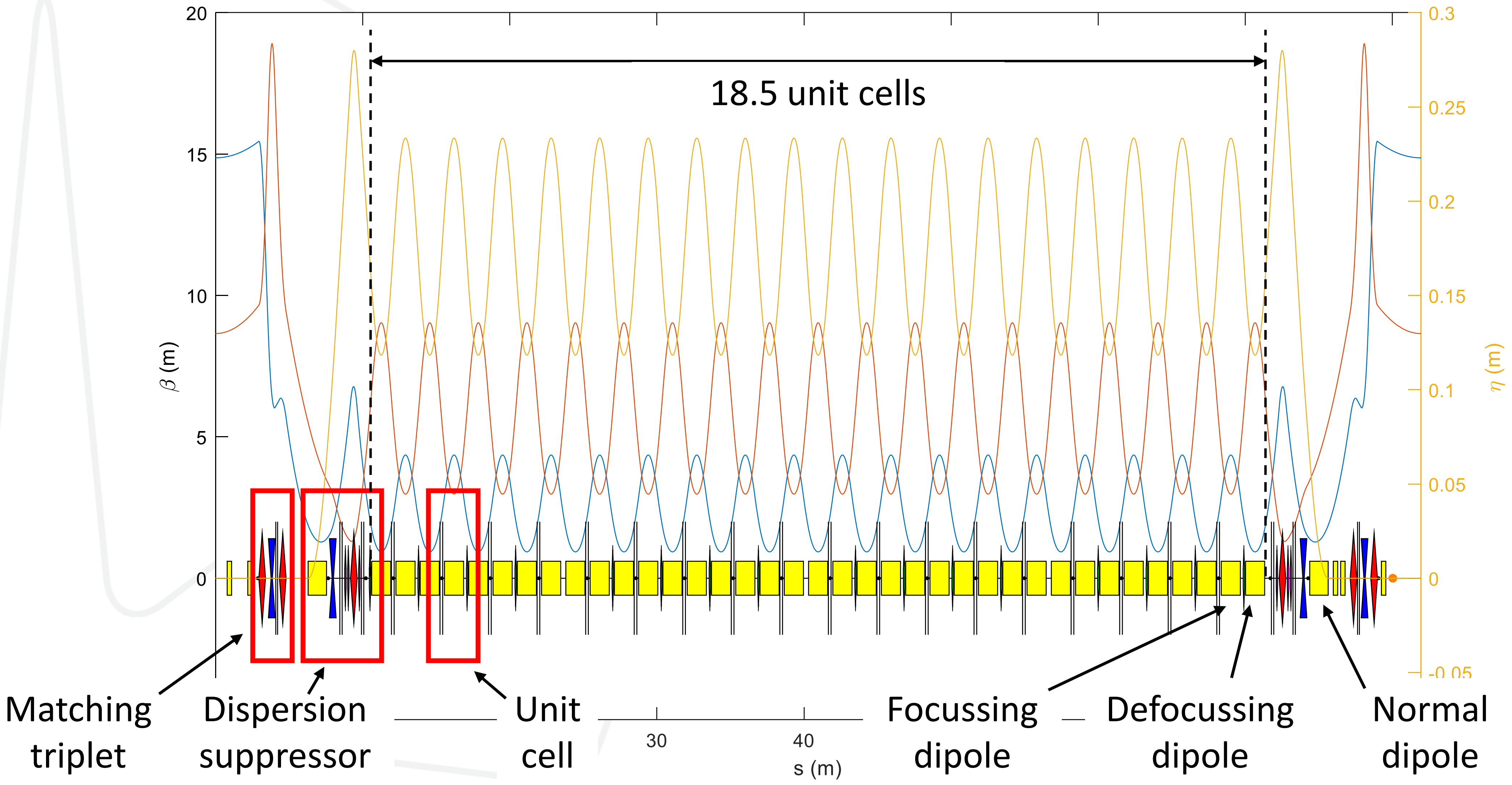
<u>Constraints:</u>

- Magnet separation 0.35 m
- Ratio B/G > 0.035 to keep design of focussing dipole practical





Booster-II Super-Period



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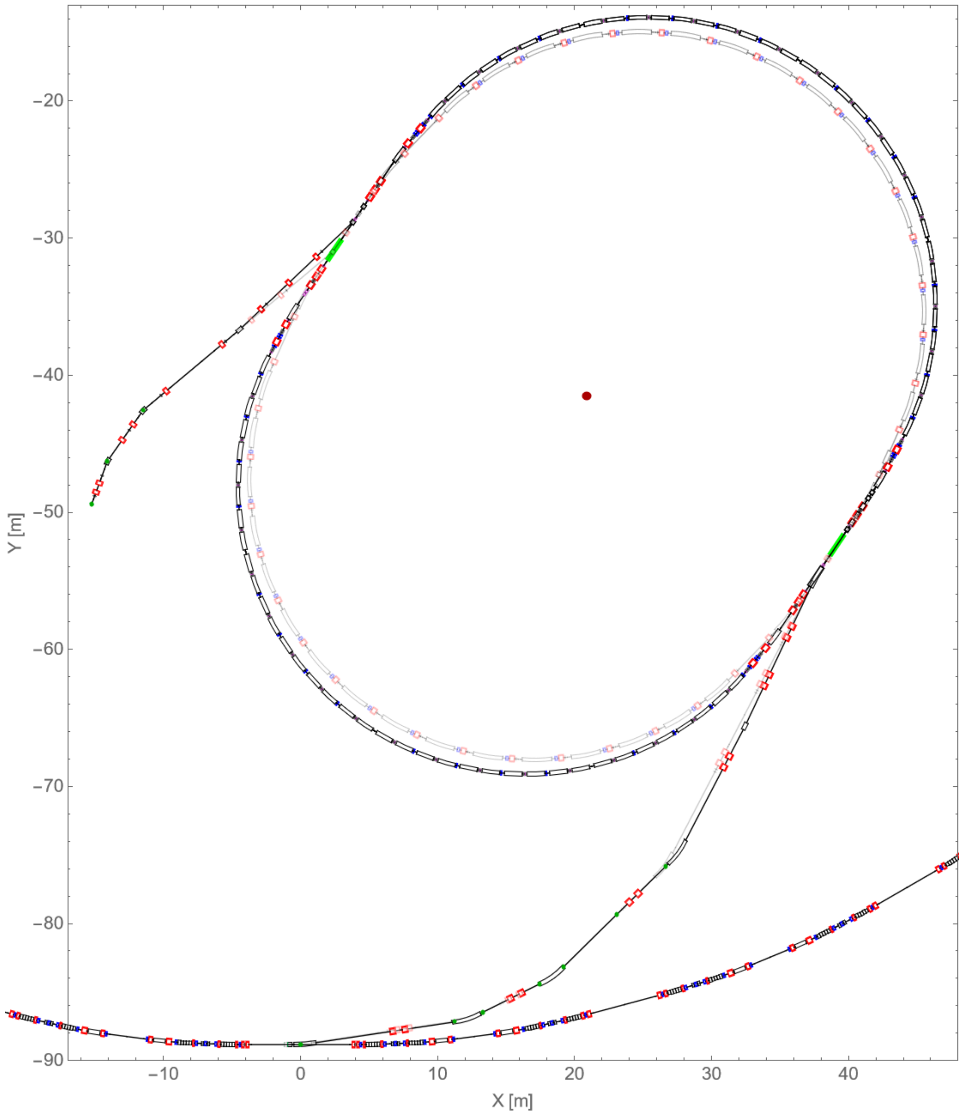
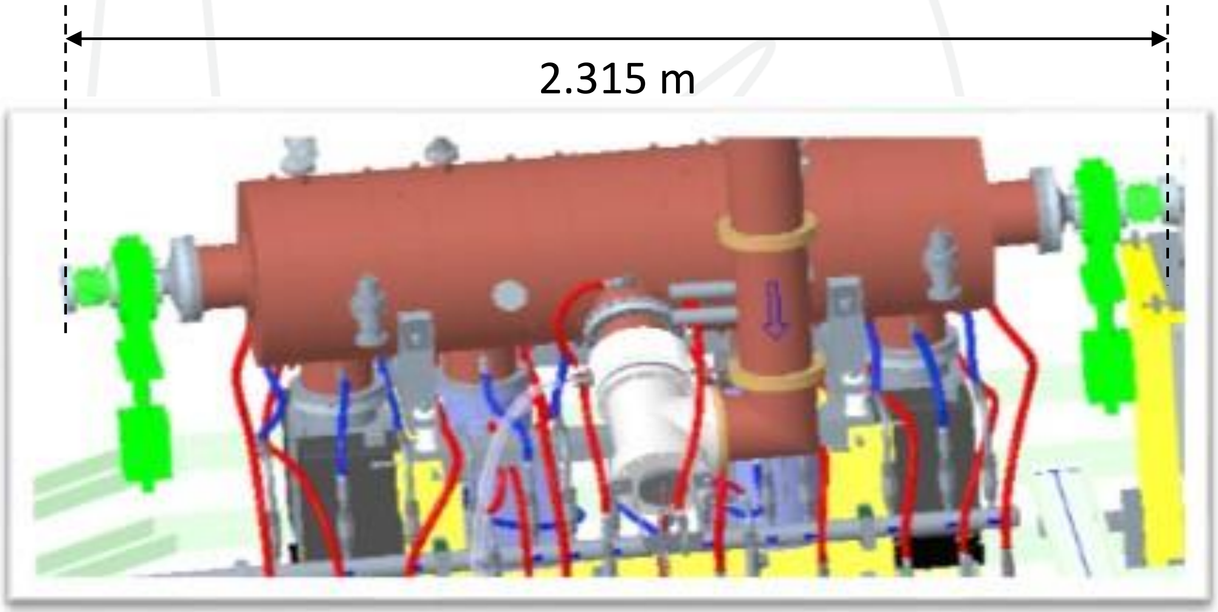
Booster-II Parameters

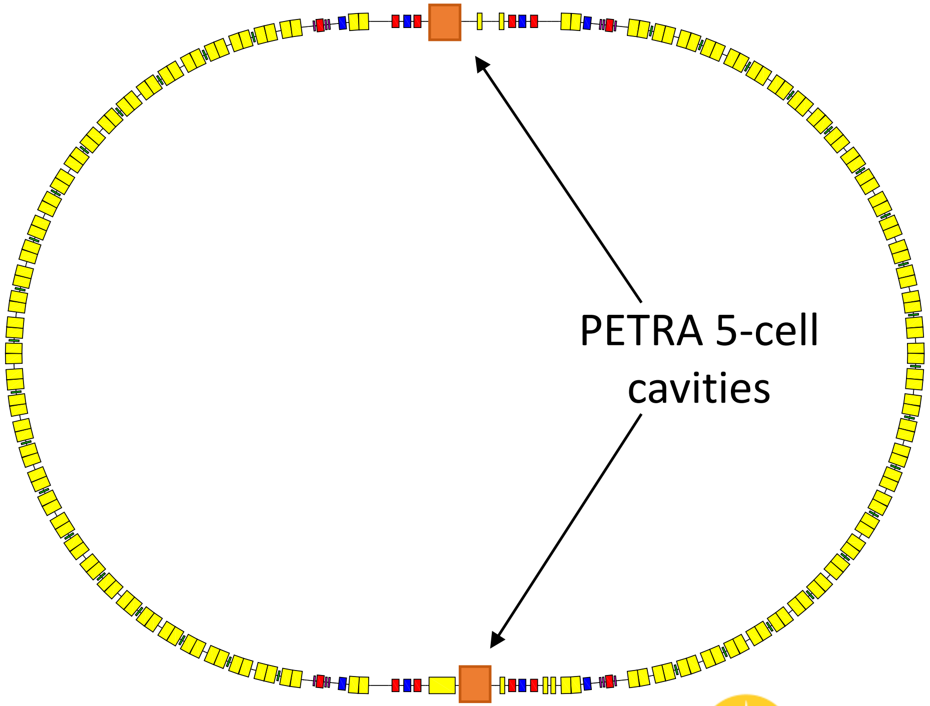
Parameter	Units	Target	Existing booster	Booster-II
Energy range	GeV	0.1 – 3.5	0.1 - 3	0.1 - 3.5
Number of cells	-	-	22	37+4
Circumference	m	-	158.4	163.847
Betatron tunes	-	-	[7.18, 4.27]	[12.41, 5.38]
Natural chromaticity	-	-	[-9.7, -6.3]	[-13.5, -11.9]
Mom. comp. factor	-	-	25.2×10^{-3}	5.65×10^{-3}
Emittance	nm.rad	<30	134.4	17.3
Energy spread	%	-	0.073	0.086
Loss per turn	MeV	-	0.58	0.95
Nat. bun. len.	ps	<40	99.3	38.0
RF voltage	MV	-	1.0	2.0
RF acceptance	%	-	0.61	0.93
$[J_x, J_y, J_E]$	-	-	[1.00, 1.00, 2.00]	[1.10, 1.00, 1.90]
Damping times	ms	-	[5.46, 5.47, 2.74]	[3.66, 4.04, 2.13]



Booster-II RF

- **Re-use existing two PETRA 5-cell normal conducting cavities**
- Install one in each of the two long straights
- Can provide **>1 MV per cavity** (nominal operating voltage = 2 MV total)
- Need to modify tuner assembly to match to the D-II storage ring RF frequency (499.5 MHz)
- Existing IOTs to be replaced with solid-state amplifiers
- Digital LLRF system





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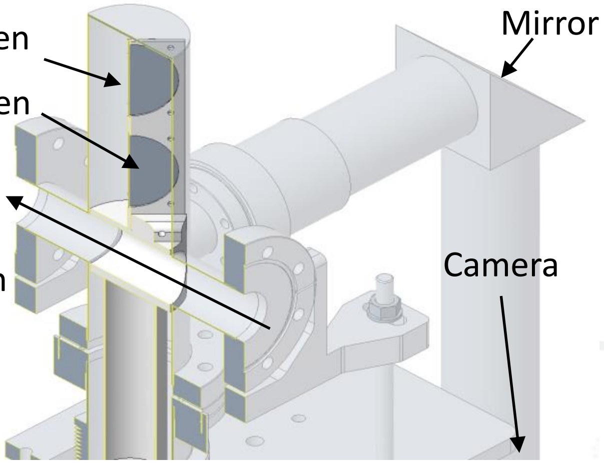
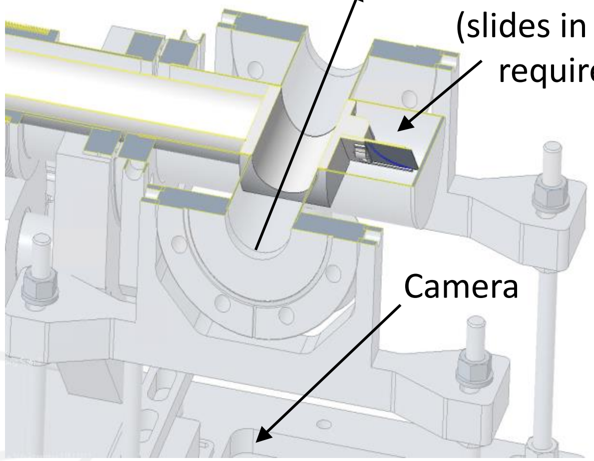
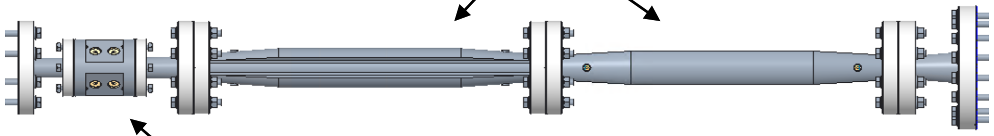
Booster-II Diagnostics

Diagnostic	Beam Parameter	Quantity	Location
BPMs	Position	48	Distributed
Beam loss detectors (BLDs)	Losses	32	Distributed
DCCT	Beam current	1	Injection straight
OTR / YAG screens	Transverse profile	1	Downstream of injection septum
		1	Upstream of extraction septum
Stripline kickers	Multibunch feedback*	2	Injection straight
Extra BPMs buttons		1	

*open-loop only for day 1



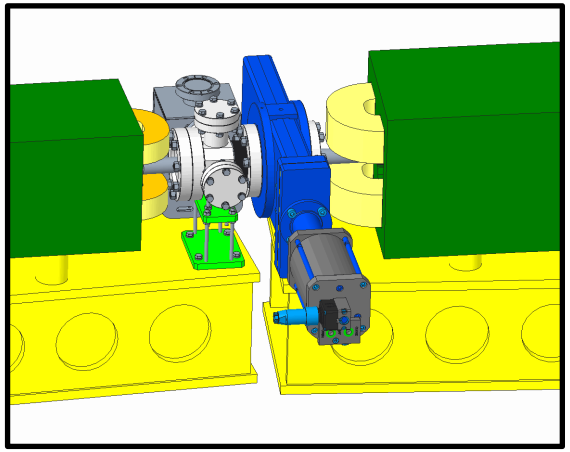




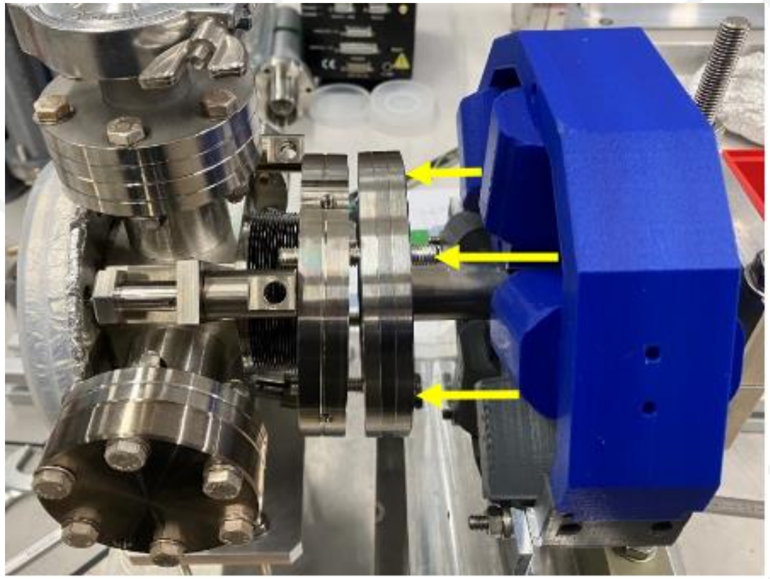
Booster-II Vacuum Chamber Components

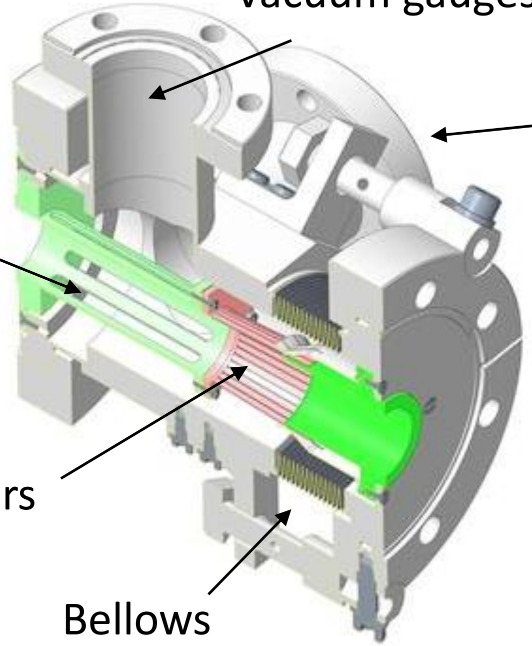
- 1 mm thick stainless steel vacuum chamber; circular cross section
- 1 mm clearance between chamber and magnet poles
- Minimise impedance where practical / cost effective
- 11.5 mm radius in arcs, 18.3 mm in straights and matching sections (internal)
- One ceramic break and two gate valves per arc
- Combined pumping cross / bellows section designed for low impedance

Arc girder with gate valve

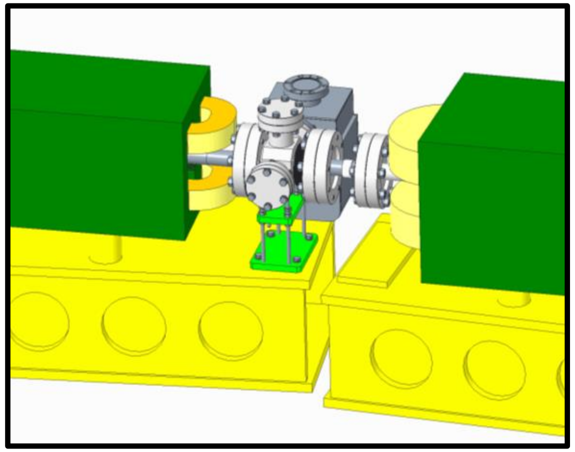


Prototype pumping cross and dummy sextupole



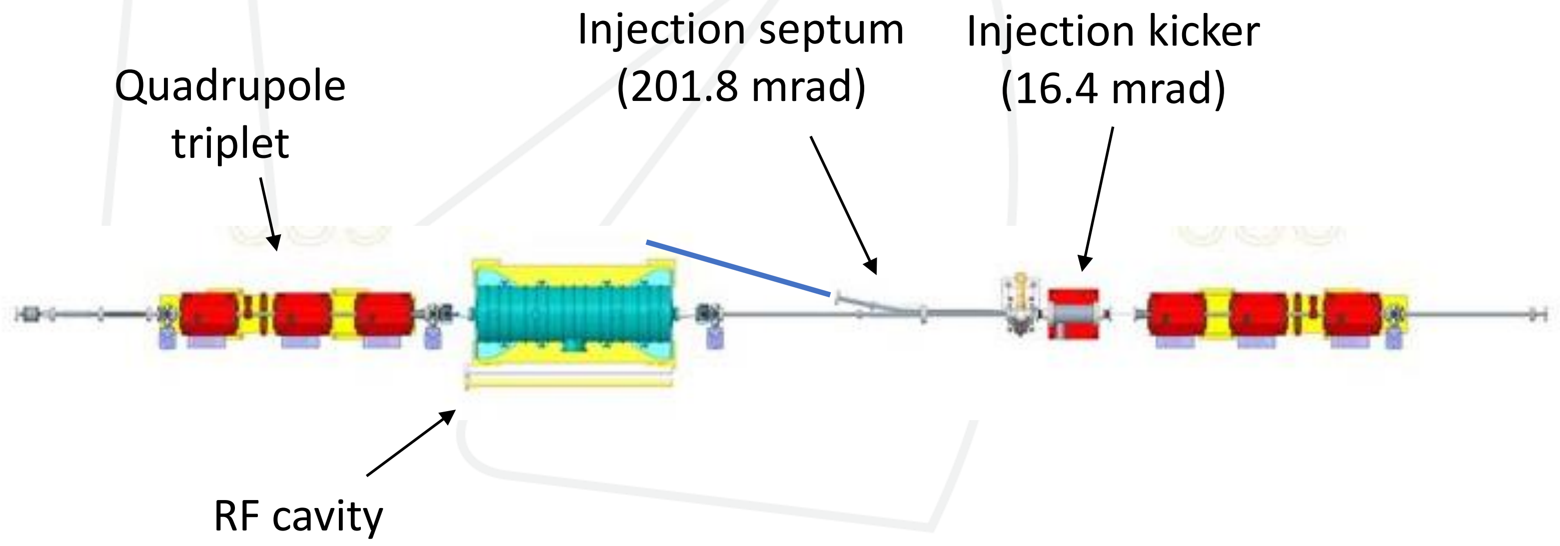


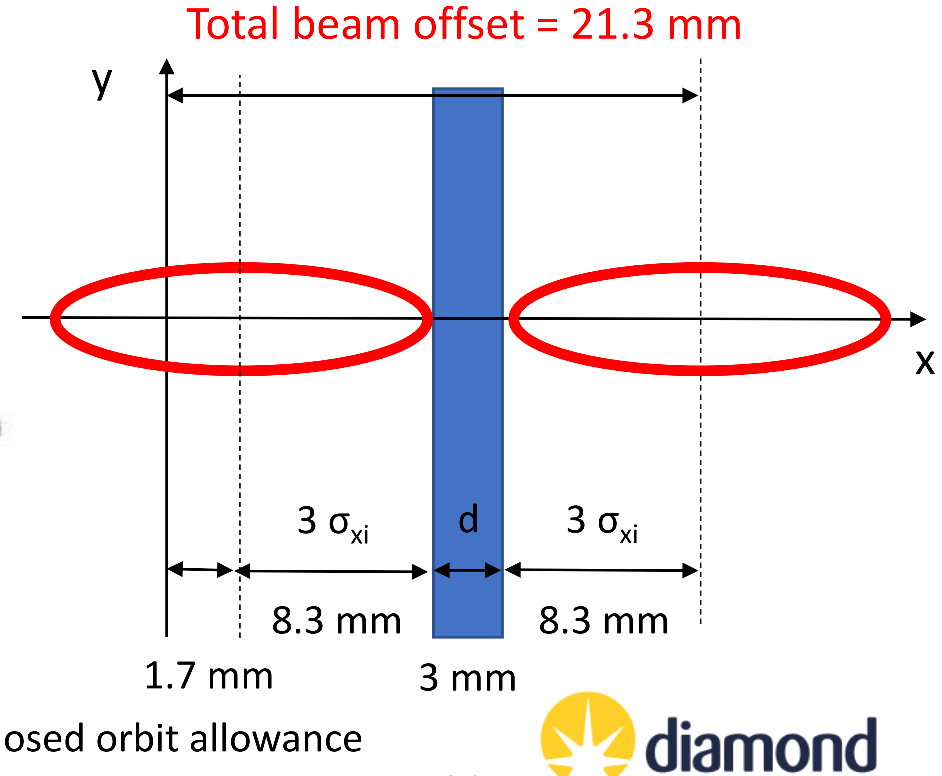
Arc girder with ceramic break



Injection

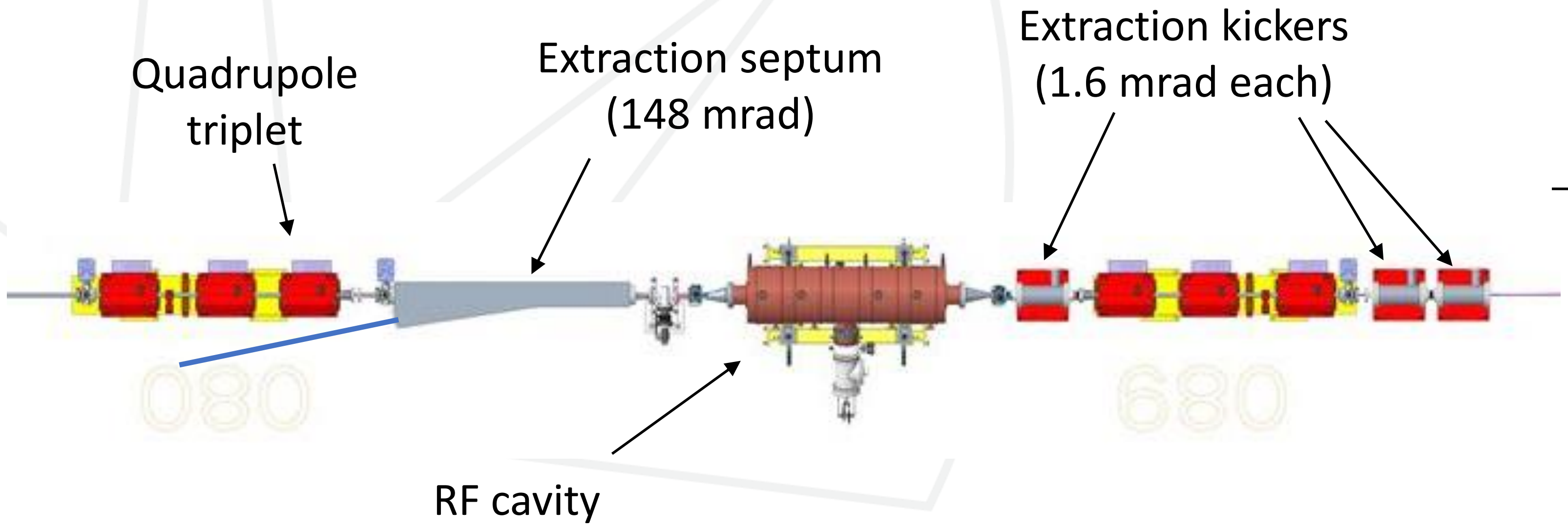
- **On-axis injection** using single septum and kicker (100 MeV nominal, potential for 150 MeV)
- All components in main straight
- Septum offset positioned to give space for $3\sigma_{xi}$ for injected beam, plus contingency for closed orbit distortions
- Booster injection point moved downstream to give LTB space to clear RF cavity
- Beam exits LTB at $3\sigma_{xi}$ on the outside edge
- Conservative assumption for linac emittance (ε_N = 100 mm.mrad)

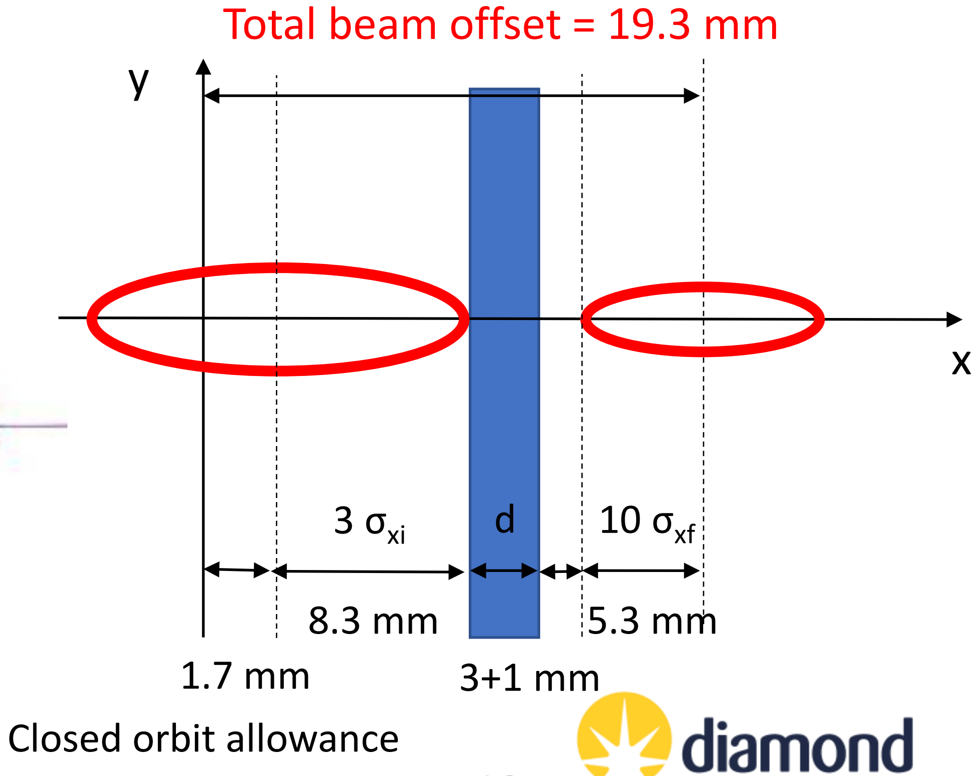




Extraction

- **Single-turn extraction** using single septum and three kicker magnets (two before triplet and one after)
- Extracted beam passes off-axis through the quadrupole triplet and the RF cavity
  - ➢ Beam offset in RF cavity: 13.3 mm at entrance, 19.0 mm at exit.
  - ➢ Cavity minimum bore 120 mm. Negligible perturbation from off-axis field in CST model.
- Extraction septum bend angle increased so that BTS clears downstream quadrupoles
- Beam enters extraction septum at 10 σ_{xf} from septum plate (+1 mm tolerance)
- Extraction septum horizontal offset matched to injection septum





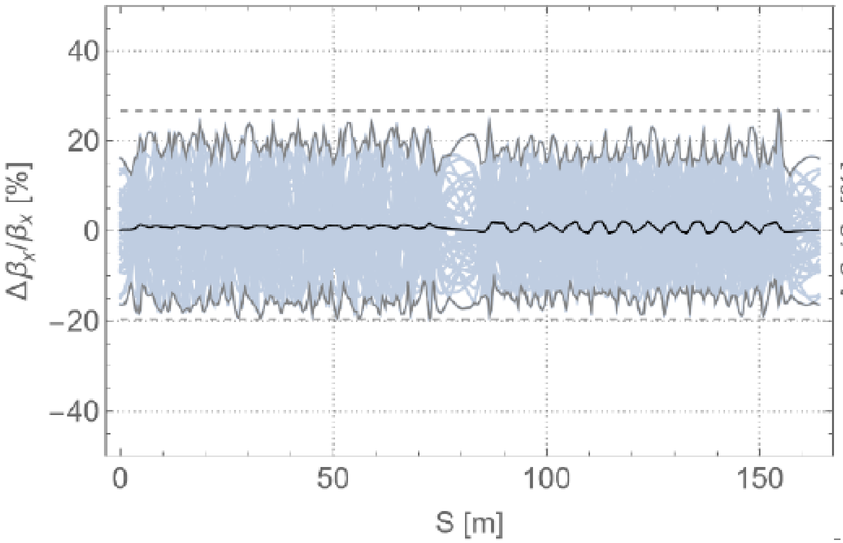
Orbit and Optics Control

- Orbit correction using 48 BPMs + 48 dedicated HCMs and VCMs (separated function)
  - ➢ Correctors can be ramped with beam energy, if required
  - ➢ Residual orbit distortion <0.5 mm in both planes (excluding BBA offsets)
- Tune correction by adjusting matching-section quadrupole ramp waveforms (no beta-beat correction)
  - ➢ Trade-off between beta-beat and tune control: quadrupole correctors far from source of errors
- Chromaticity control using dedicated trim sextupoles

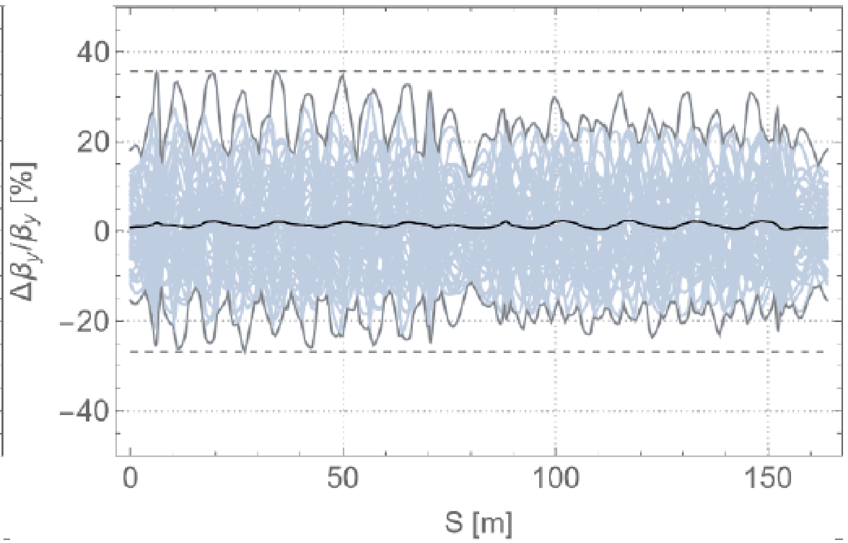
Error Table

Element	Alignment (µm)	Roll (mrad)	Strength (%)
Dipole	100	0.2	0.2
Quadrupole	50	0.2	0.5
Sextupole	50	0.2	1.0
Girder	150	0.15	-
BPM	500	10.0	-

Residual Horizontal Beta-beat

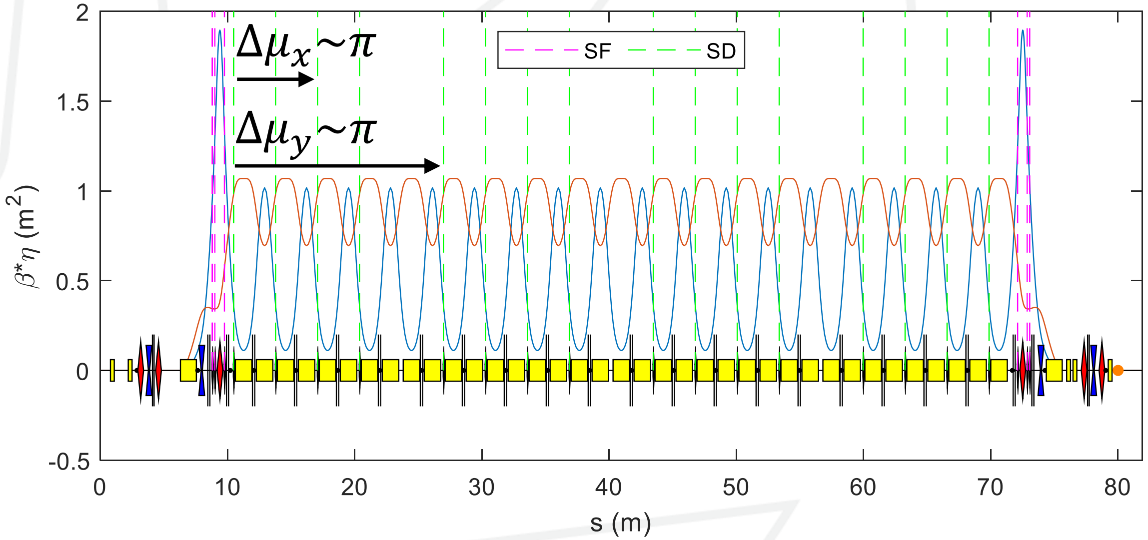


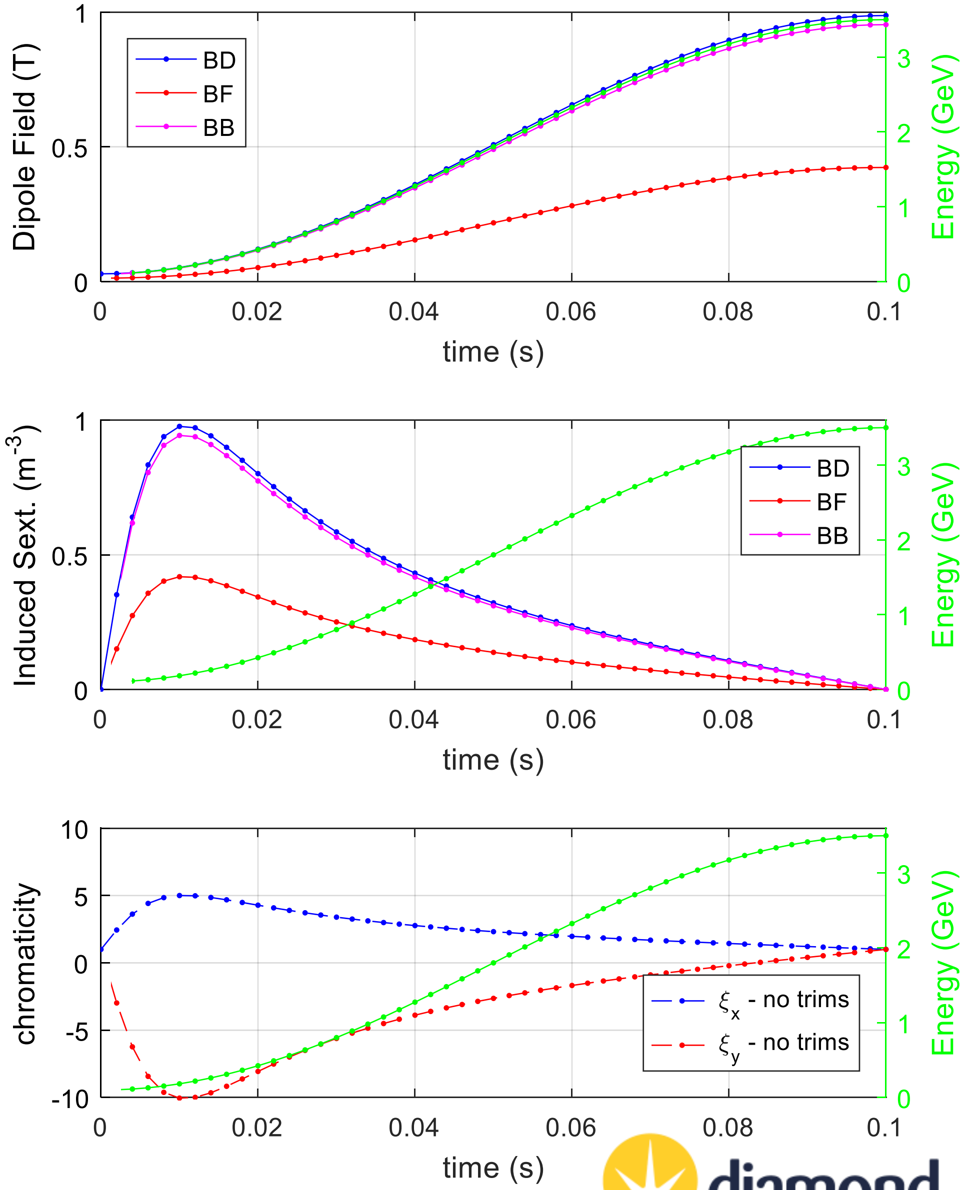
Residual Vertical Beta-beat



Impact of Eddy Currents

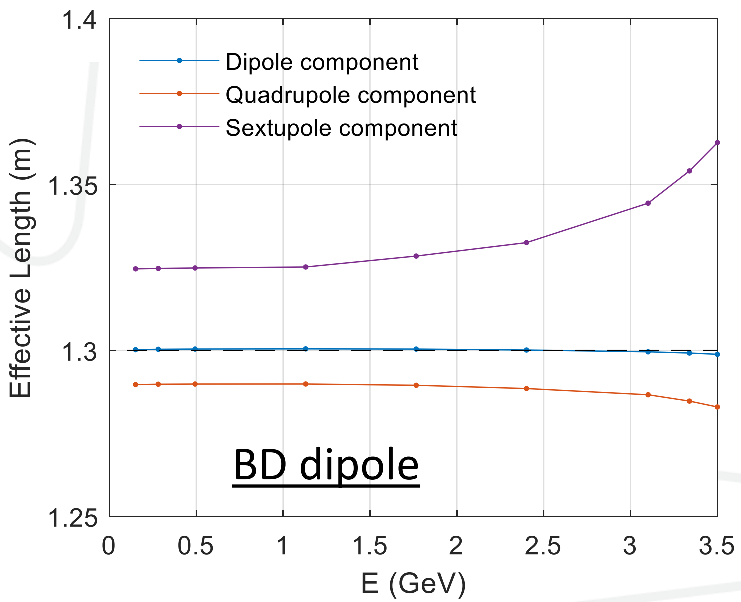
- Trim sextupoles used to compensate induced eddy-current sextupole fields driven by ramping main dipoles
  - ➢ Positive induced sextupole component
  - ➢ Requires defocussing sextupoles to compensate
- Trim sextupole locations chosen for maximum $\beta_{x,y} \times \eta_x$
  - ➢ Defocussing trim sextupoles grouped in sets of 4 to give natural cancellation of driving terms
  - ➢ Focussing trim sextupoles in dispersion suppressor

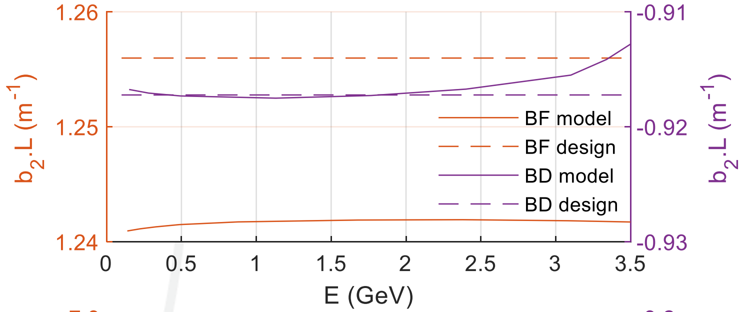


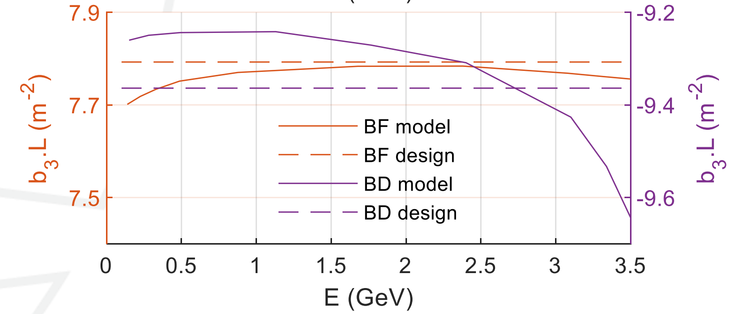


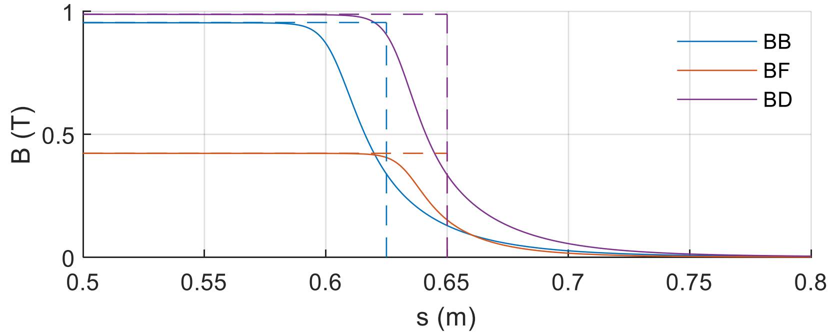
Combined-Function Dipole Modelling

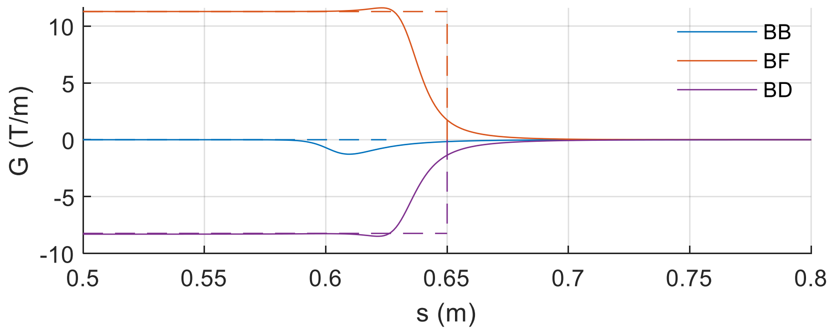
- Edge effects for combined-function dipoles found to be significant
- Dipoles modelled as hard-edge magnets
  - Bulk parameters set to match integrated values
  - Thin lenses at entrance/exit to account for edge-effects
- OPERA magnet models as a function of beam energy used to extract s-dependent multipole expansion field data
- Magnet parameters vary during the ramp

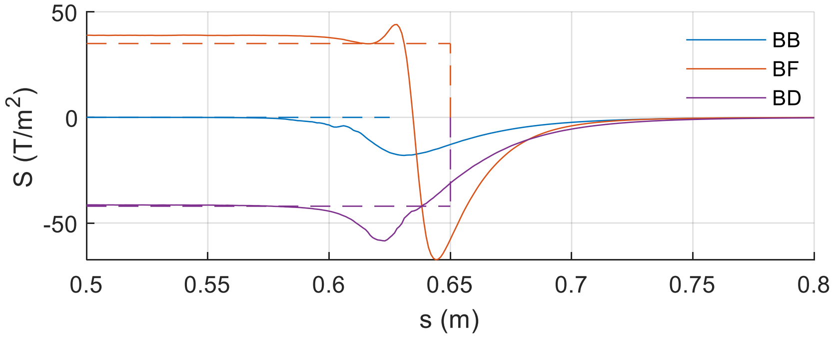






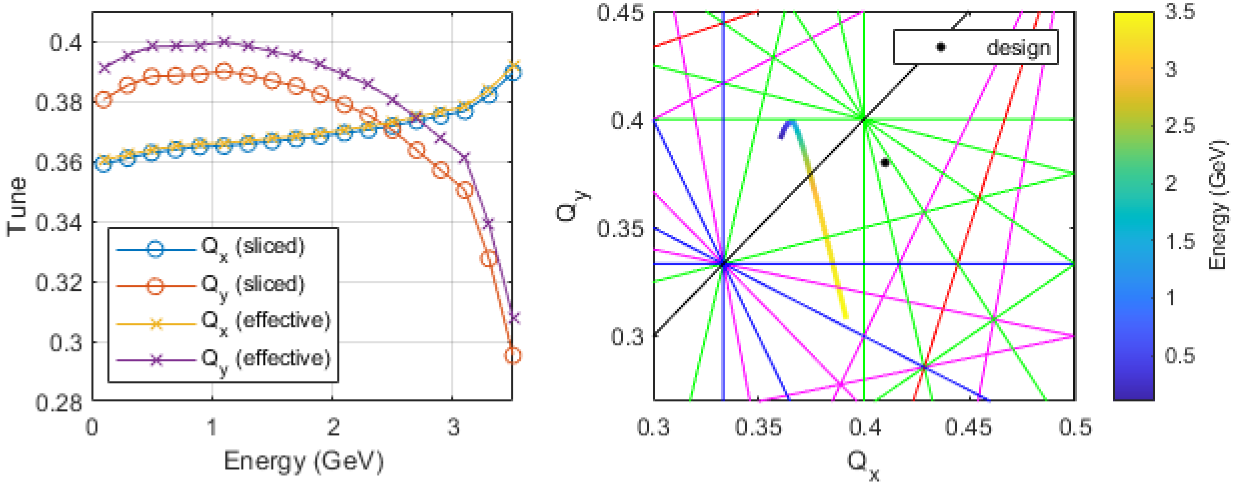


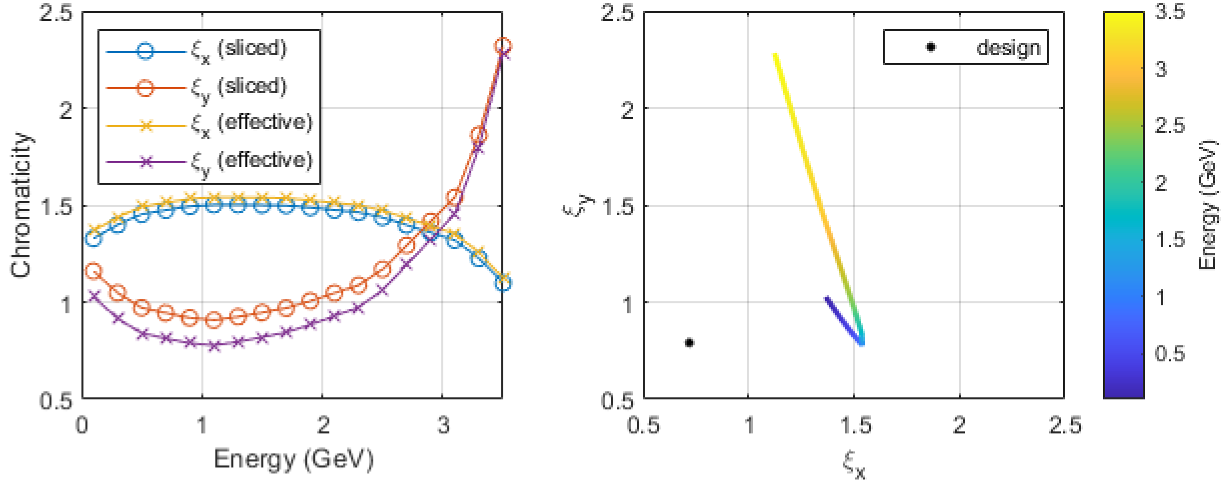




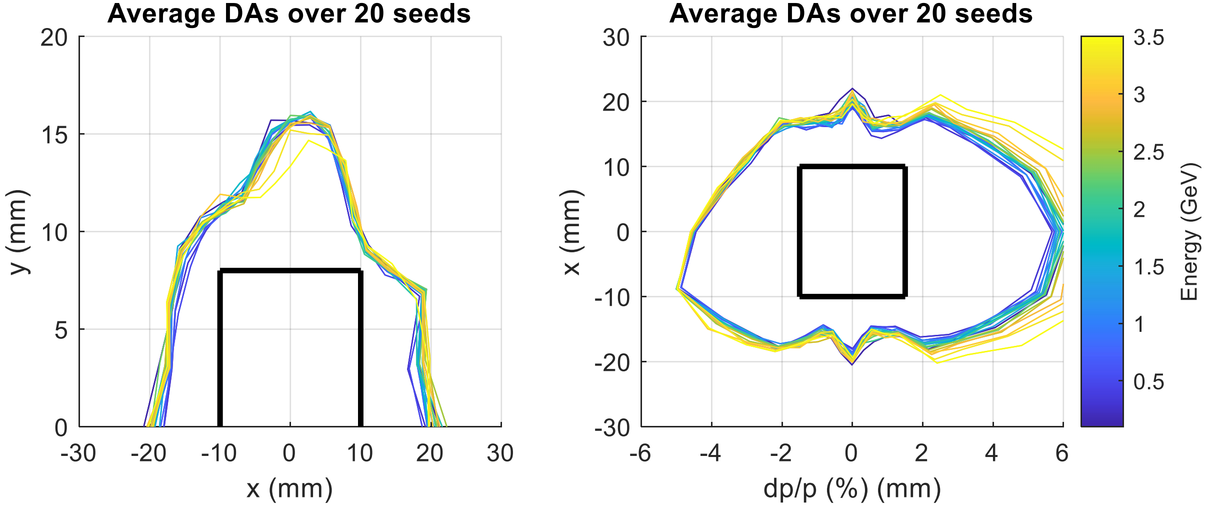
Booster Optics During the Ramp

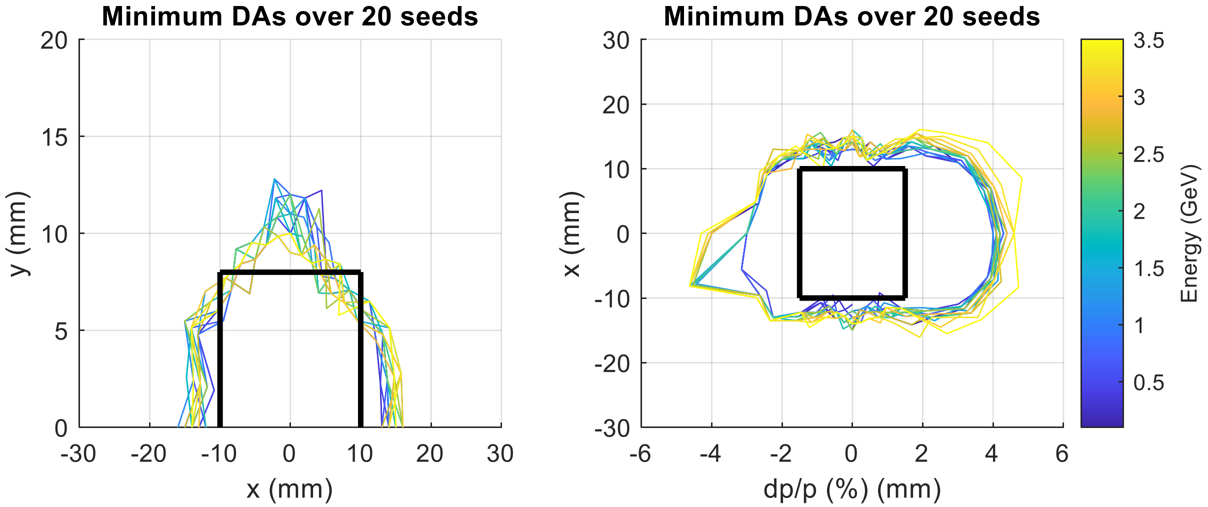
Uncorrected tunes and chromaticity during the ramp





Dynamic aperture including eddy currents, field and alignment errors after tune and chromaticity correction





Impedance Database

Impedance database has been created using a 0.5 mm drive-bunch in CST simulations

(Note: s-band bunchlet from linac σ_L = 1.5 mm)

Resistive wall contributions calculated using ImpedanceWake2D:

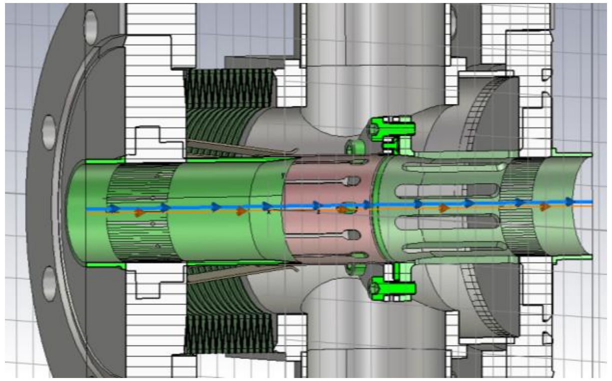
- 140 m SS pipe
- Booster kickers (assumes 1 µm-thick TiN coating – actual coating on ferrite TBC)
- Ceramic breaks

RF cavity HOMs modelled as narrow-band resonators

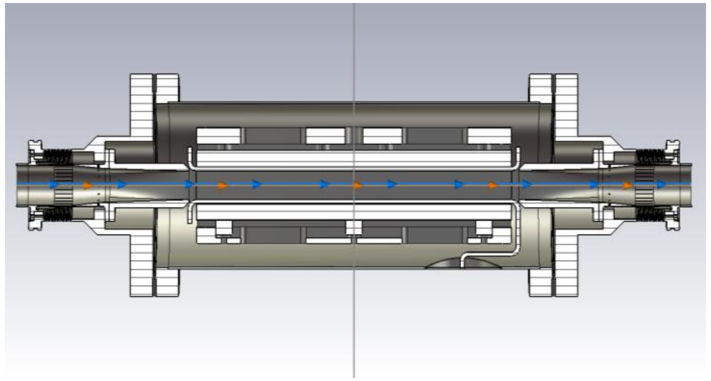
Largest contributions to short-range wakefield:

- Resistive wall
- Injection / extraction kickers
- RF cavity tapers

Pumping cross



Injection/extraction kicker



Wakefield Contributions (12 mm bunch)

Element	Number	H-kick factor (V/pC/mm)	V-kick factor (V/pC/mm)	Loss factor (V/pC)
Screens	2	0.008	0.005	0.039
Valves	8	0.006	0.007	0.003
BPMs	48	0.016	0.019	0.000
Pumps	55	0.087	0.085	0.037
Kickers	4	0.075	0.192	0.682
Cavity tapers	2	0.019	0.191	0.381
Resistive wall	140 m	0.683	0.697	1.329
Total		**0.894**	**1.024**	**2.471**

Beam Parameters During the Ramp

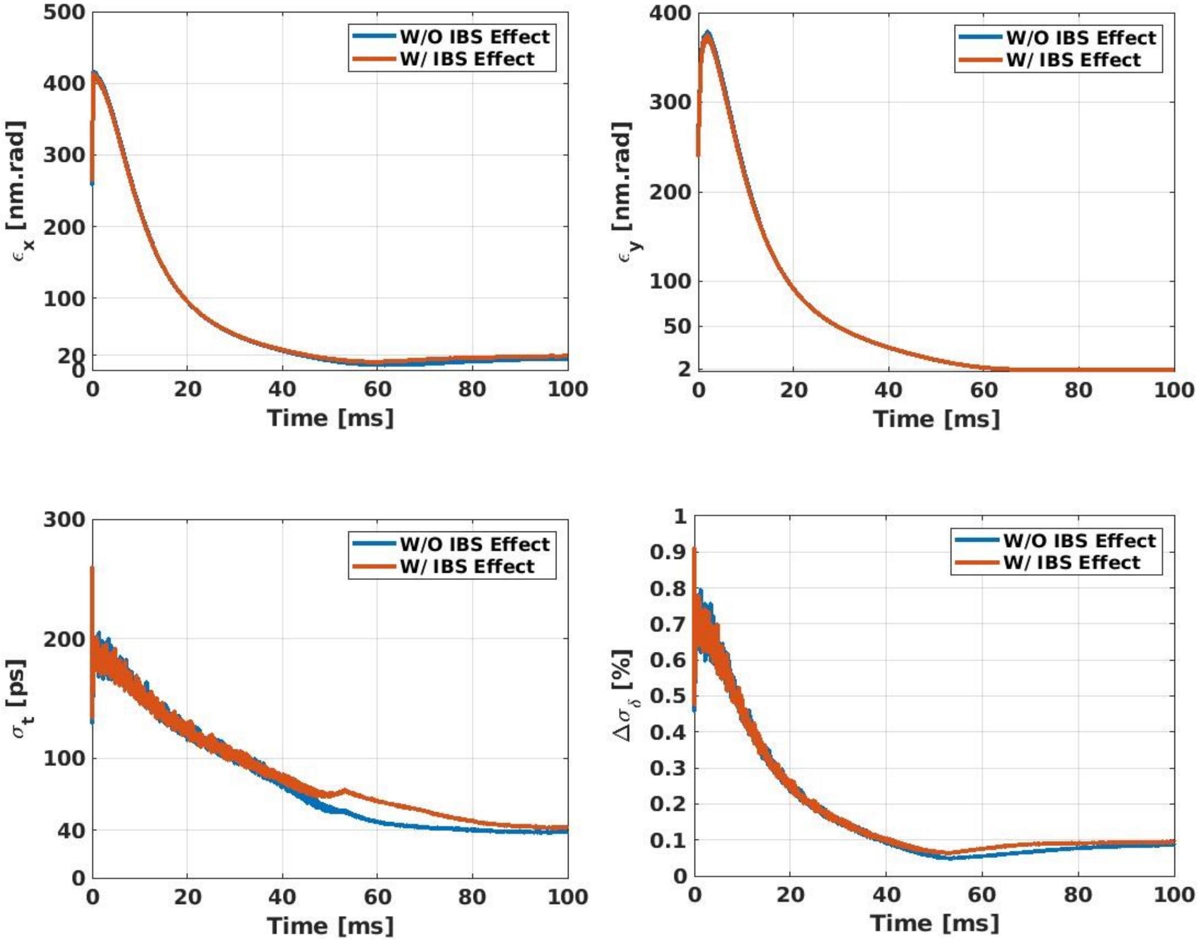
ELEGANT used to study collective effects in the booster

Various aspects have been investigated:

- ➢ Injected bunch charge
- ➢ Chromaticity
- ➢ Injection energy
- ➢ Intra-beam scattering

Impact of IBS

(0.72 nC / chromaticity = 0.5)



Bunch Parameters at Extraction with IBS

Charge (nC)	ε_x (nm.rad)	ε_y (nm.rad)	σ_L (ps)	σ_E (%)
0.0	17.3	1.6	38.0	0.086
0.7	19.0	1.6	42.5	0.094
1.4	20.8	1.6	44.4	0.100

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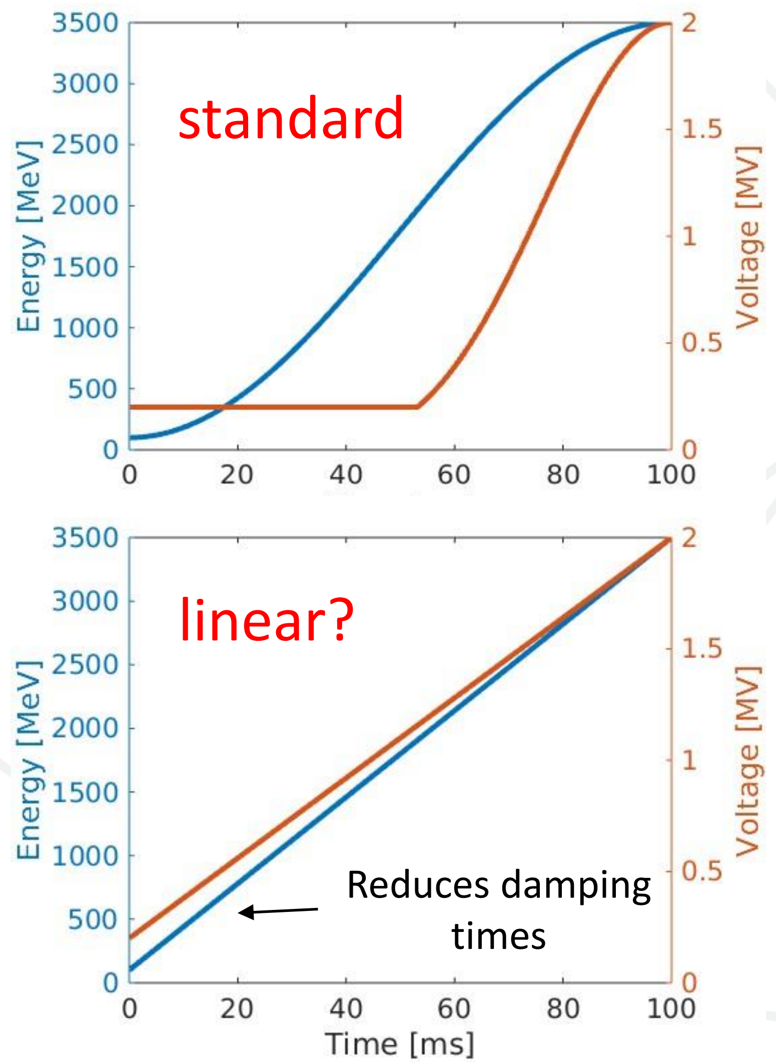
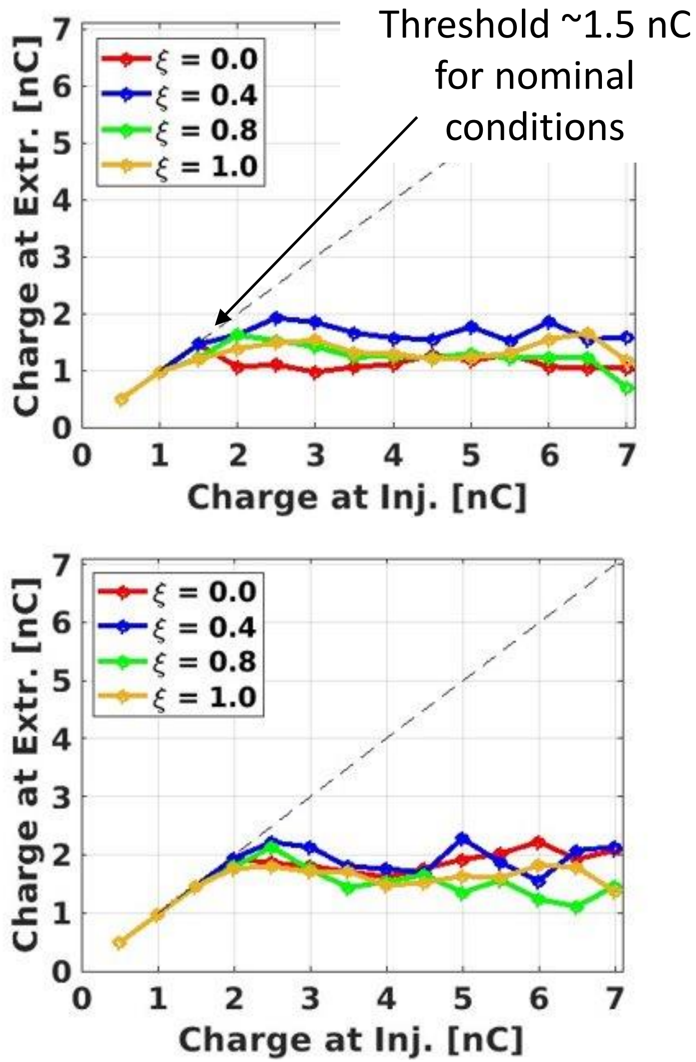
Single Bunch Thresholds

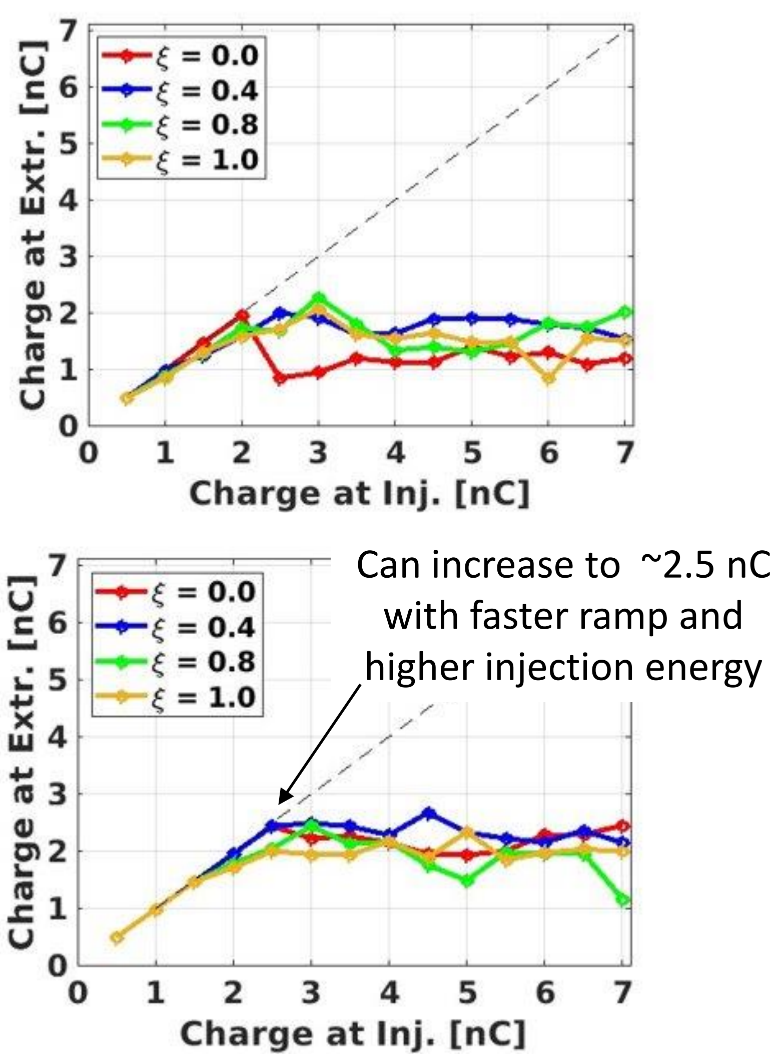
Ramp Profiles



Ramp from **100 MeV**



Ramp from **150 MeV**



Note: Aperture-sharing injection for Diamond-II requires 0.1 nC/shot to maintain fill-flatness with 3HC

Coupled Bunch Thresholds

Coupled bunch thresholds also studied with ELEGANT using one-turn-map (ILMATRIX incl. nonlinear terms)

Impedance model:

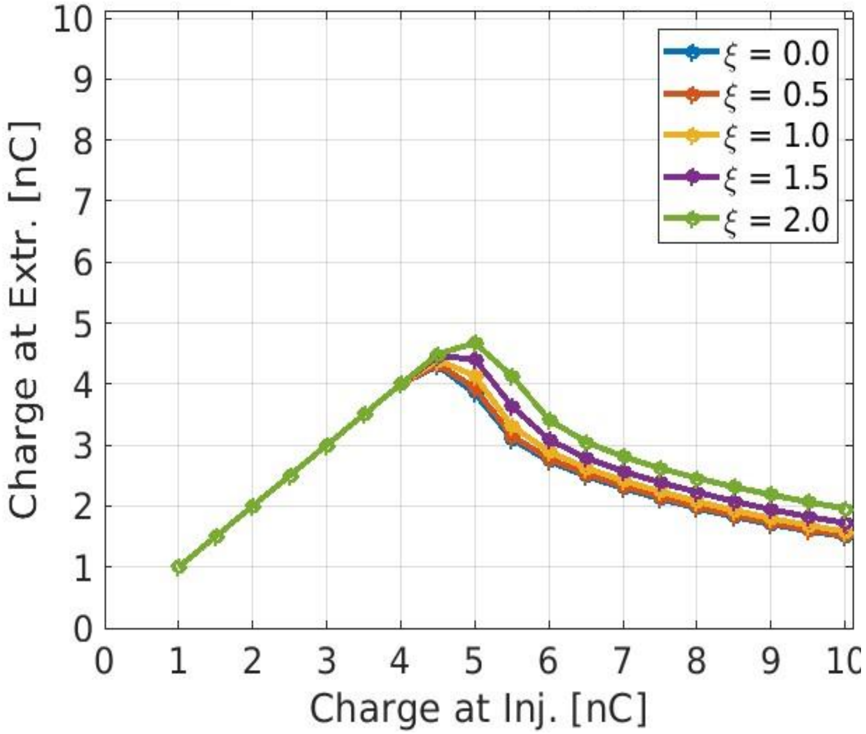
- Long range resistive wall
- 2×PETRA 5-Cell RF cavity higher-order modes (HOMs)

Assumptions:

- Single train of 180 bunches (harmonic number = 263)
- 10K macro-particles per bunch
- Sinusoidal energy ramp (100 MeV => 3.5 GeV)
- Physical apertures

Conclusions:

- Extracted multi-bunch charge limited to ~4-5 nC
- Preliminary studies indicate >10 nC can be extracted with MBF system



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Conclusions

Booster-II design status:

- Engineering and magnet designs almost complete (few outstanding items)
    - ➢ Pulsed magnet design ongoing
- Booster girder call for tender expected to be issued in April/May 2024
- Girders to be purchased as complete assemblies (Diamond staff to install / commission)
- Pulsed magnets, RF, diagnostic components issued as separate contracts
- Booster installation / commissioning anticipated during Dec’27 => Oct’28 ready for storage ring commissioning (from Dec’28)

AP studies ongoing:

- Simulated commissioning has started
- Analysis of collective effects continues
    - ➢ Impedance database continually updated
    - ➢ Need to study long-range geometric wakes

Extra Slides

Booster-II Magnets

Magnet	Parameter	Units	Existing booster	Booster-II
Defocussing Dipole	Number	-	-	38
	Length	m	-	1.30
	[B, Q, S]	[T, T/m, T/m^2]	-	[0.99, -8.24, -42.0]
Focussing Dipole	Number	-	-	36
	Length	m	-	1.30
	[B, Q, S]	[T, T/m, T/m^2]	-	[0.42, +11.30, +35.0]
Normal dipole	Number	-	36	4
	Length	m	2.16	1.25
	B	T	0.81	0.95
Quadrupoles	Number	-	44	20
	Length	m	0.34	0.45
	Peak gradient	T/m	14.1	30
Sextupoles	Number	-	28	44
	Length	m	0.16	0.05
	Peak strength	T/m^2	40.8	300

Pulsed Magnet Parameters

- Design of injection and extraction pulsed magnets is ongoing
- Aiming to use the same design of septum magnets for booster extraction as used for storage ring injection
  - Combination of thin eddy-current septum + PM main septum
  - Stabilises extracted beam trajectory; static leakage field; reduced number of spares
- Investigating coating ferrites for injection / extraction kickers to reduce impedance

	Injection kicker	Injection septum	Extraction kicker	Extraction thin septum	Extraction PM septum
Magnetic length	0.3 m	0.3 m	3×0.3 m	0.4 m	~1.6 m
Bend angle	16.4 mrad	11.56 degree	1.62 mrad	1.1 degree	7.4 degree
Peak field	27.4 mT*	0.34 T*	>0.078 T	0.6 T	0.6 T, 1.0 T, 1.6 T
Pulse profile	Flat-top	Full sine	Flat-top	Full sine	-
Pulse duration	400 ns	160 µs (?)	400 ns	10 µs (?)	-
Rise time	<0.1s	-	<150 ns	-	-
Fall time	<150 ns	-	<0.1 s	-	-

*rated for 150 MeV injected beam energy