April 29th, 2008, FELSI Meeting for PSI XFEL

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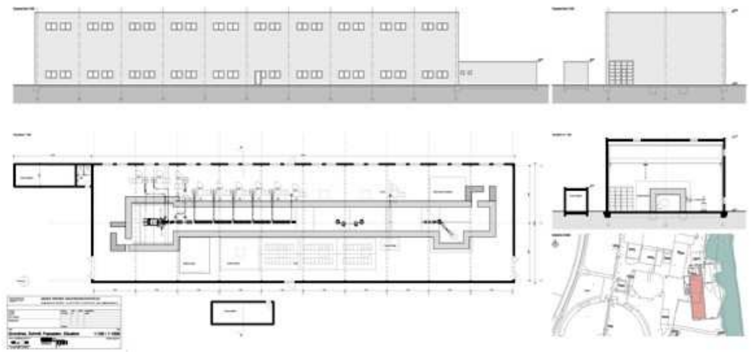

Start-To-End Simulation of 250 MeV Injector with CTF3 Gun Type V

including Diagnostic Section

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PSI XFEL-2008-07

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  - Possibility of New Layout for Diagnostic Section
- Summary & Acknowledgement

CTF3 2.5 Cell S-band RF Gun Type V

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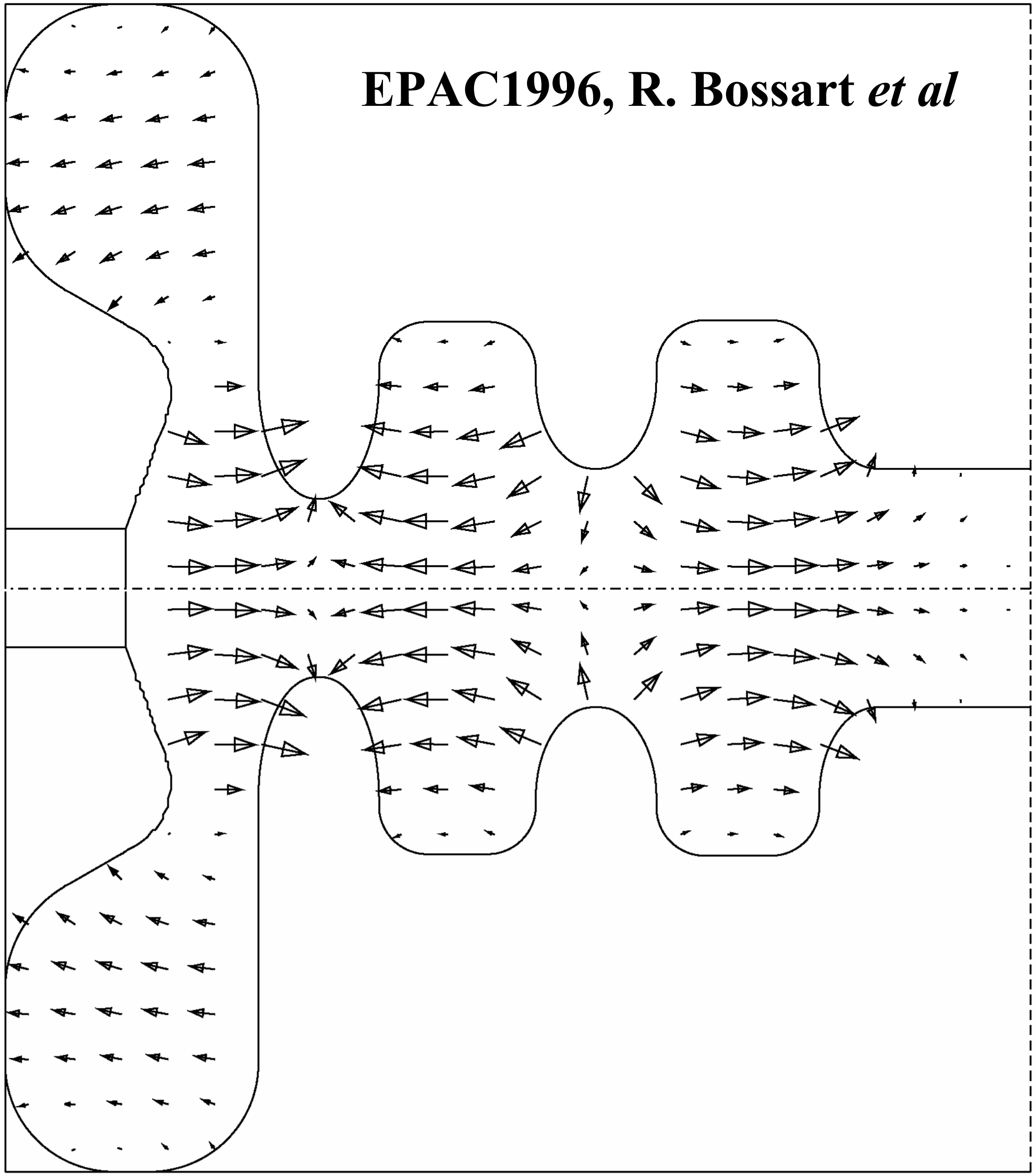

From Micha & Rudi Bossart communication

RF tested @ 100 MV/m - two weeks operation
power for 100 MV/m = 22 MW with 4.5 μs RF pulse
power for 120 MV/m = 25 MW
RF frequency ~ 2998.5 MHz
cell = 2.5 cells (One TM02 + Two TM01)
Q_0 = 16300
number of bunch in a train = 48
cathode wall angle = 20 degree
total length ~ 0.25 m
full cell length ~ 50 mm
designed charge ~ 2.33 nC

CTF3 2.5 Cell S-band RF Gun Type V

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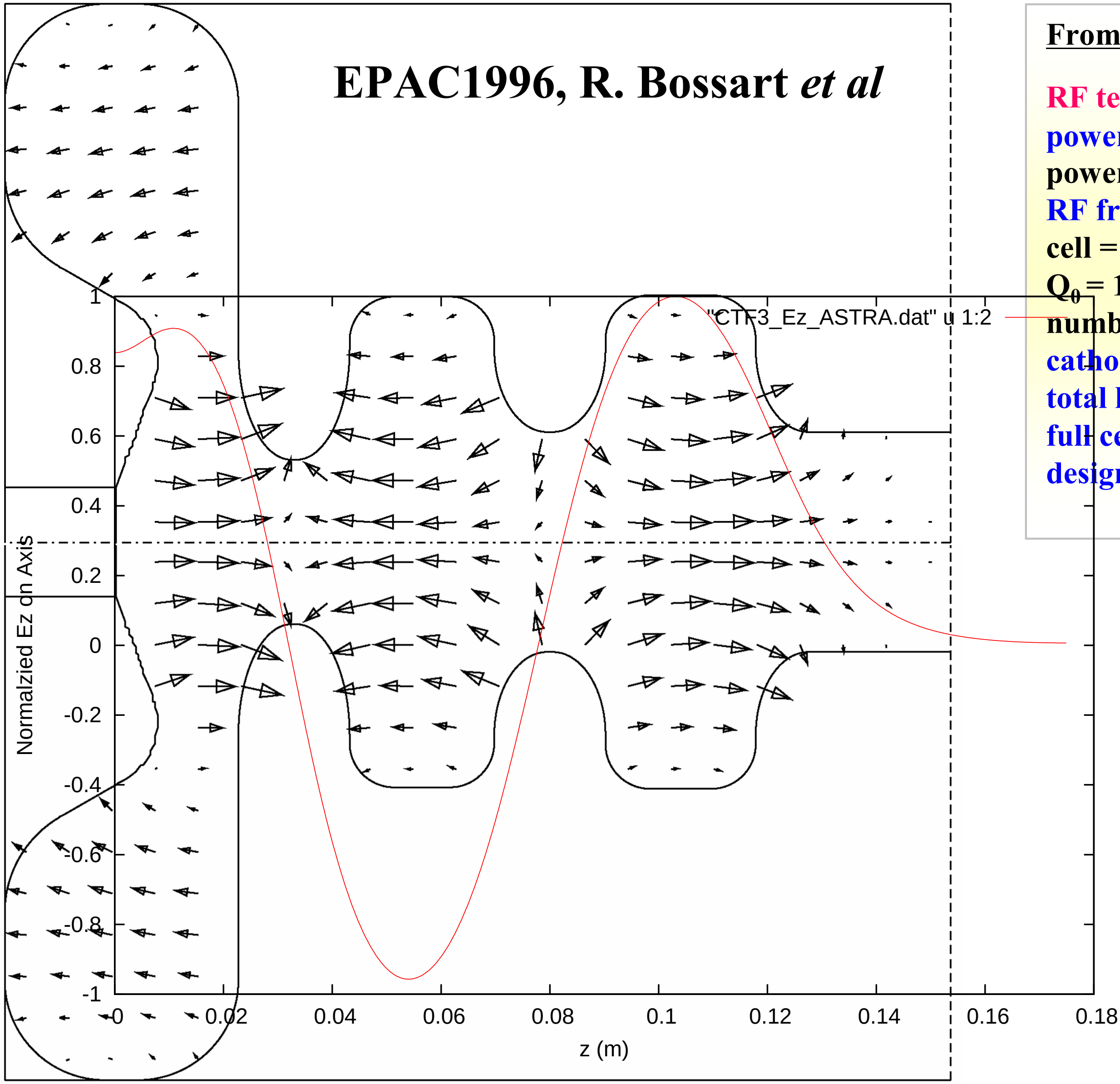

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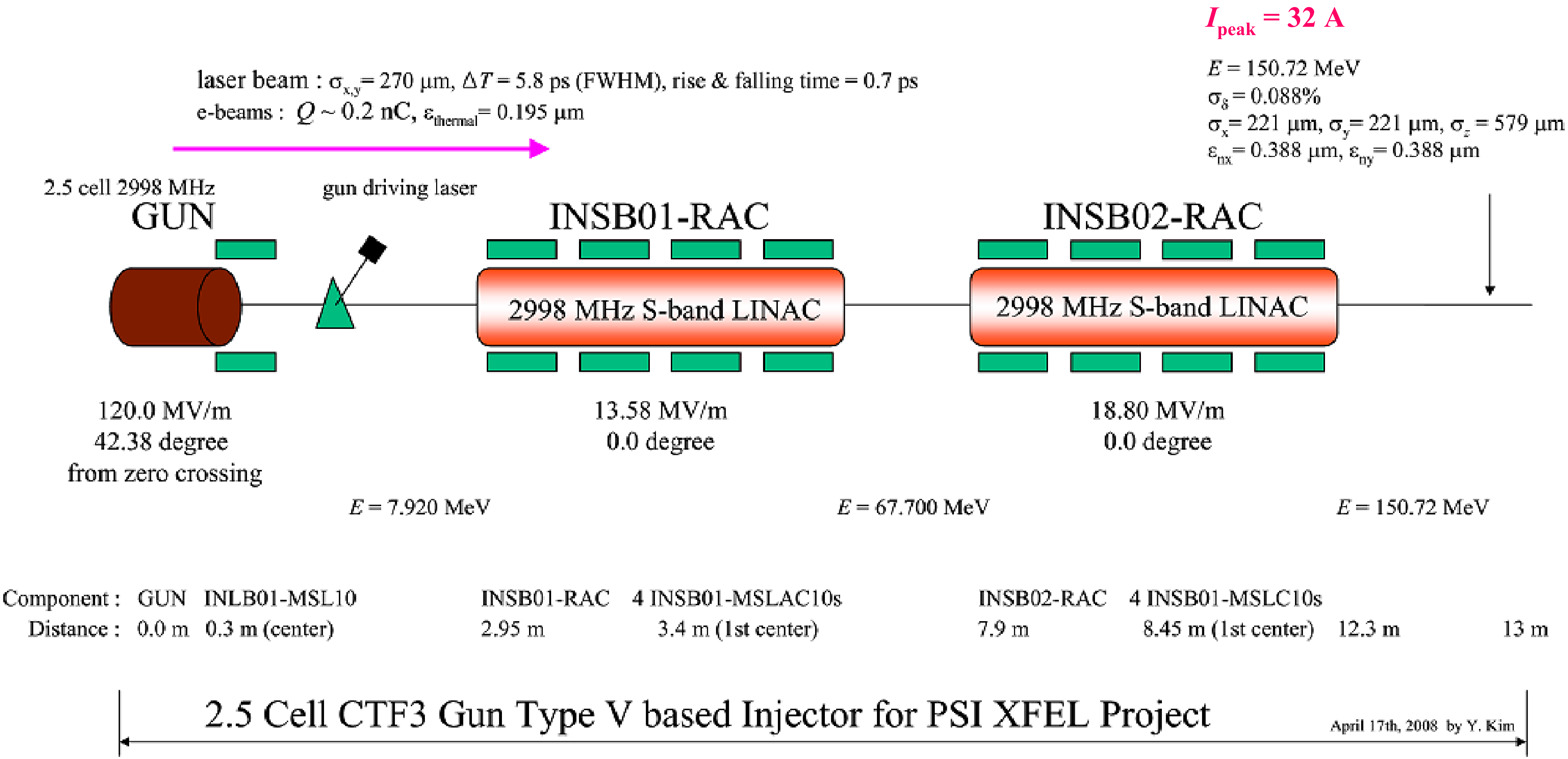
Layout with CTF3 RF Gun Type V



S2E Simulation Method with CTF3 Gun

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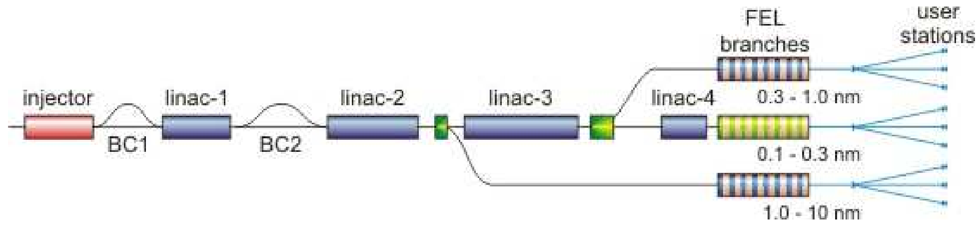
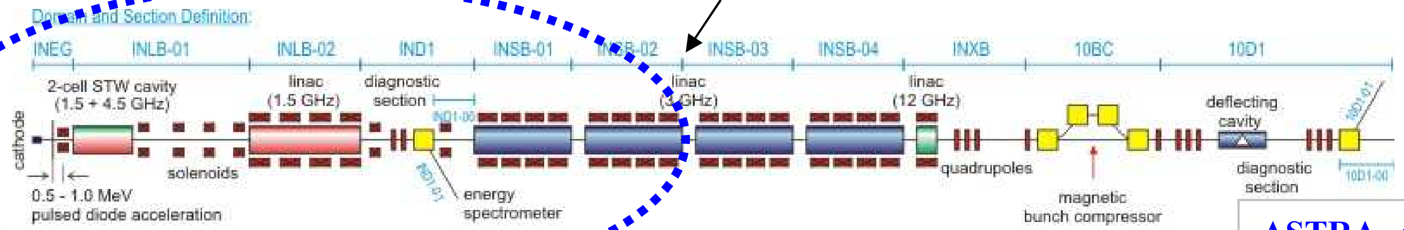
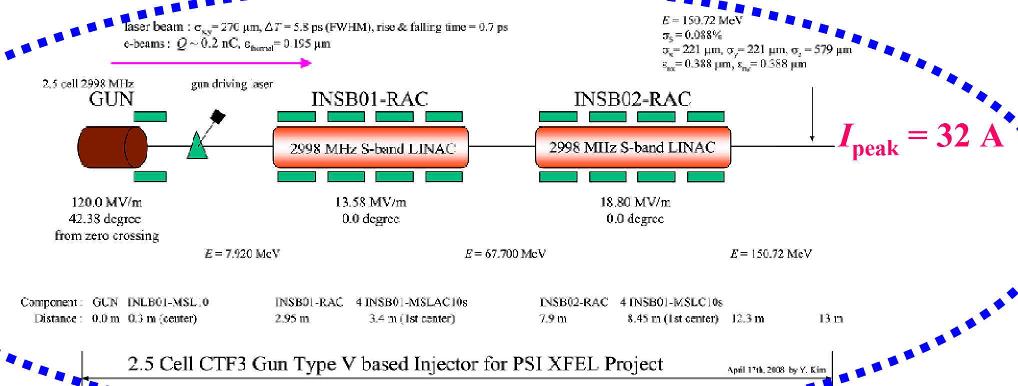


With a new layout, **overall compression factor of 272 for I_{peak} = 1.5 kA** can be reduced **to 63 for I_{peak} = 2.0 kA with an initial peak current of 32 A.**

ELEGANT Tracking Start Point = 17.873 m in Romain's Excel file - Version 1.31



DUMP Start Point = 59.8 m



ASTRA Tracking up to 150 MeV (~ 13 m from the cathode)

ASTRA code was used to consider space charge effects from cathode to 150 MeV. ELEGANT code was used to consider short-range longitudinal and transverse wakefields in S-band and X-band linac tubes, coherent synchrotron radiation (CSR) and incoherent synchrotron radiation (ISR) at dipoles in BC DUMP. Additionally, ELEGANT code was used to simulate 3FODO cells for projected emittance measurement and LOLA transverse deflection cavity for bunch length, slice energy spread, slice energy spread, longitudinal phase space measurements. ASTRA output was directly converted to ELEGANT input at 17.873 m for the S2E simulation. Therefore, this S2E simulation covers whole 250 MeV injector including diagnostic section and dump.

ASTRA Simulation - Used Field Maps

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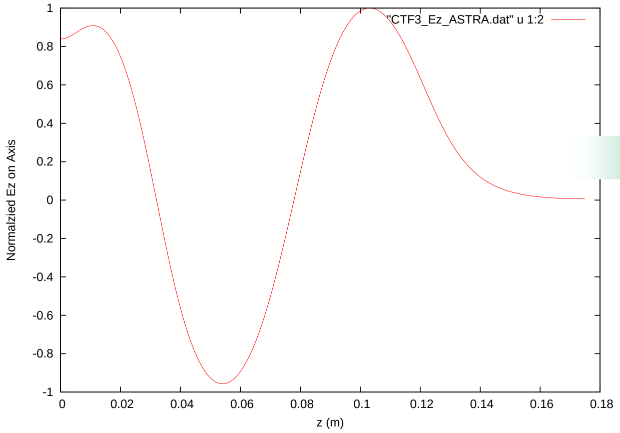
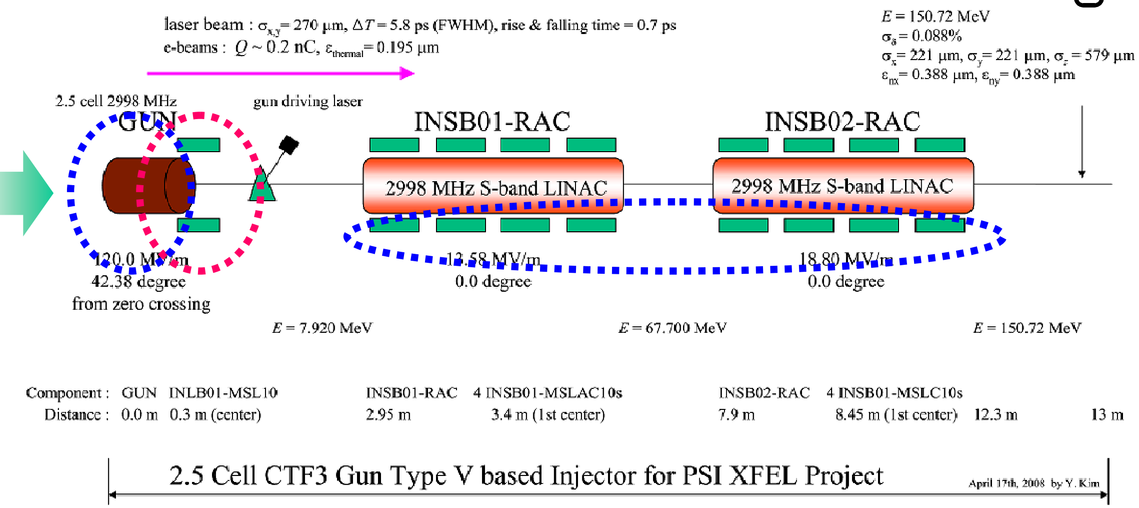
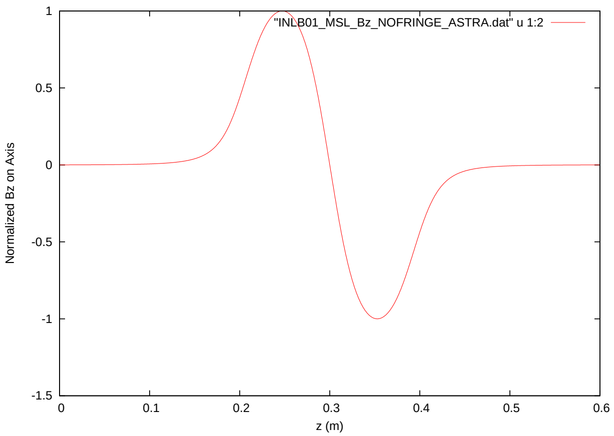
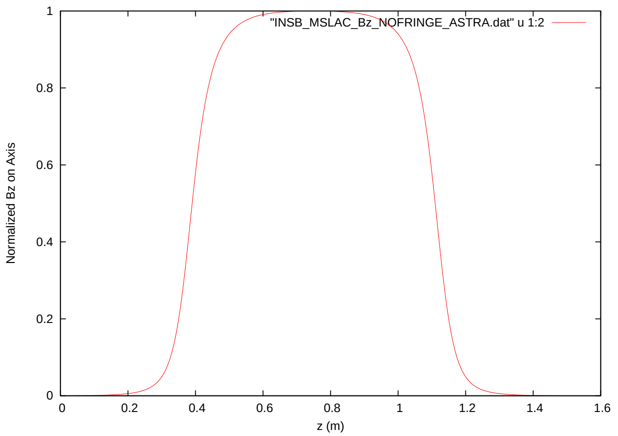
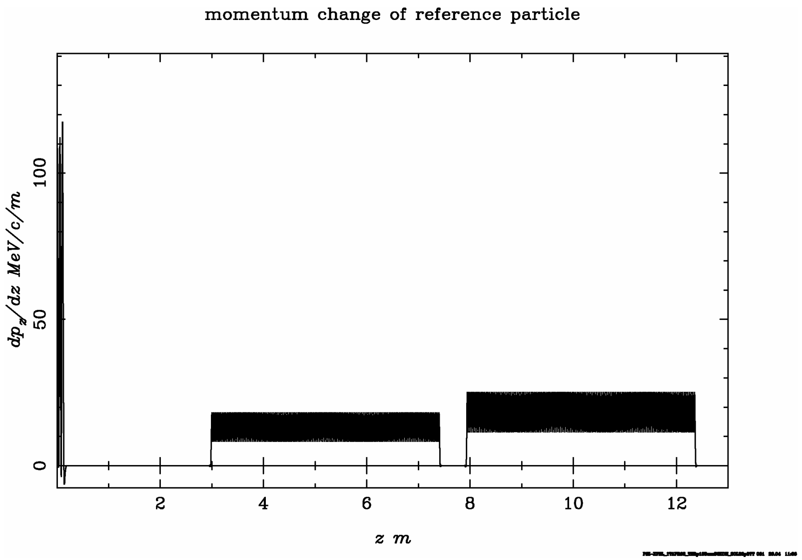
From Micha Dehler











ASTRA Simulation - LCLS Type Injector

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- ☐ Note that thermal emittance is the most biggest contribution in slice emittance
- ☐ We can reduce slice emittance by reducing thermal emittance on the cathode !

$$\varepsilon_{th} \approx \sigma_{x,y}\sqrt{\frac{2K}{3m_e c^2}}, \quad \sigma_x = \sigma_y \text{ for a round beam}$$

Here we assumed $K = 0.4$ eV for Cu cathode

Optimization of LCLS Type RF Photoinjector with a gradient of 120 MV/m

Q	laser length (FWHM)	$I_{\text{peak, cathode}}$	laser $\sigma_{\text{x,or y}}$	$\varepsilon_{\text{thermal}}$	$\varepsilon_{\text{projected, exit}}$
0.4 nC	7.4 ps	54 A	0.44 mm	0.32 μm	~ 0.47 μm
0.2 nC	5.8 ps	34 A	0.35 mm	0.25 μm	~ 0.37 μm
0.1 nC	4.6 ps	22 A	0.28 mm	0.20 μm	~ 0.28 μm

Note that peak current is much higher than 5.5 A !

ASTRA Simulation - CTF3 Gun Type V

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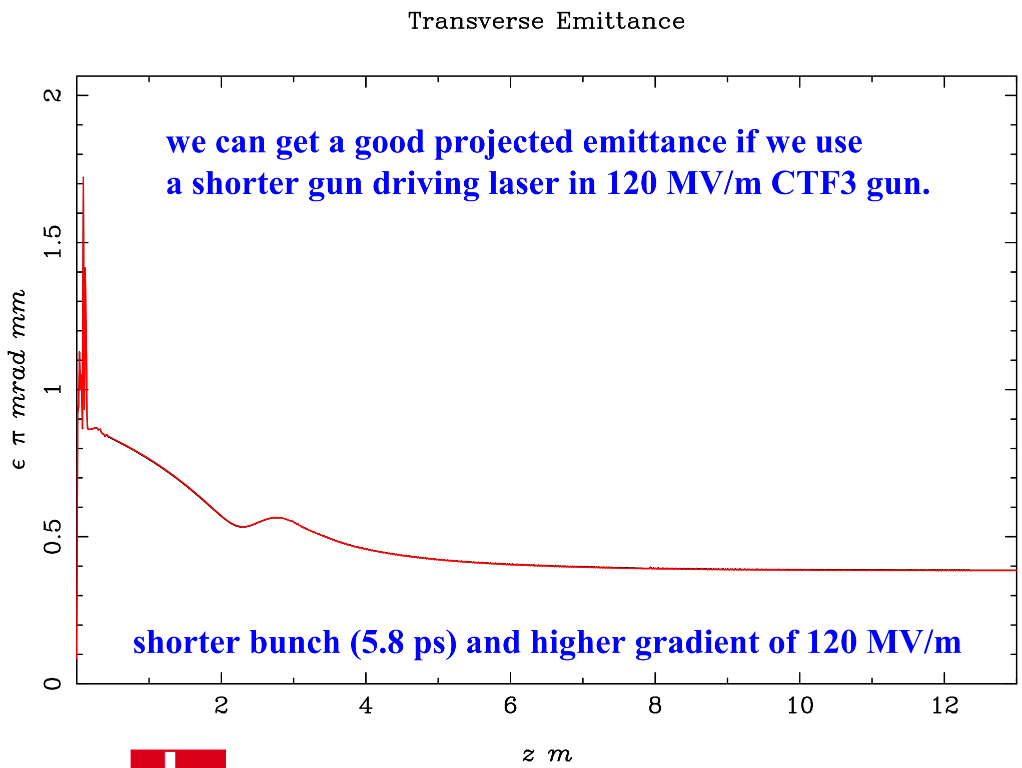
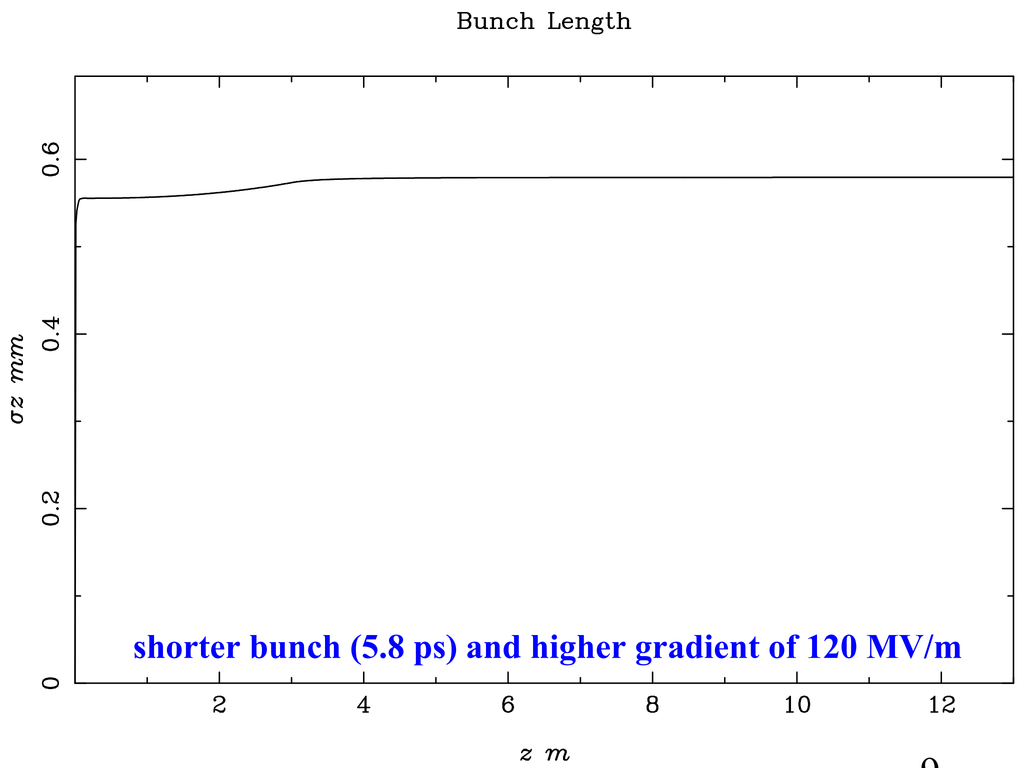
☐ If 120 MV/m is available in CTF3 Gun Type V, a shorter gun driving laser can be also used to obtain good beam parameters.

Q	laser length (FWHM)	$I_{peak, cathode}$	laser $\sigma_{x,or\ y}$	$\varepsilon_{thermal}$	$\varepsilon_{projected, exit}$
0.2 nC	5.8 ps	32 A	0.27 mm	0.195 µm	~ 0.388 µm

Note that its peak current is similar to that of LCLS type backup injector !





ASTRA Simulation Results @ 13 m

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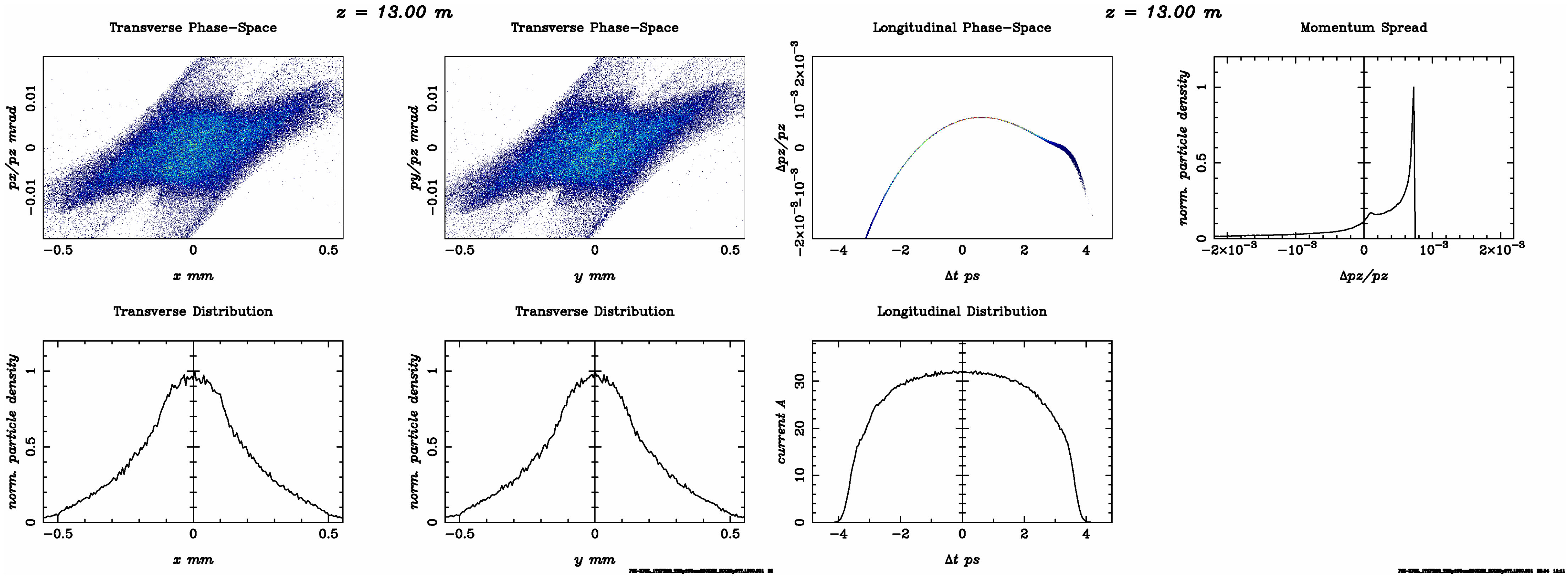
ASTRA Tracking results from the cathode to 150 MeV with 200,000 particles



$E = 150.72$ MeV

$\sigma_\delta = 0.088\%$

$\sigma_x = 221$ μm, $\sigma_y = 221$ μm, $\sigma_z = 579$ μm

$\varepsilon_{nx} = 0.388$ μm, $\varepsilon_{ny} = 0.388$ μm

$Q = 0.2$ nC, $I_{peak} \sim 32$ A

ASTRA Simulation Results @ 13 m

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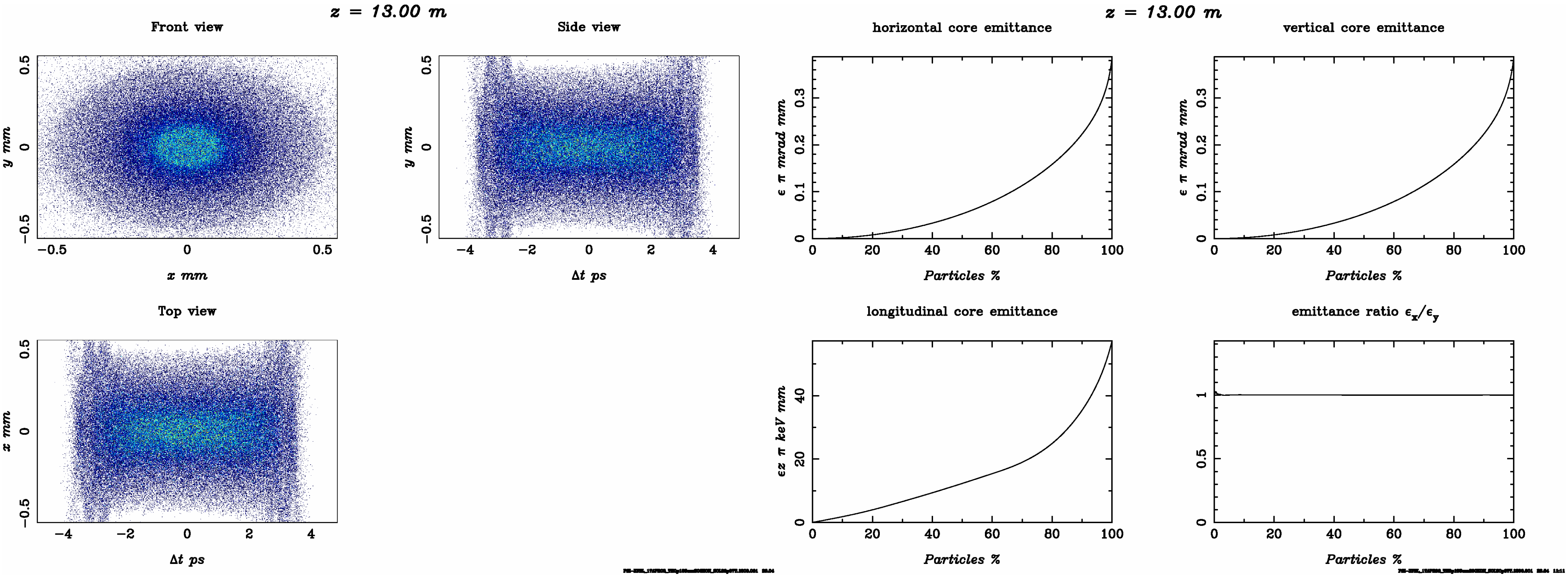

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ASTRA Results - Slice Parameters @ 13 m

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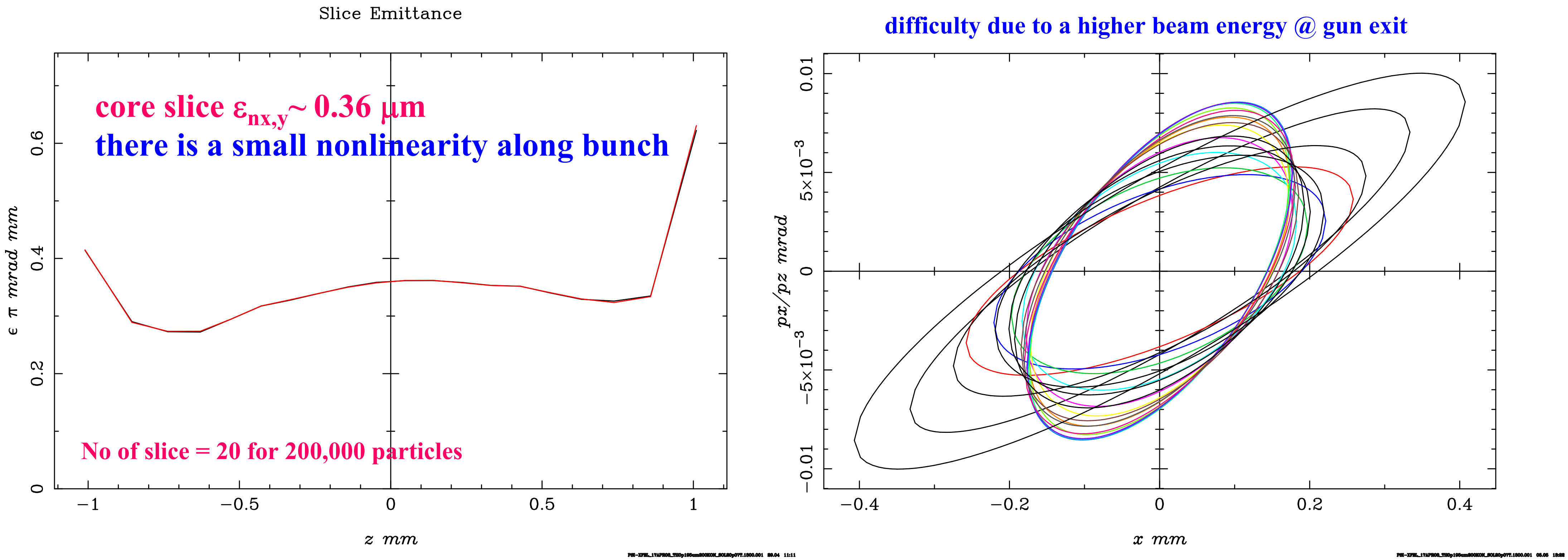

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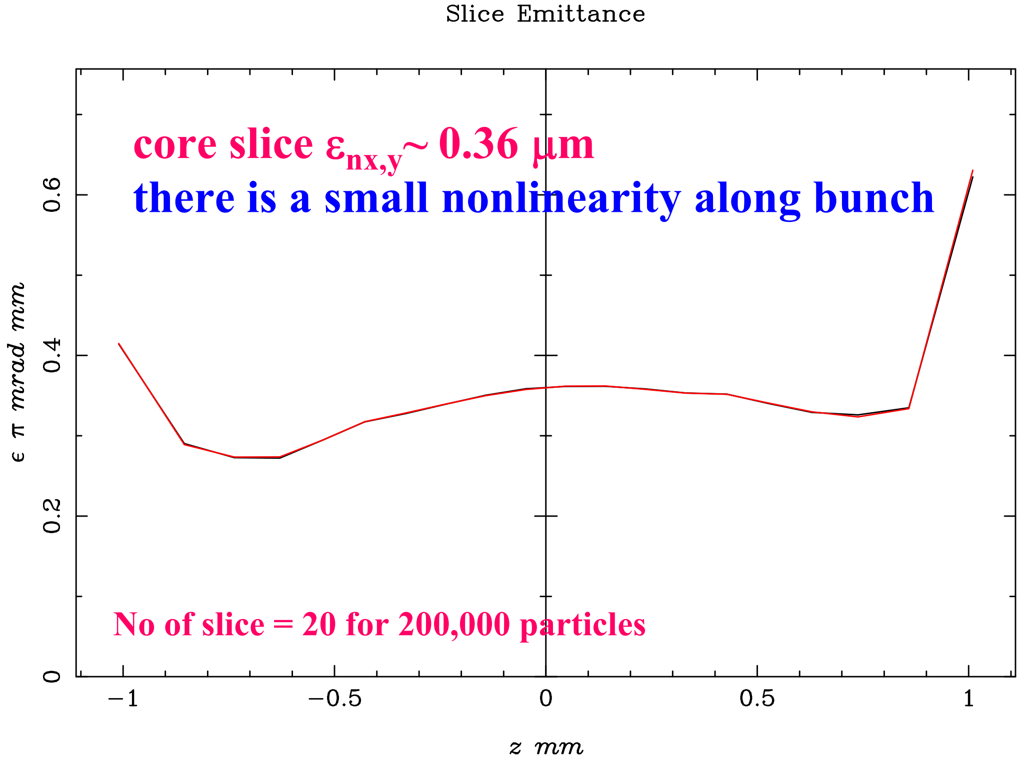
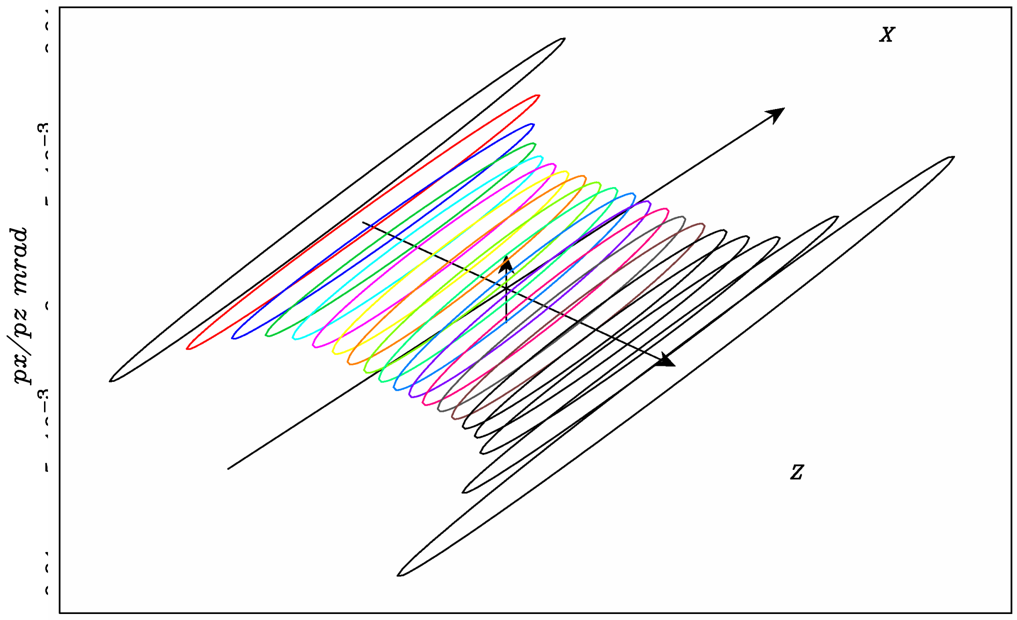


difficulty due to a higher beam energy @ gun exit



E = 150.72 MeV

σ_δ = 0.088%

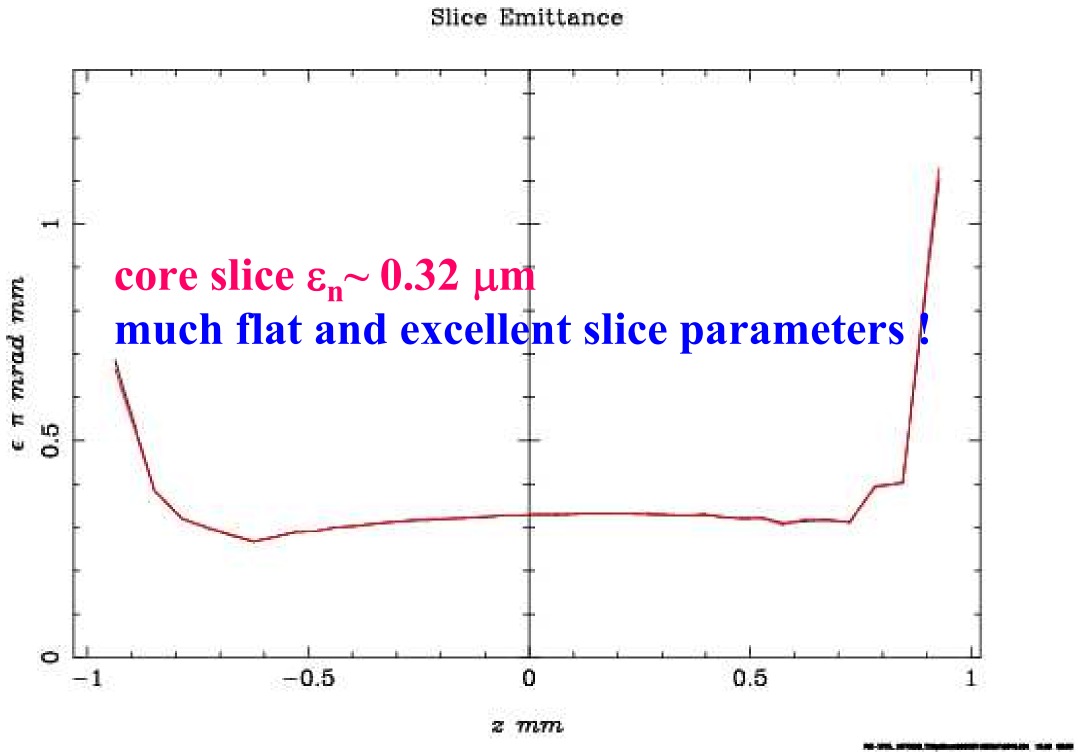
σ_x= 221 μm, σ_y= 221 μm, σ_z = 579 μm

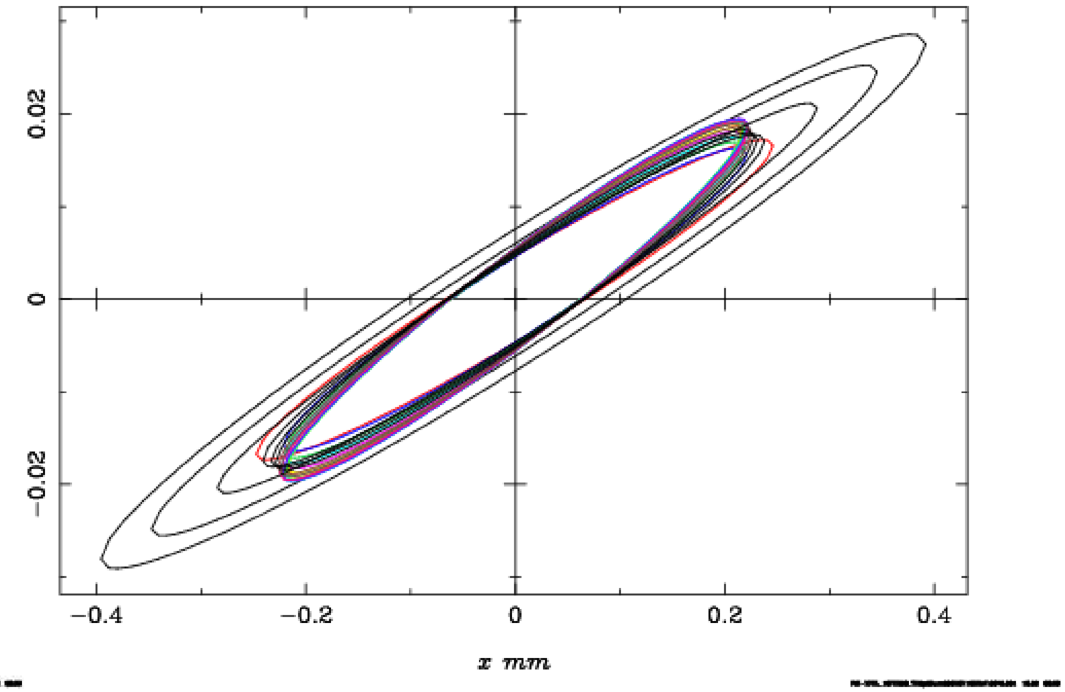
ε_{nx}= 0.388 μm, ε_{ny}= 0.388 μm

Q = 0.2 nC, I_{peak} ~ 32 A

Performance Comparison - LCLS Type Gun

ASTRA Simulation Results at the end of LCLS Type Backup Injector





E = 137.7 MeV, Q = 0.2 nC

σ_δ = 0.07%

σ_x = 247 μm, σ_y = 247 μm, σ_z = 510 μm

ε_{nx} = 0.369 μm, ε_{ny} = 0.369 μm

Performance Comparison - LCLS Type Gun

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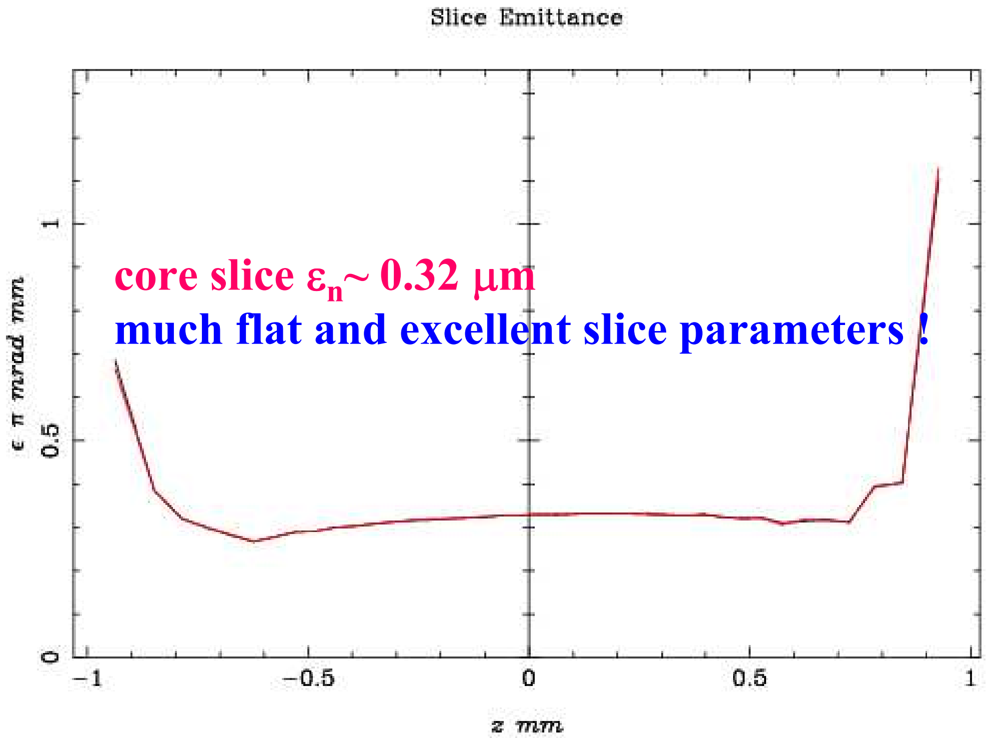
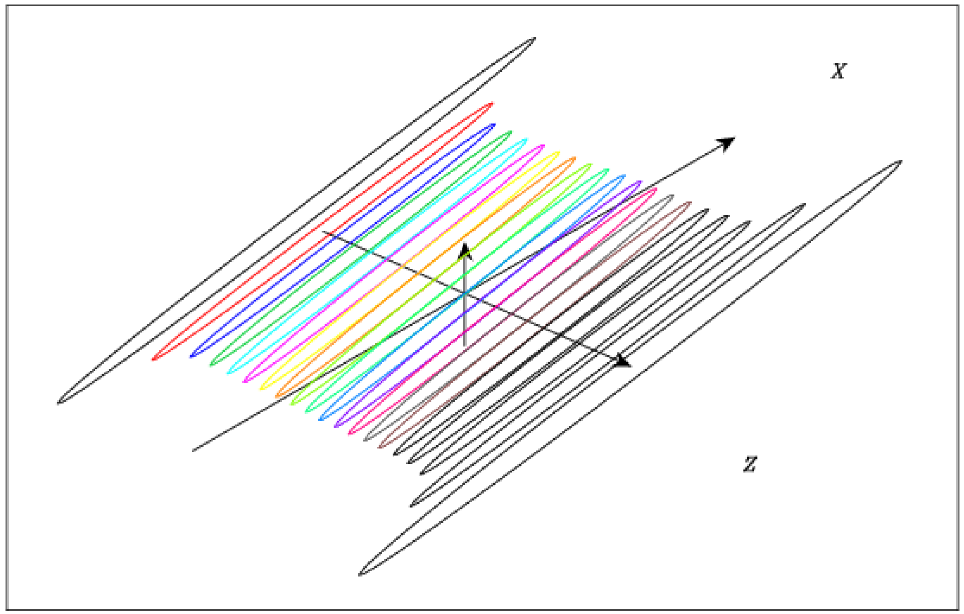
ASTRA Simulation Results at the end of LCLS Type Backup Injector



core slice $\varepsilon_n \sim 0.32\ \mu m$

much flat and excellent slice parameters !



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ELEGANT Results from 150 MeV to Dump

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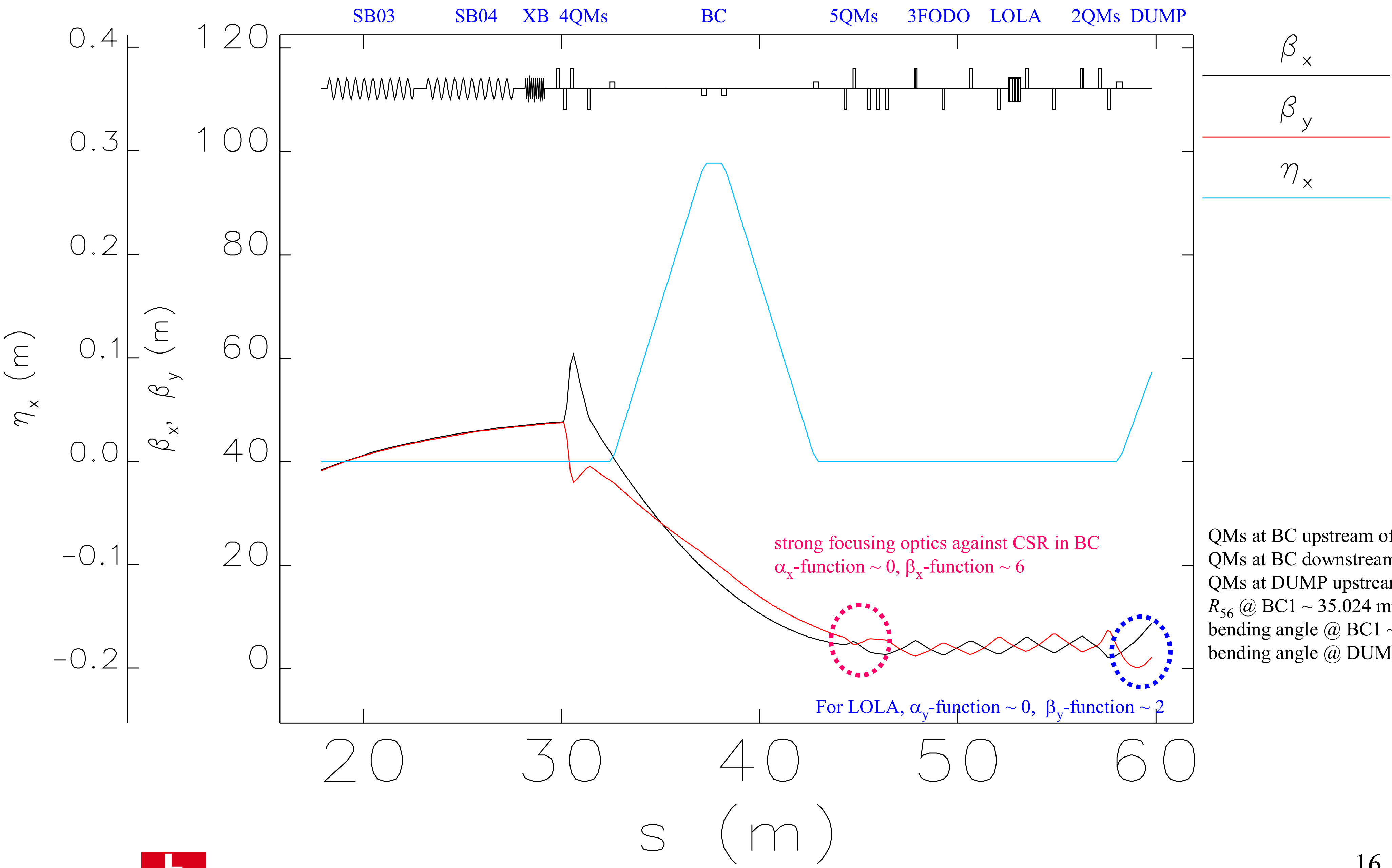

QMs at BC upstream of BC = 4
QMs at BC downstream = 5
QMs at DUMP upstream = 2
R_{56} @ BC1 ~ 35.024 mm
bending angle @ BC1 ~ 3.55 deg
bending angle @ DUMP ~ 3 deg

ELEGANT Results from 150 MeV to Dump

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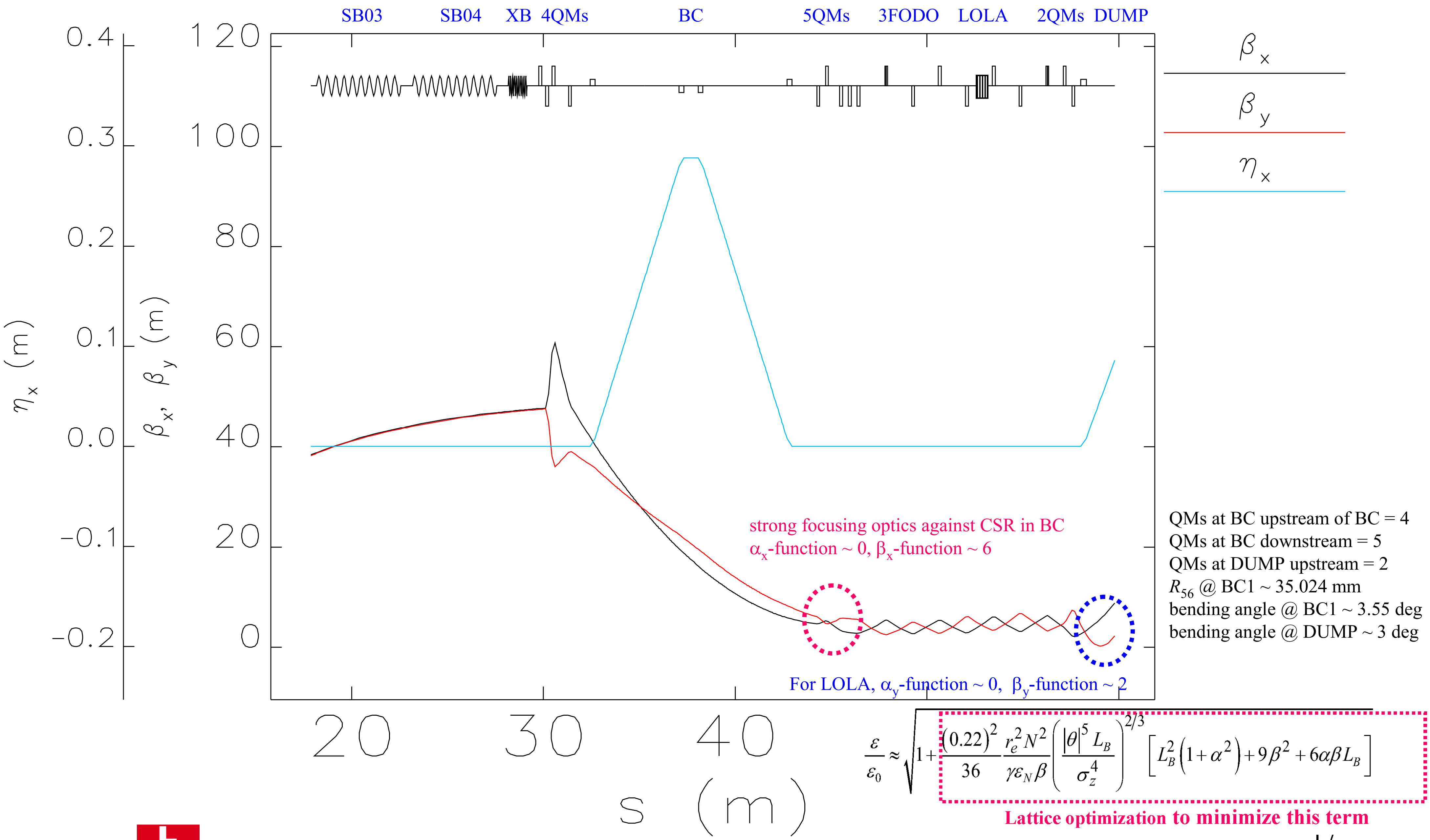

$$\frac{\varepsilon}{\varepsilon_0} \approx \sqrt{1 + \frac{(0.22)^2}{36}\frac{r_e^2 N^2}{\gamma \varepsilon_N \beta}\left(\frac{|\theta|^5 L_B}{\sigma_z^4}\right)^{2/3}\left[L_B^2\left(1+\alpha^2\right)+9\beta^2+6\alpha\beta L_B\right]}$$

Lattice optimization to minimize this term

ELEGANT Results from 150 MeV to Dump

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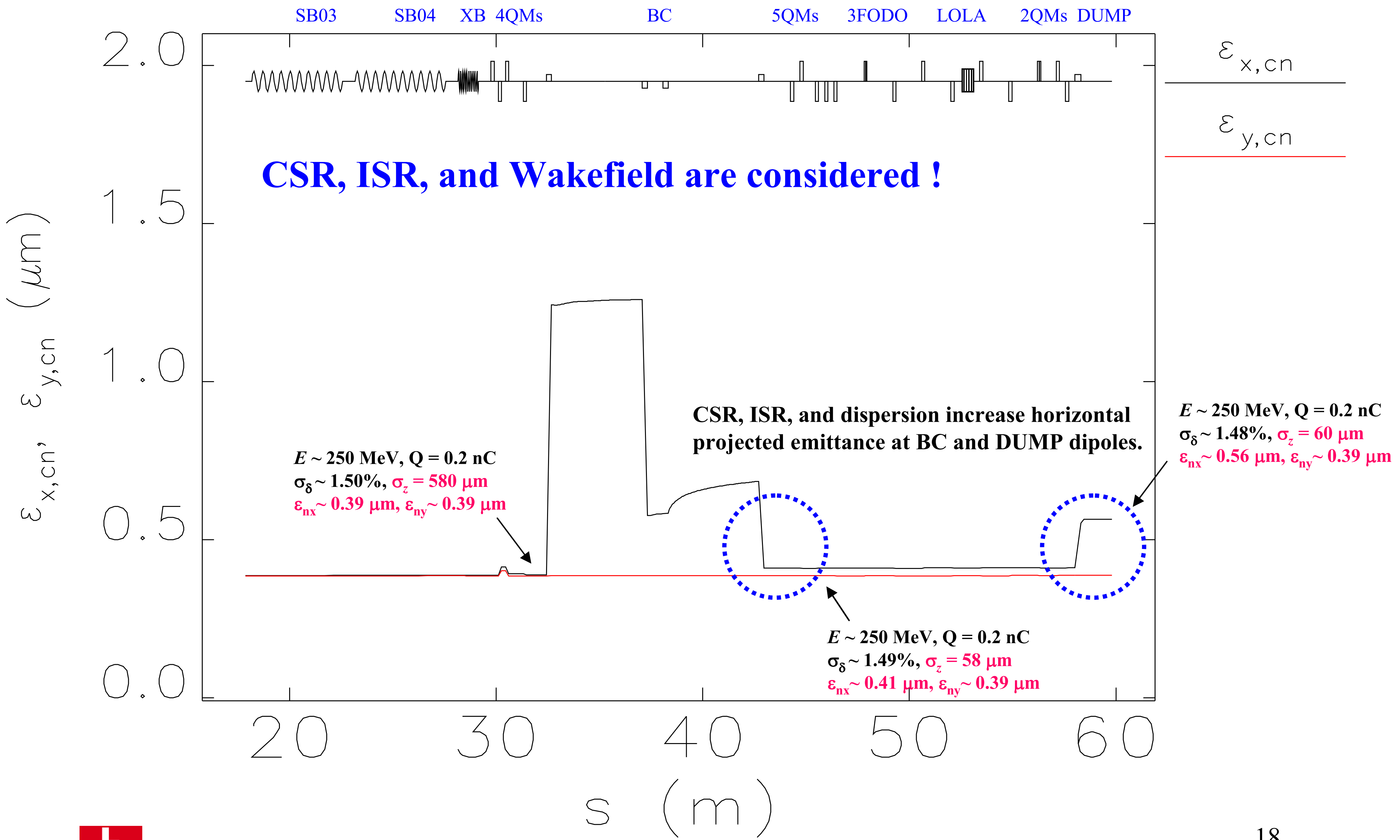

ELEGANT Results from 150 MeV to Dump

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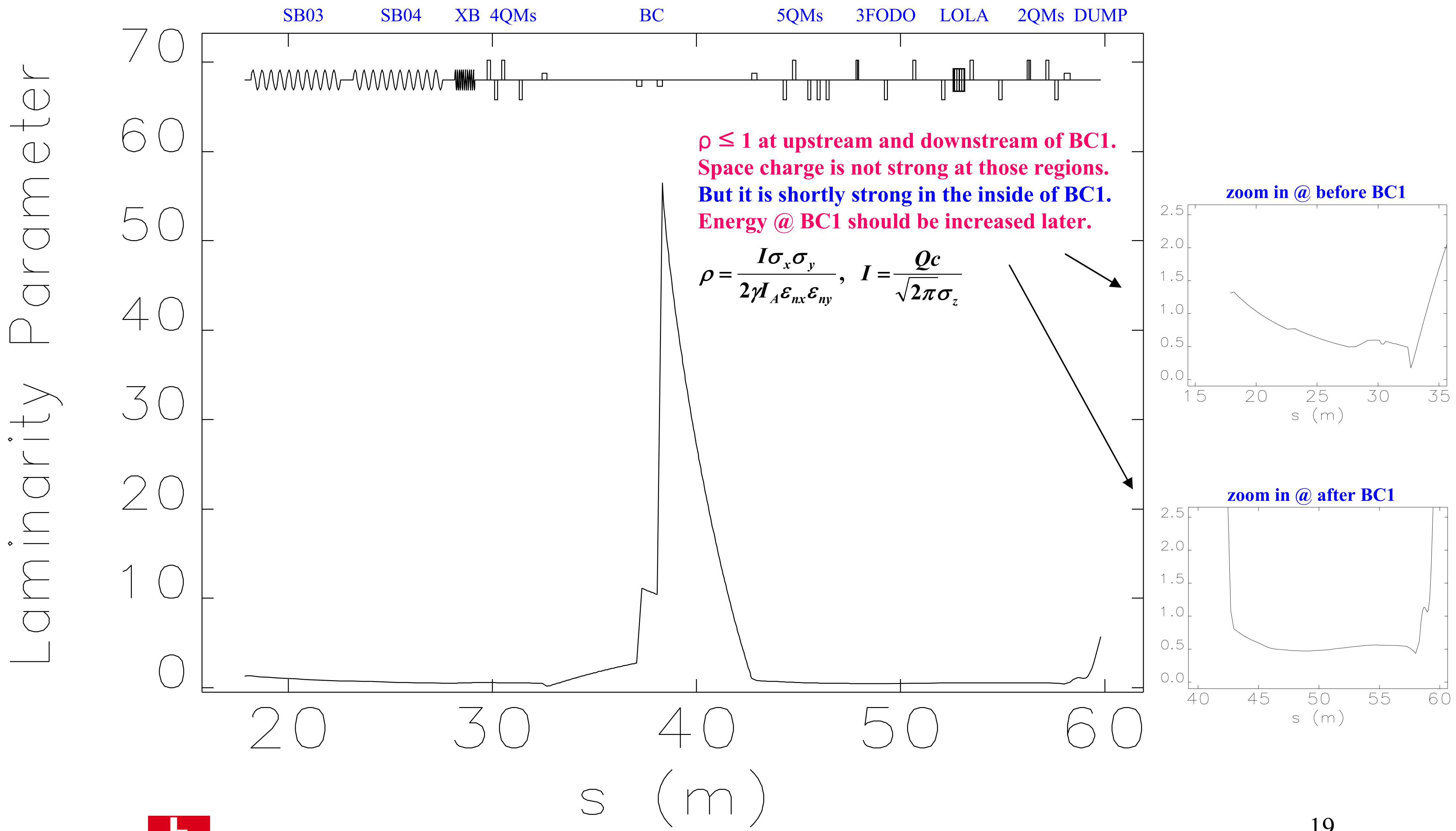

ρ ≤ 1 at upstream and downstream of BC1.
Space charge is not strong at those regions.
But it is shortly strong in the inside of BC1.
Energy @ BC1 should be increased later.

$$\rho = \frac{I\sigma_x\sigma_y}{2\gamma I_A \varepsilon_{nx}\varepsilon_{ny}}, \quad I = \frac{Qc}{\sqrt{2\pi}\sigma_z}$$

ELEGANT Results - Before BC1

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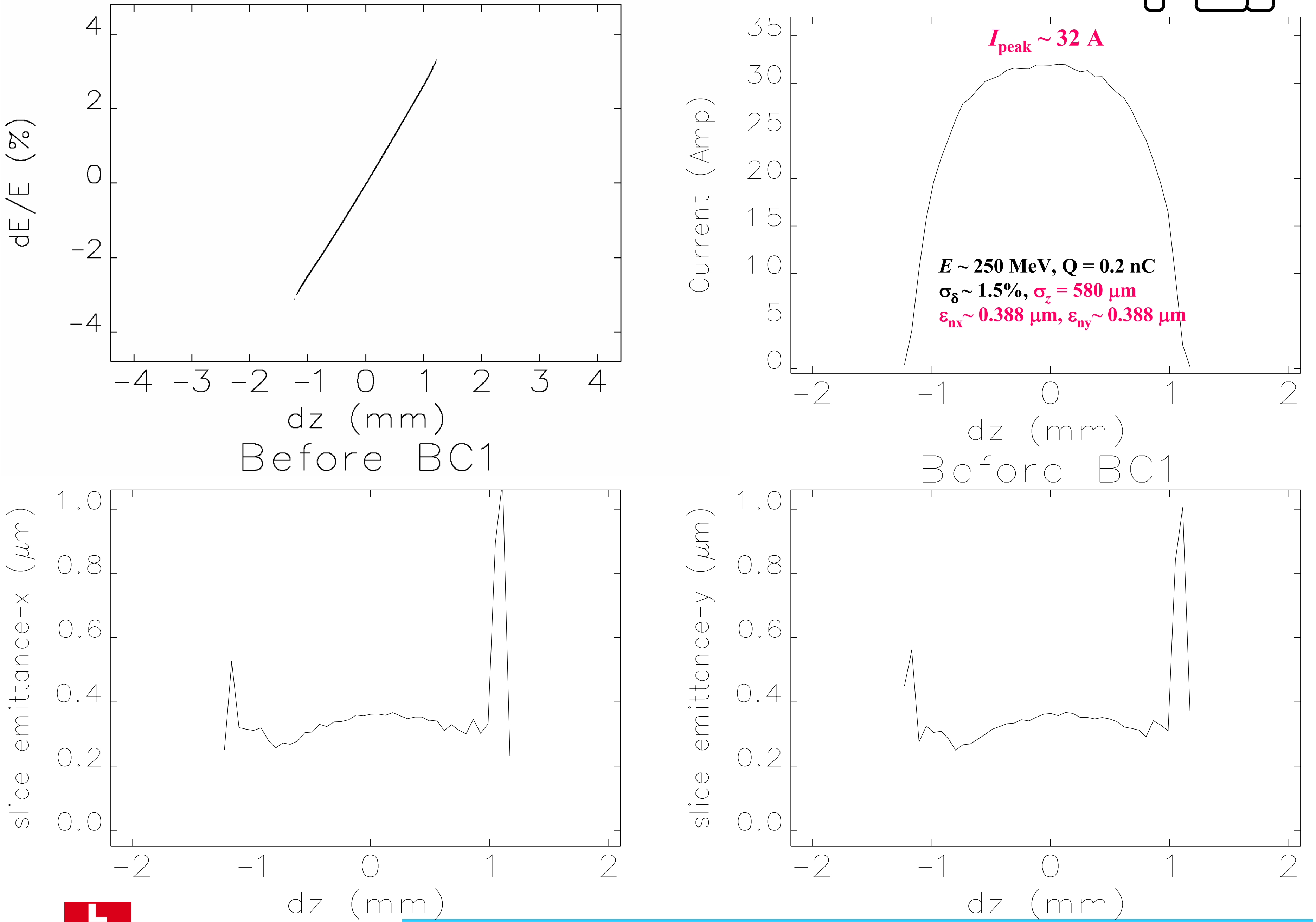
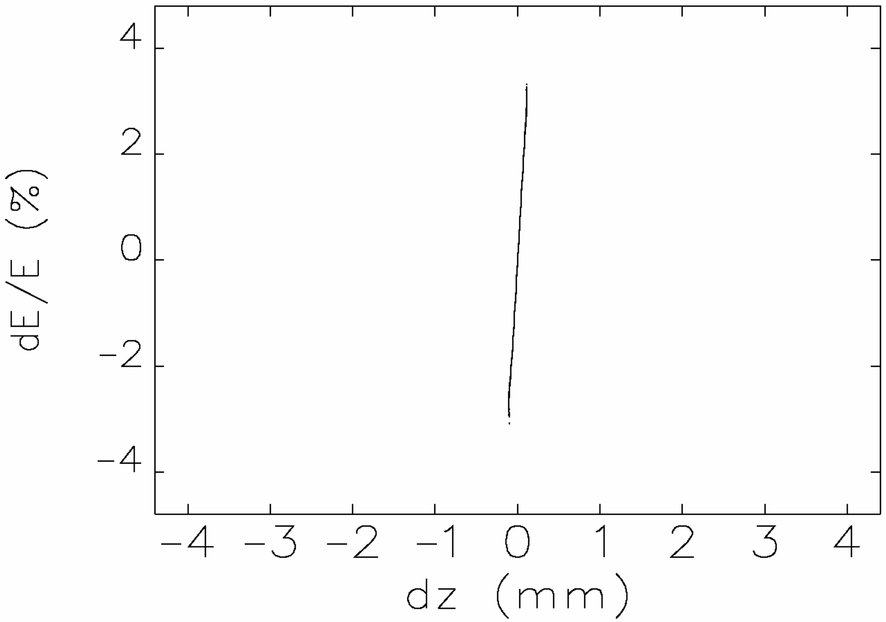
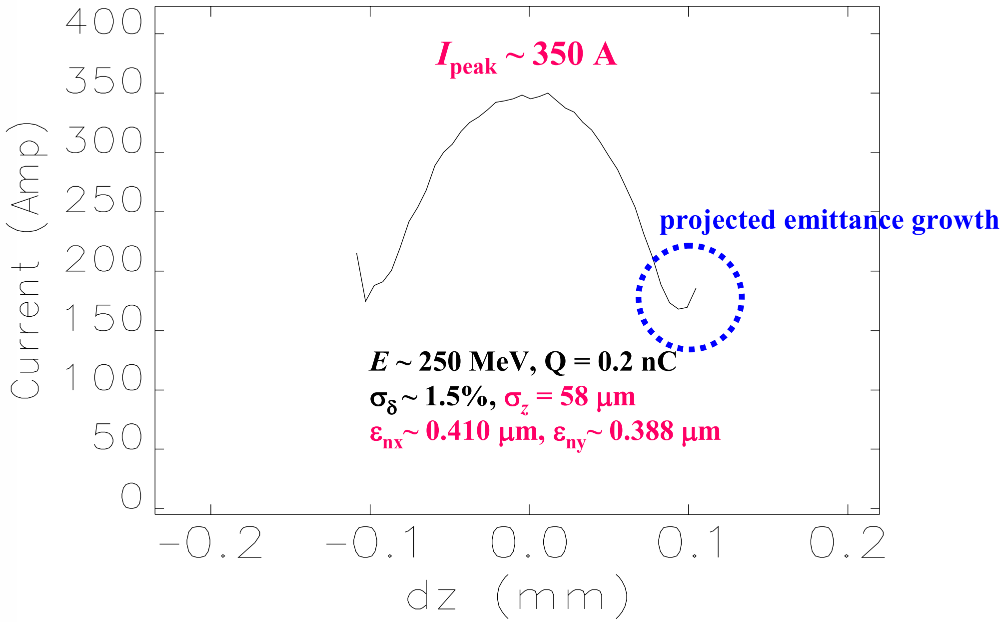
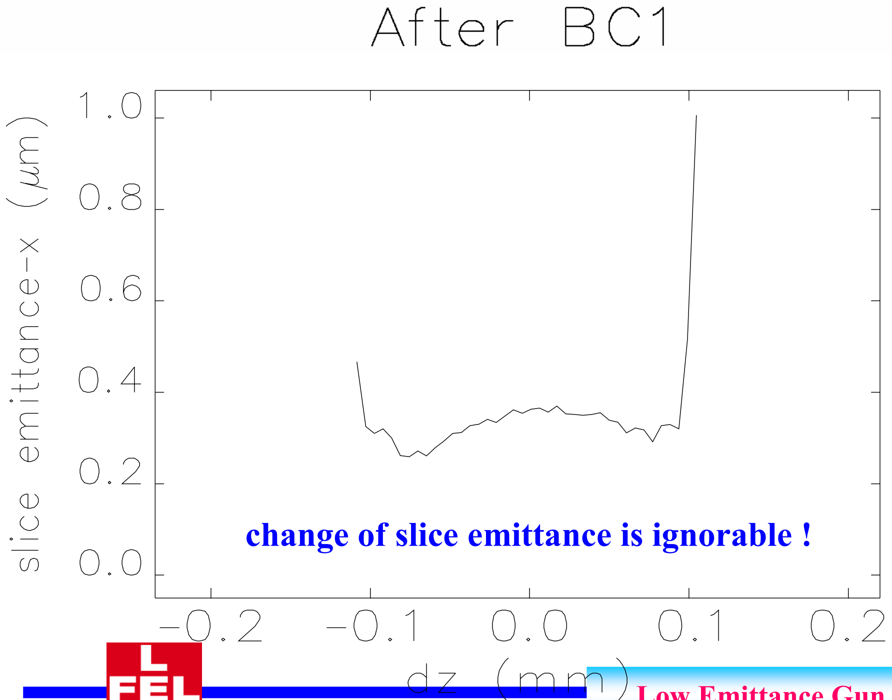
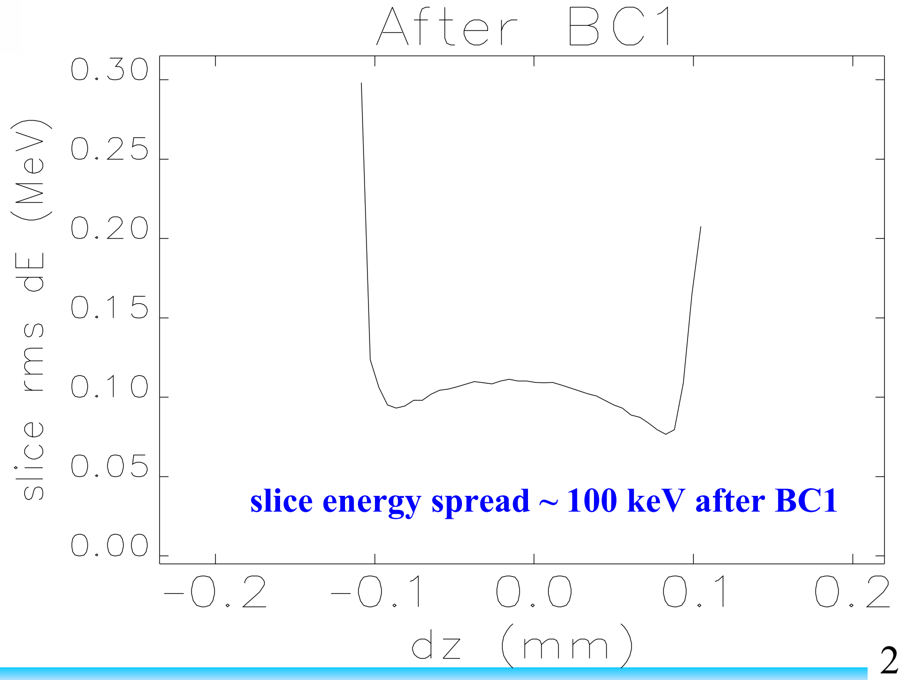


ELEGANT Results - After BC1









ELEGANT Results - Zoom in around BC1

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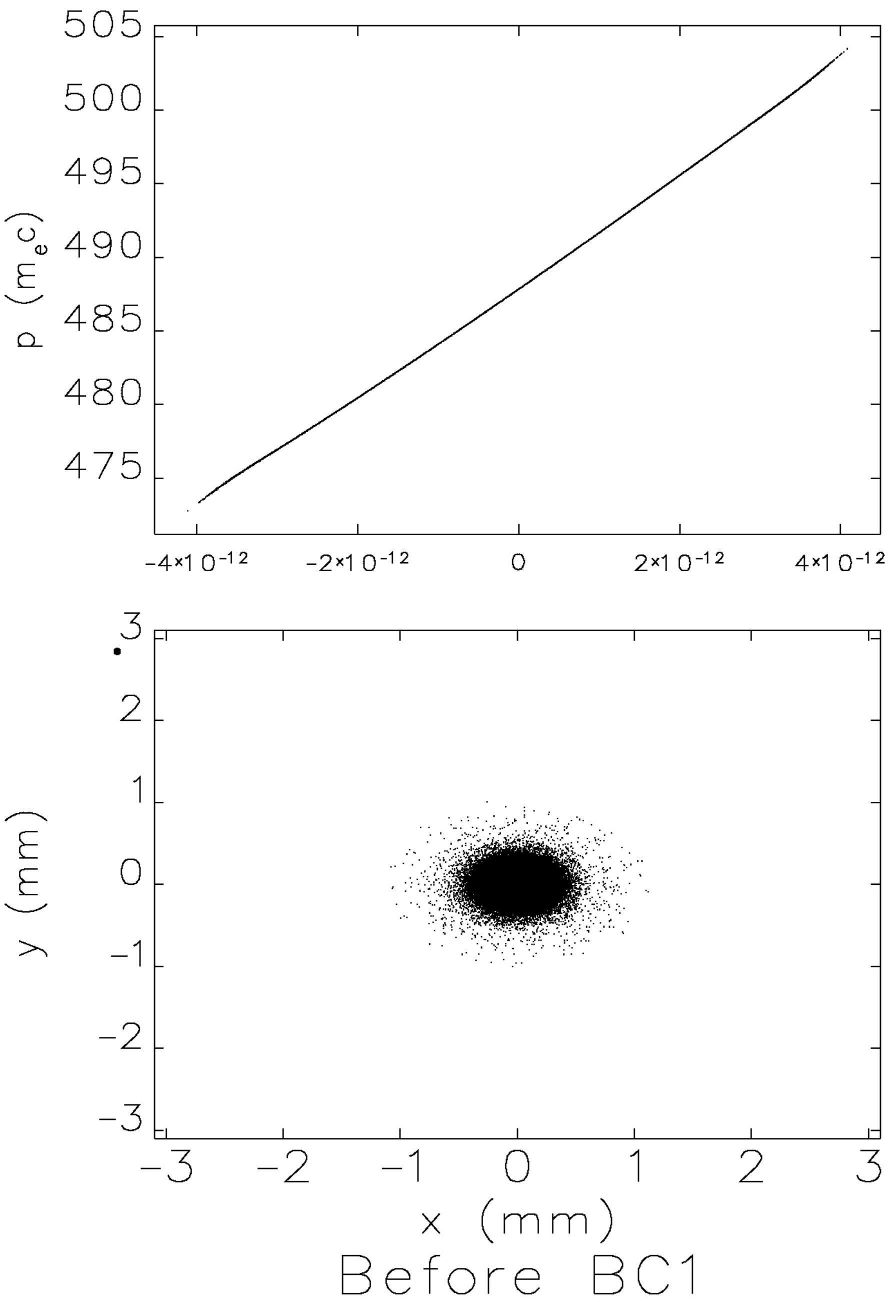
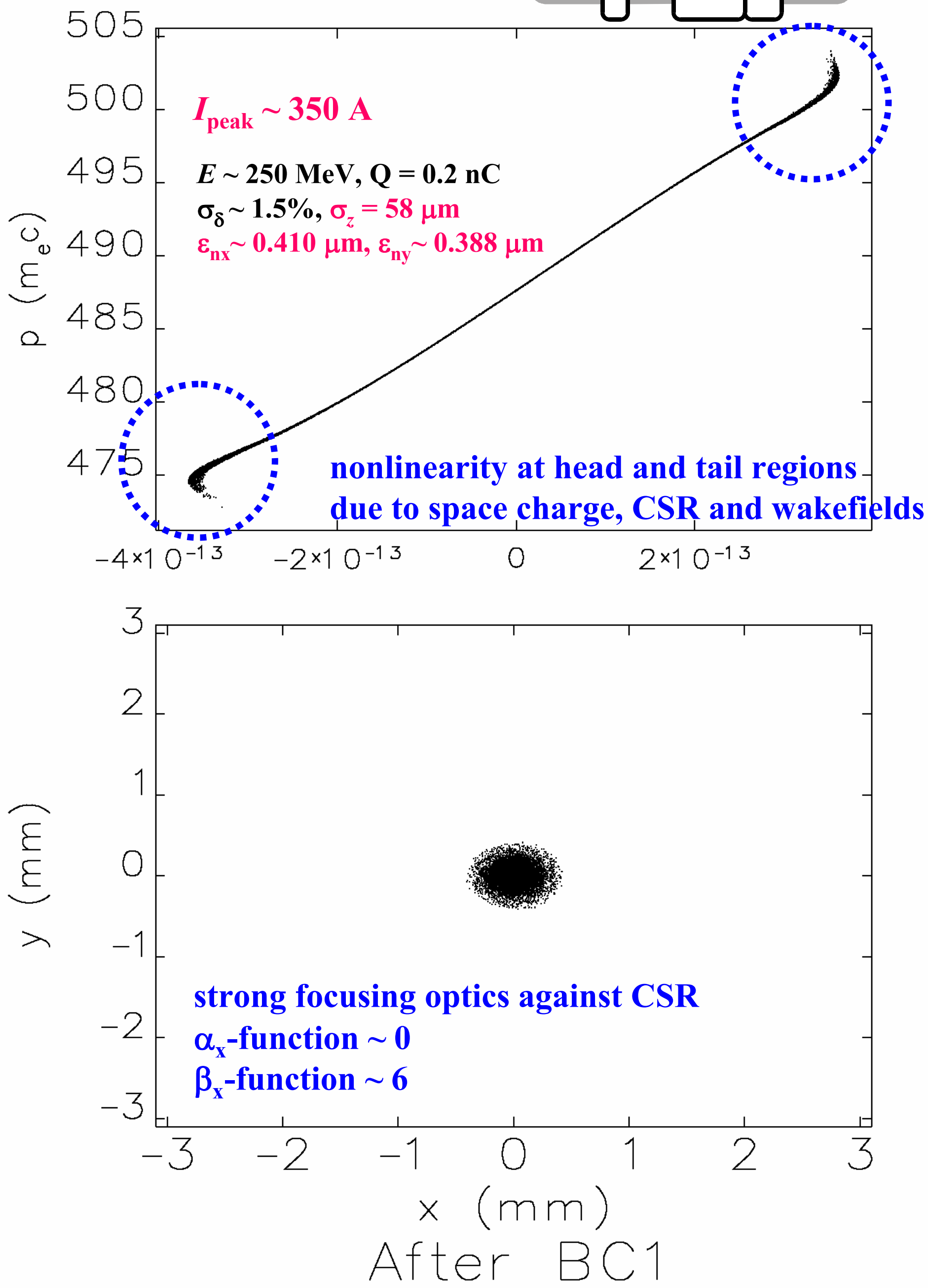




Magnets for Diagnostic Section

ELEGANT Starting Point = 17.873 m from Romain's Excel file - Version 1.31
QM length = 0.15 m
Maximum QM gradient = 20 T/m
Length of DUMP dipole = 0.3 m
Bending angle of DUMP dipole = from 3 degree (but it is not fixed completely).

Starting Point of four QMs at upstream of BC1
- Q1@UBC1 at 29.759 m
- Q2@UBC1 at 30.109 m
- Q3@UBC1 at 30.459 m
- Q4@UBC1 at 31.309 m

Starting Point of 1st Dipole in BC1 = 32.439 m
Ending Point of 4th Dipole in BC1 = 32.439 + 10.5 = 42.939 m

Starting Point of five QMs at downstream of BC1
- Q1@DBC1 at 44.239 m
- Q2@DBC1 at 44.689 m
- Q3@DBC1 at 45.439 m
- Q4@DBC1 at 45.889 m
- Q5@DBC1 at 46.339 m

Starting Point of seven QMs in 3FODO
- Q1@FODO at 47.789 m
- Q2@FODO at 49.189 m
- Q3@FODO at 50.589 m
- Q4@FODO at 51.989 m
- Q5@FODO at 53.389 m
- Q6@FODO at 54.789 m
- Q7@FODO at 56.189 m

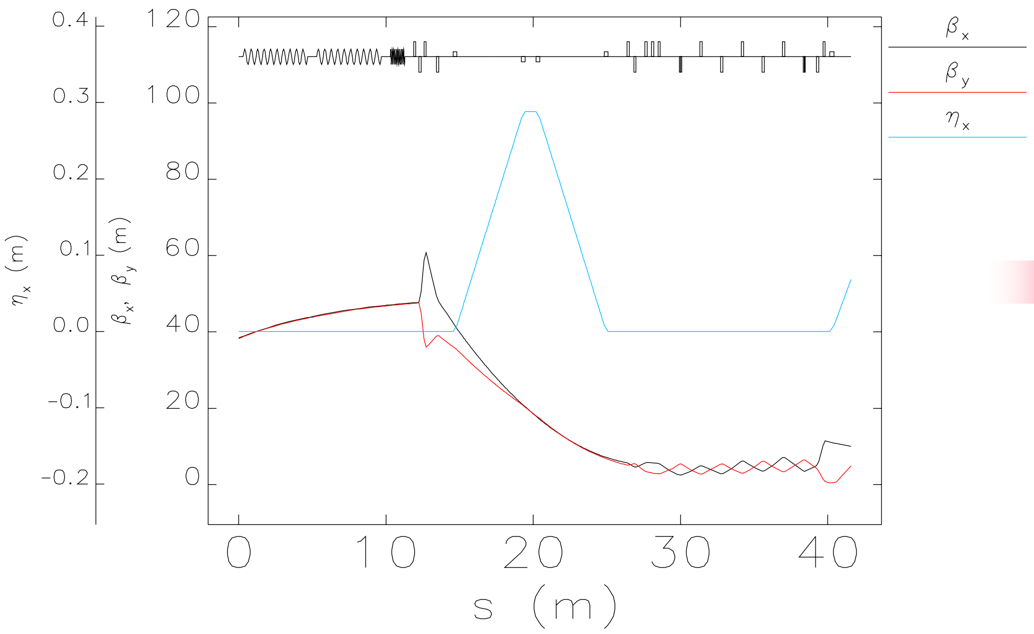
Starting Point of two QMs at downstream of 3FODO
- Q1@DFODO at 57.0916 m
- Q2@DFODO at 57.5416 m

Starting Point of 0.3 m long Dump Dipole = 57.9916 m
Starting Point of OTR@DUMP for LOLA = 59.4592 m
Starting Point of Dump = 59.8 m

Re-Matching of Poor FODO Cells

<u>**Initial Twiss Parameters @ 150 MeV**</u>
α_x-function ~ -0.75
α_y-function ~ -0.75
β_x-function ~ 38 m
β_y-function ~ 38 m

DOFO optics in 3FODO cells



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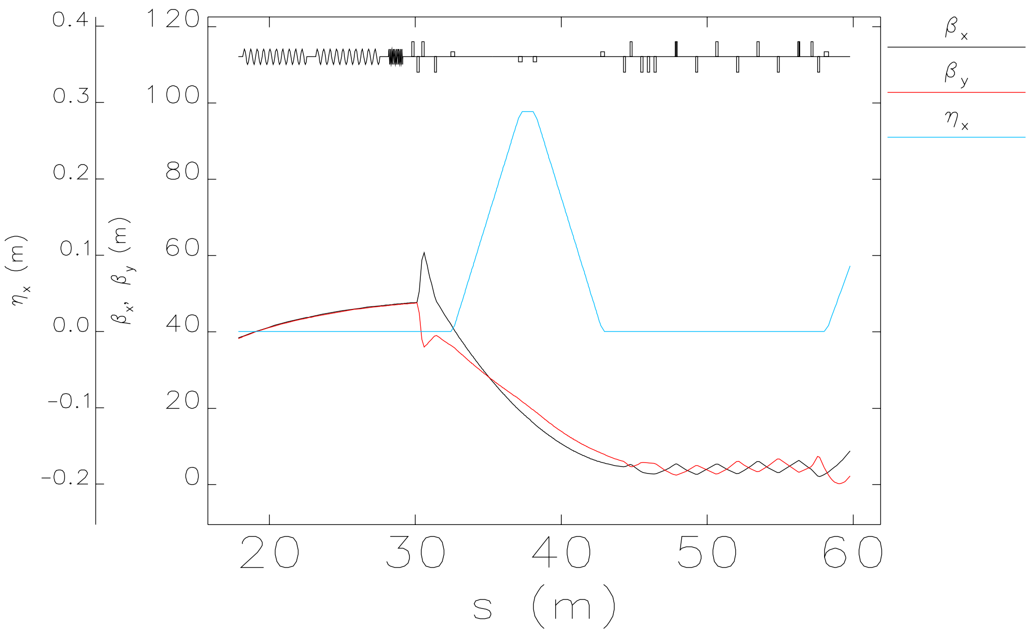


Reoptimization of QM Strength and Polarity

Maximum K in QMs < 15.0 (1/m^2)
Maximum gradient in QMs = $K \times E$(MeV)/299.8 ~ 13 T/m for 250 MeV

Re-Matching of Poor Upstream Optics

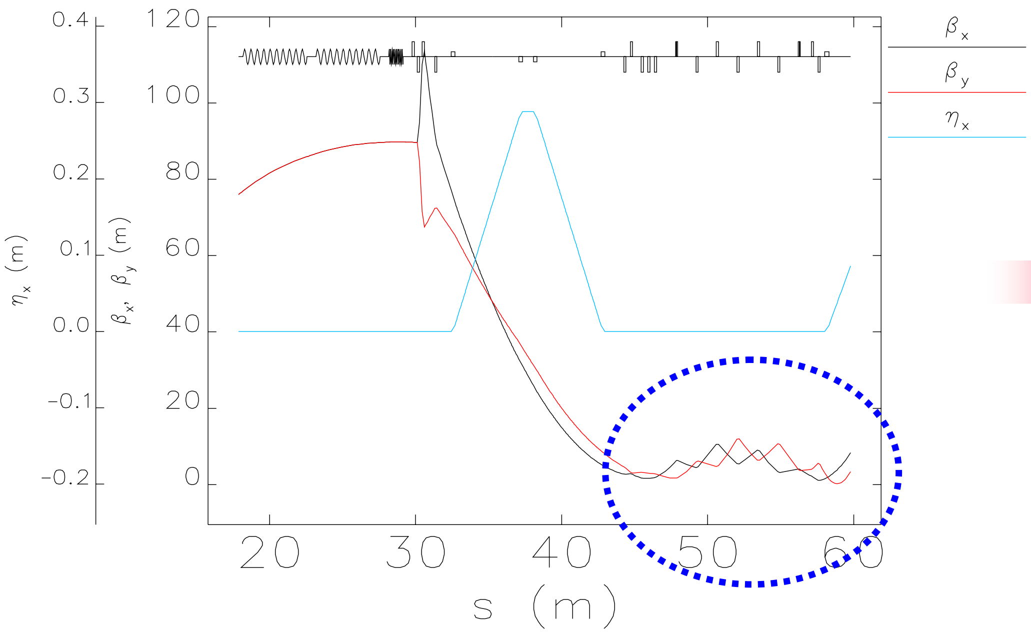
Initial Twiss Parameters @ 150 MeV

α_x-function ~ -1.5

α_y-function ~ -1.5

β_x-function ~ 76 m

β_y-function ~ 76 m



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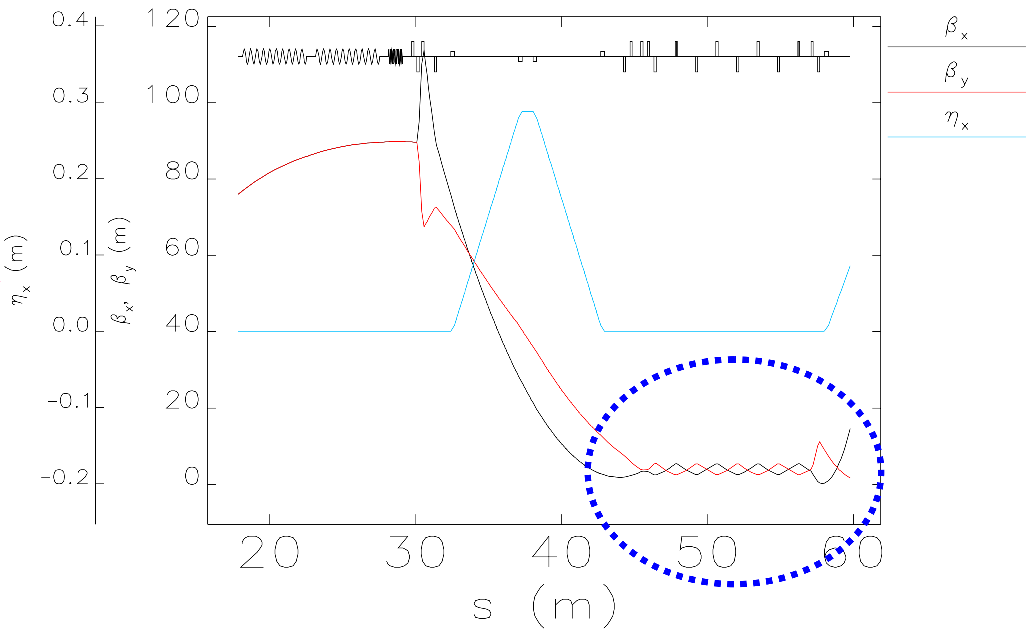
FODO optics in 3FODO cells



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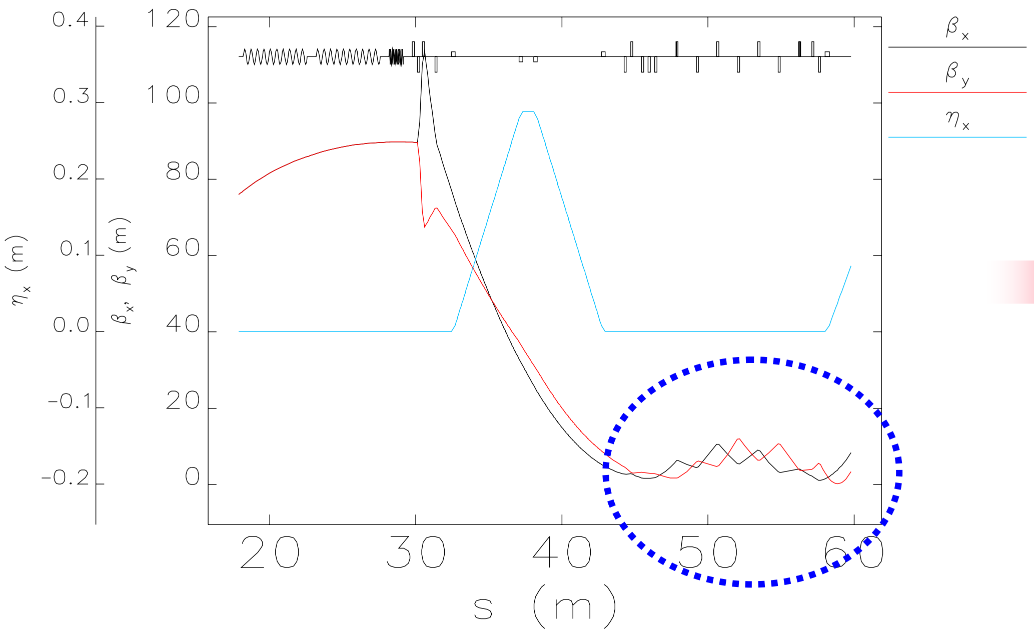
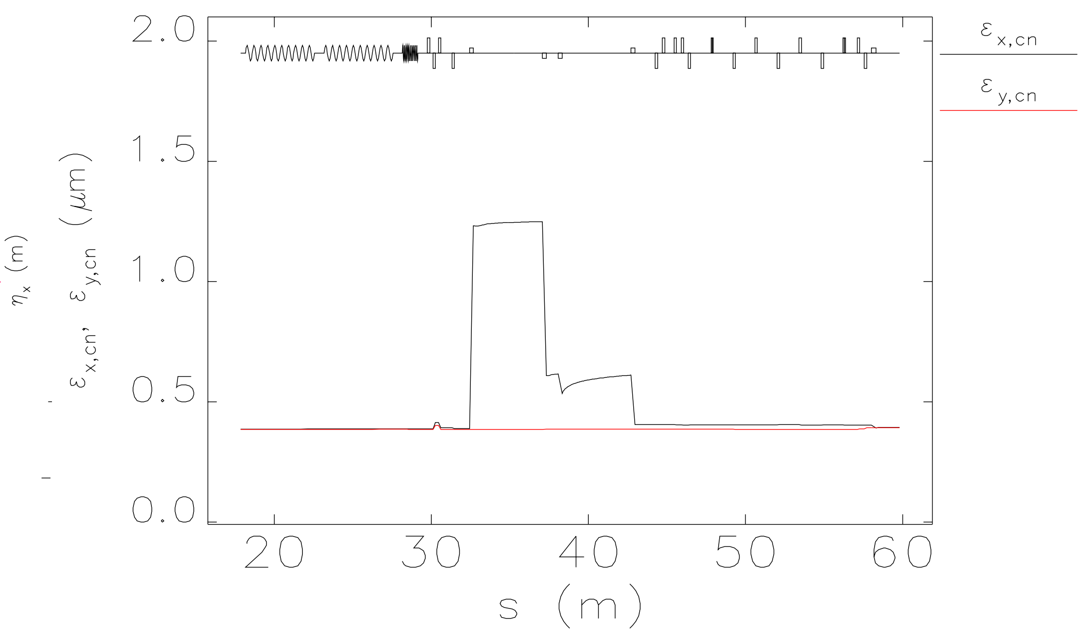
FODO optics in 3FODO cells





Reoptimization of QM Strength

Maximum K in QMs < 15.0 (1/m^2)

Maximum gradient in QMs = $K \times E$(MeV)/299.8 ~ 13 T/m for 250 MeV

Re-Matching of Optics for Pulser Injector

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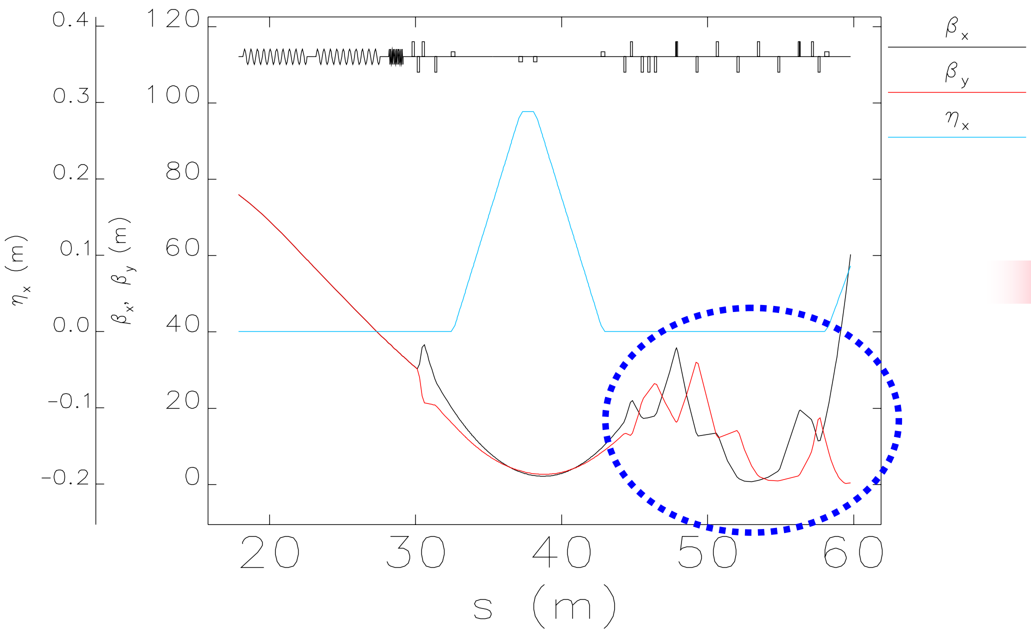
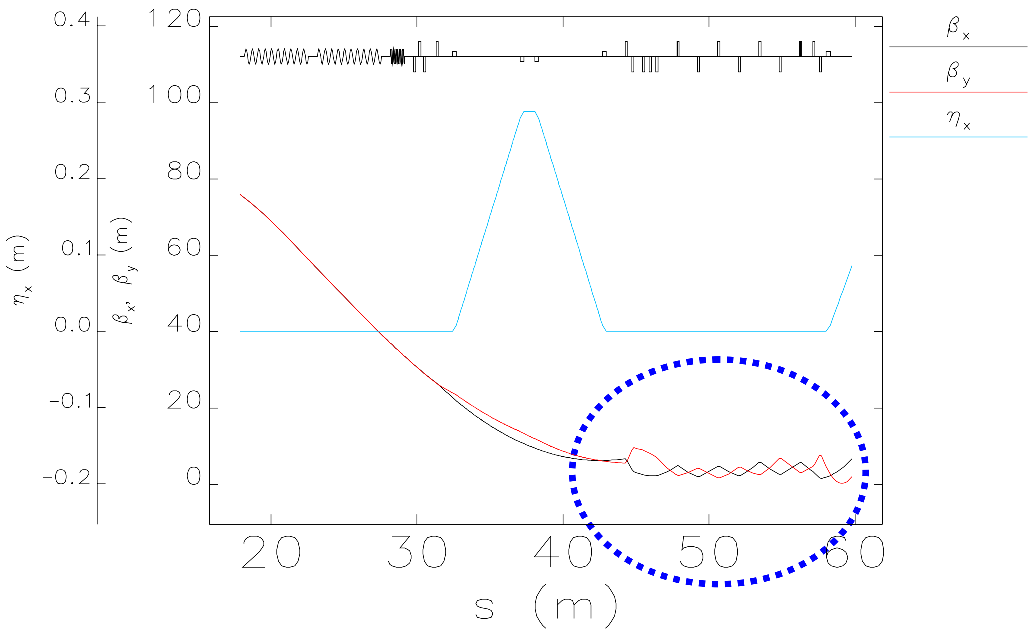
Initial Twiss Parameters @ 150 MeV
α_x-function ~ 1.5
α_y-function ~ 1.5
β_x-function ~ 76 m
β_y-function ~ 76 m

Initial Twiss Parameters @ 150 MeV
α_x-function ~ 1.5
α_y-function ~ 1.5
β_x-function ~ 76 m
β_y-function ~ 76 m

Big horizontal emittance growth in BC
Positive alpha-function gives a poor optics against CSR in BC
For a better matching, we need an optimization of Twiss parameters in pulser based injector

FODO optics in 3FODO cells





Reoptimization of QM Strength

Maximum *K* in QMs < 15.0 ($1/m^2$)
Maximum gradient in QMs = *K*×*E*(MeV)/299.8 ~ 13 T/m for 250 MeV

Re-Matching of Optics for Pulser Injector

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Initial Twiss Parameters @ 150 MeV

α_x-function ~ 1.5

α_y-function ~ 1.5

β_x-function ~ 76 m

β_y-function ~ 76 m

Initial Twiss Parameters @ 150 MeV

α_x-function ~ 1.5

α_y-function ~ 1.5

β_x-function ~ 76 m

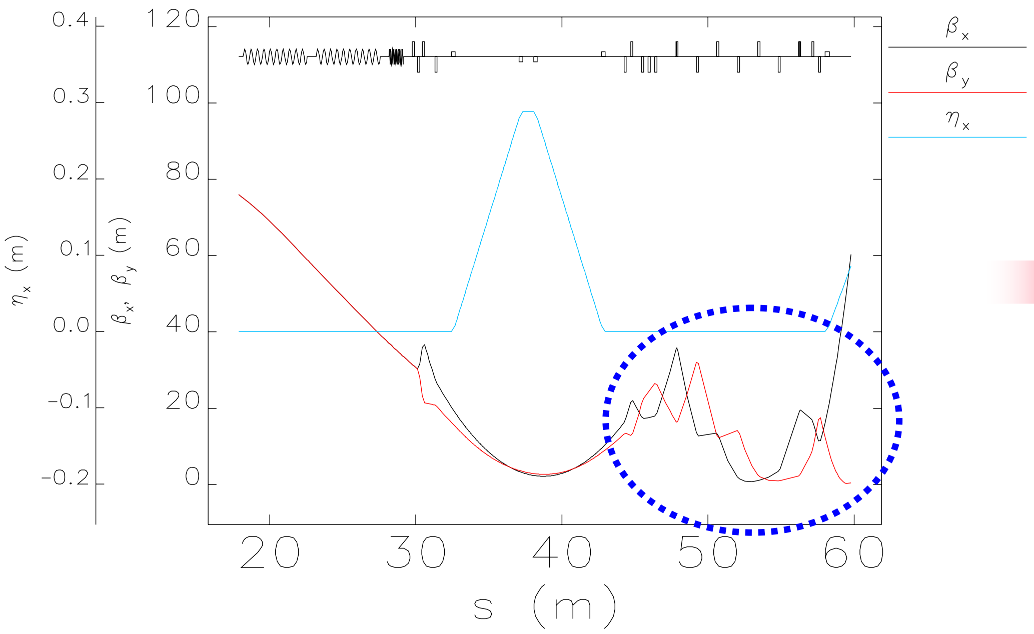
β_y-function ~ 76 m

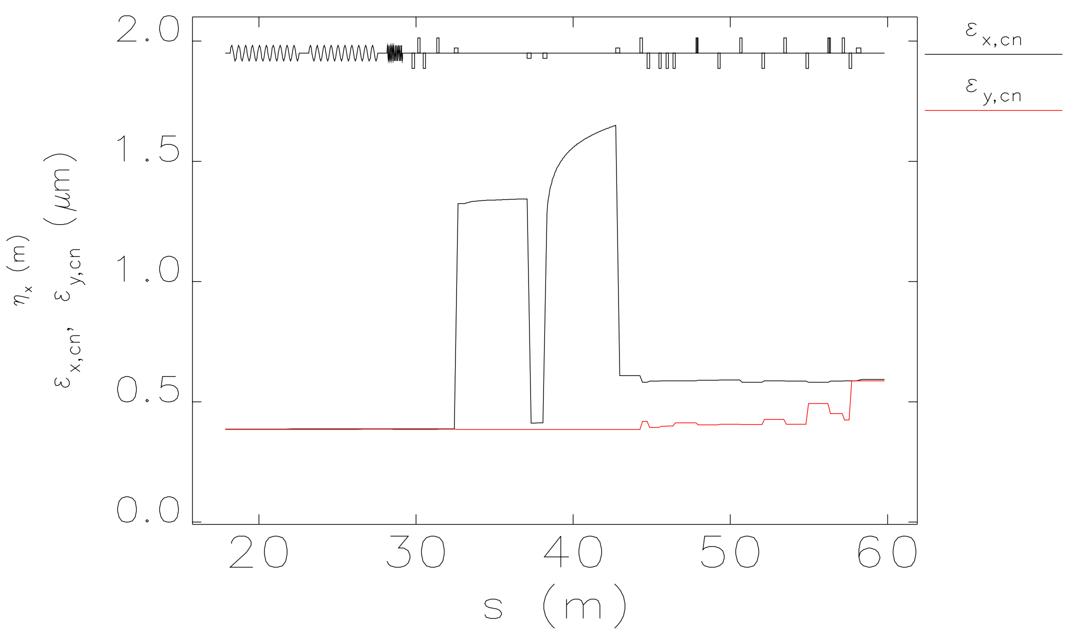
Big horizontal emittance growth in BC

Positive alpha-function gives a poor optics against CSR in BC

For a better matching, we need an optimization of Twiss parameters in pulser based injector

FODO optics in 3FODO cells



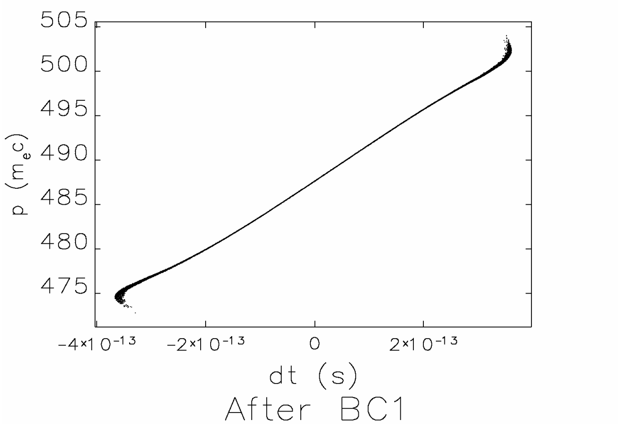


Reoptimization of QM Strength

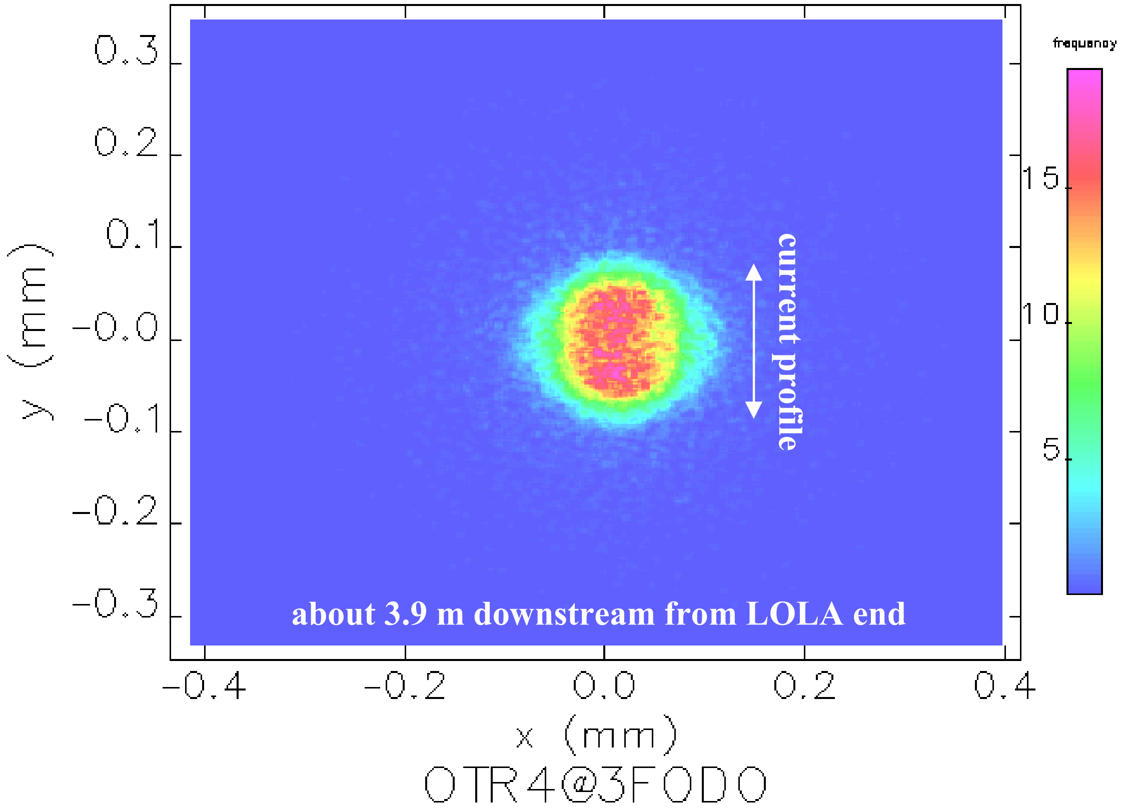
Maximum K in QMs < 15.0 (1/m^2)

Maximum gradient in QMs = $K \times E$(MeV)/299.8 ~ 13 T/m for 250 MeV

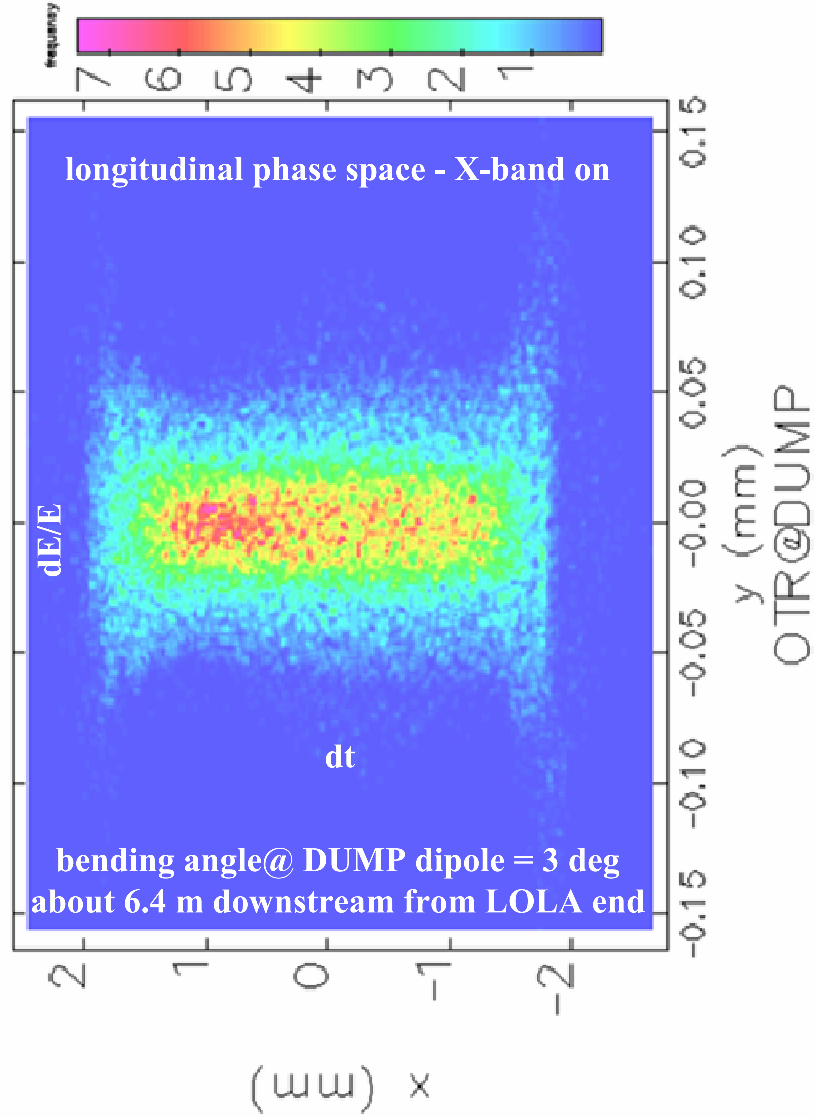
Simulation on LOLA - 0 MV & 3 deg



bunch length (rms) ~ 193 fs / 57.9 μm
bunch length (FWHM) ~ 455 fs
bunch length (FW) ~ 770 fs
σ_x= 60.2 μm @ OTR4
σ_y= 58.6 μm @ OTR4
σ_x= 1.015 mm @ DUMP
σ_y= 25.7 μm @ DUMP



1.15 m downstream from DUMP dipole



Simulation on LOLA - 1 MV & 3 deg

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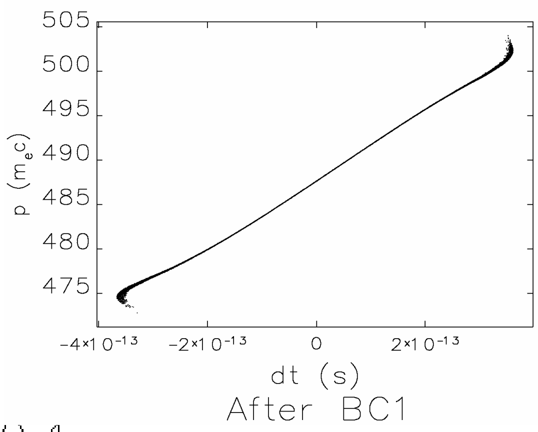
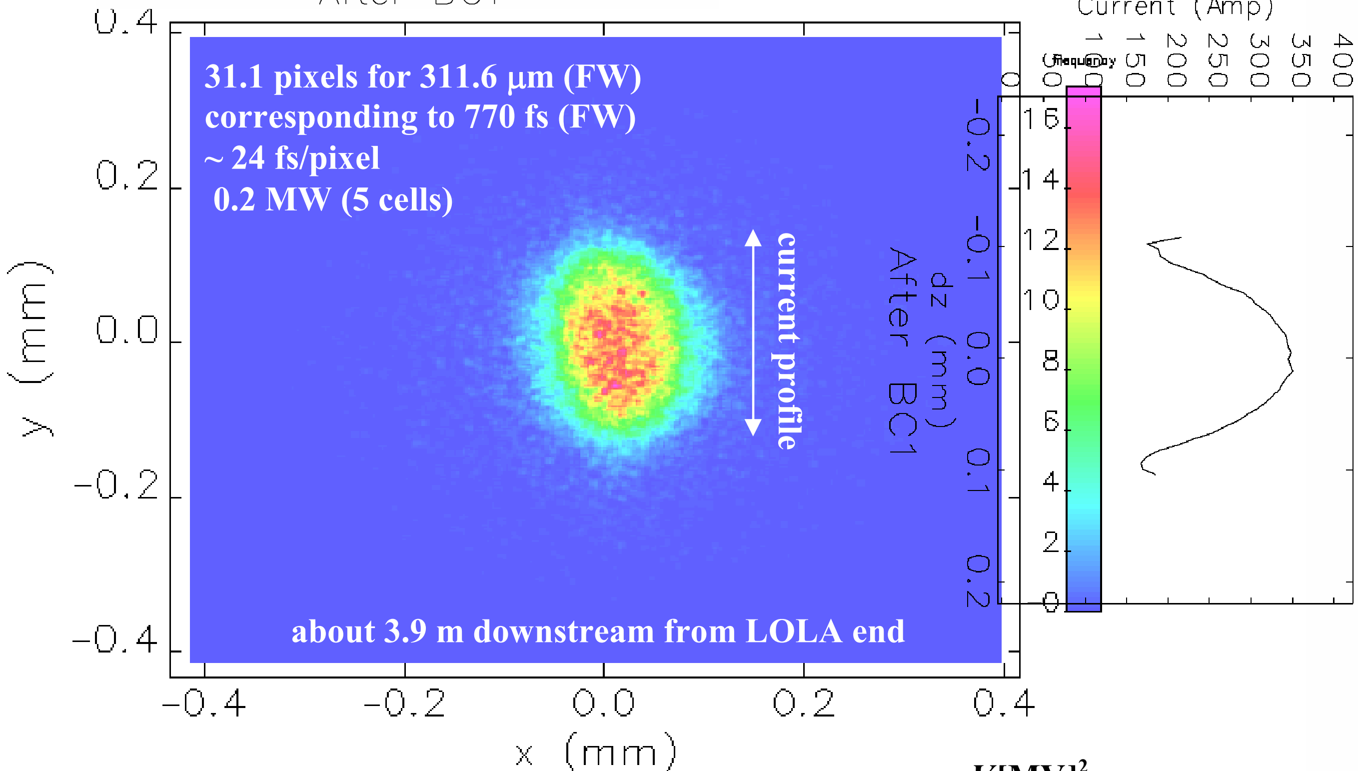
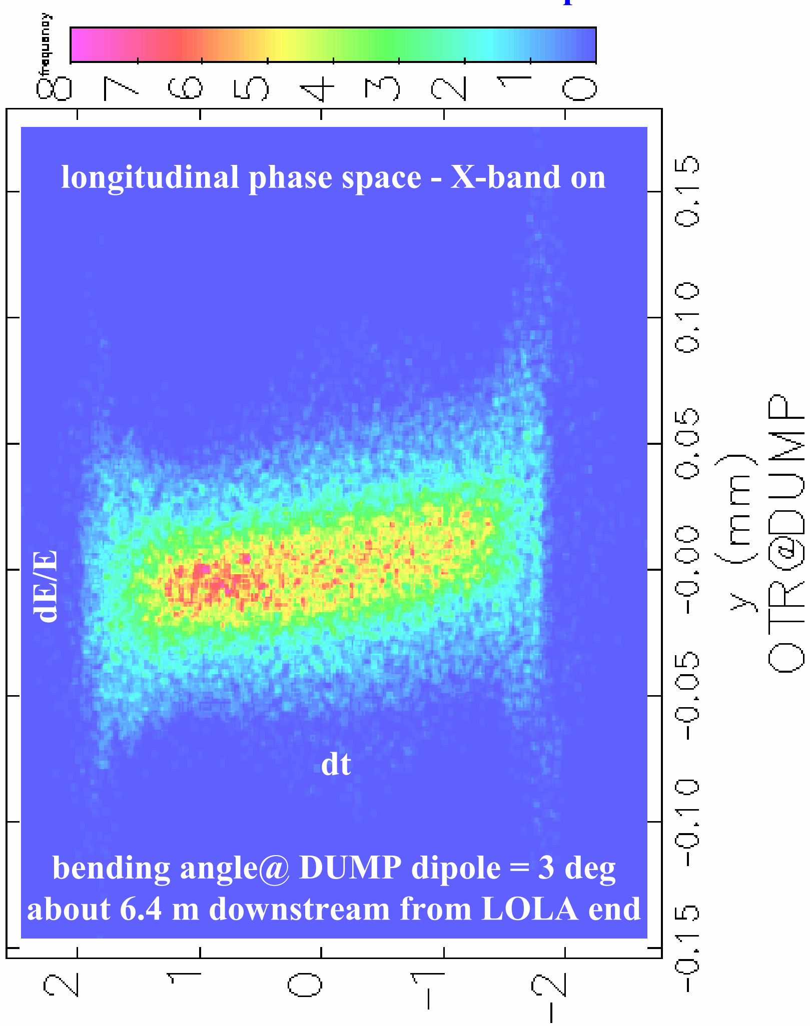


bunch length (rms) ~ 193 fs / 57.9 μm
bunch length (FWHM) ~ 455 fs
bunch length (FW) ~ 770 fs
σ_x= 60.2 μm @ OTR4
σ_y= 77.9 μm @ OTR4
σ_x= 1.015 mm @ DUMP
σ_y= 27.0 μm @ DUMP

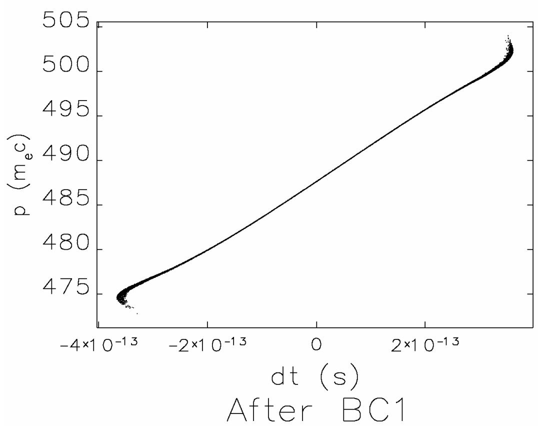
1.15 m downstream from DUMP dipole



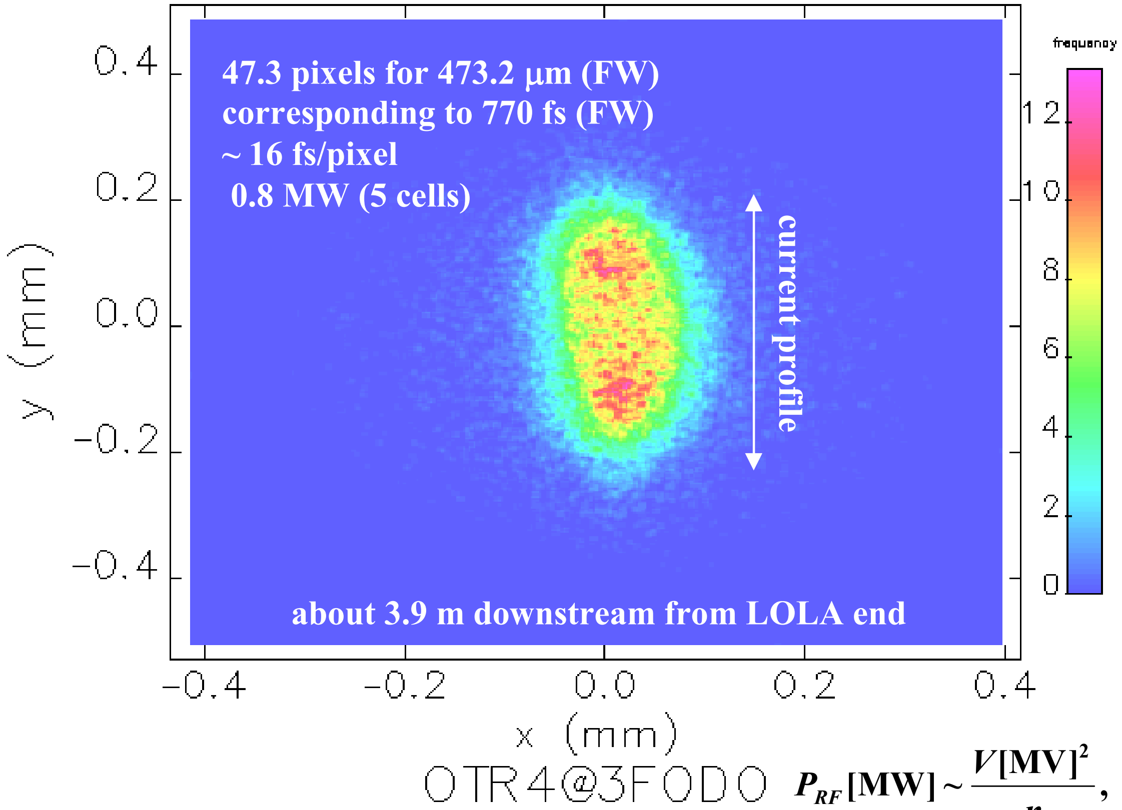


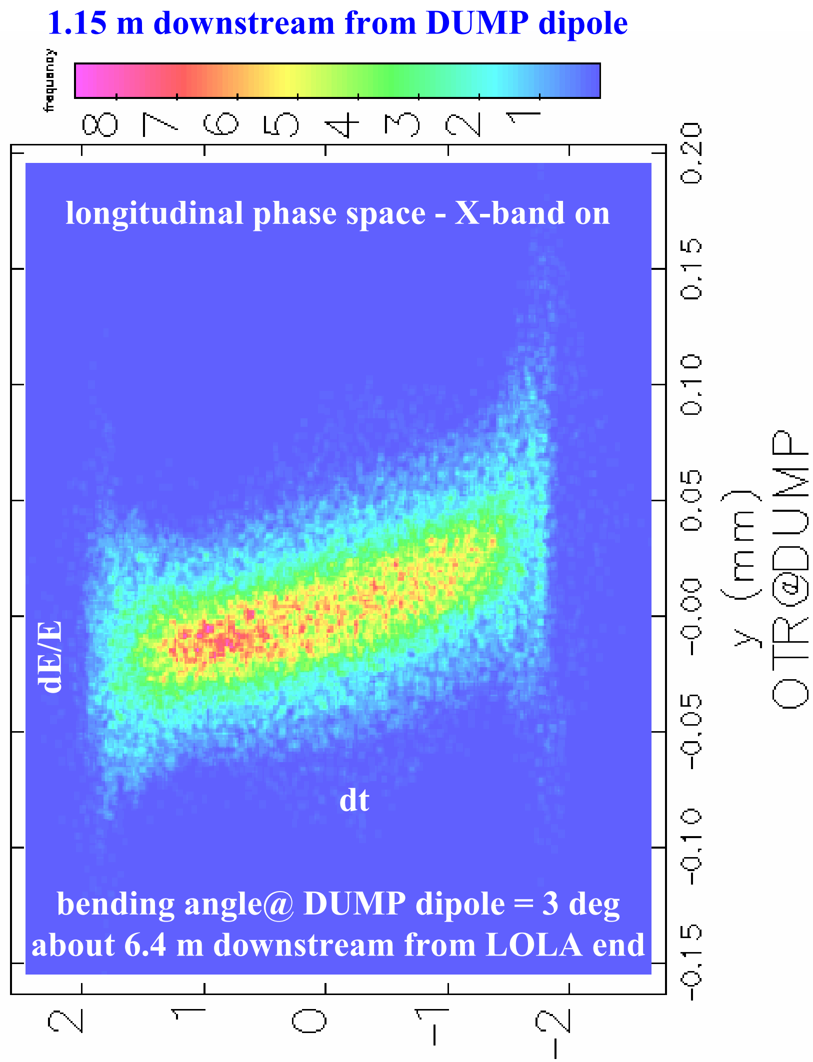
$$P_{RF}[\mathrm{MW}] \sim \frac{V[\mathrm{MV}]^2}{n}, \quad E_{peak,surf}[\mathrm{MV/m}] \sim 90\sqrt{\frac{P_{RF}[\mathrm{MW}]}{n}}$$

Simulation on LOLA - 2 MV & 3 deg



bunch length (rms) ~ 193 fs / 57.9 μm
bunch length (FWHM) ~ 455 fs
bunch length (FW) ~ 770 fs
σ_x= 60.2 μm @ OTR4
σ_y= 118.3 μm @ OTR4
σ_x= 1.015 mm @ DUMP
σ_y= 30.6 μm @ DUMP





$$P_{RF}[\text{MW}] \sim \frac{V[\text{MV}]^2}{n}, \quad E_{peak,surf}[\text{MV/m}] \sim 90\sqrt{\frac{P_{RF}[\text{MW}]}{n}}$$

Simulation on LOLA - 4 MV & 3 deg

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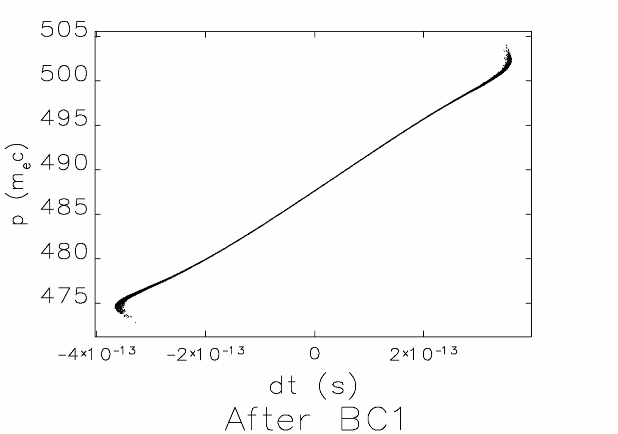
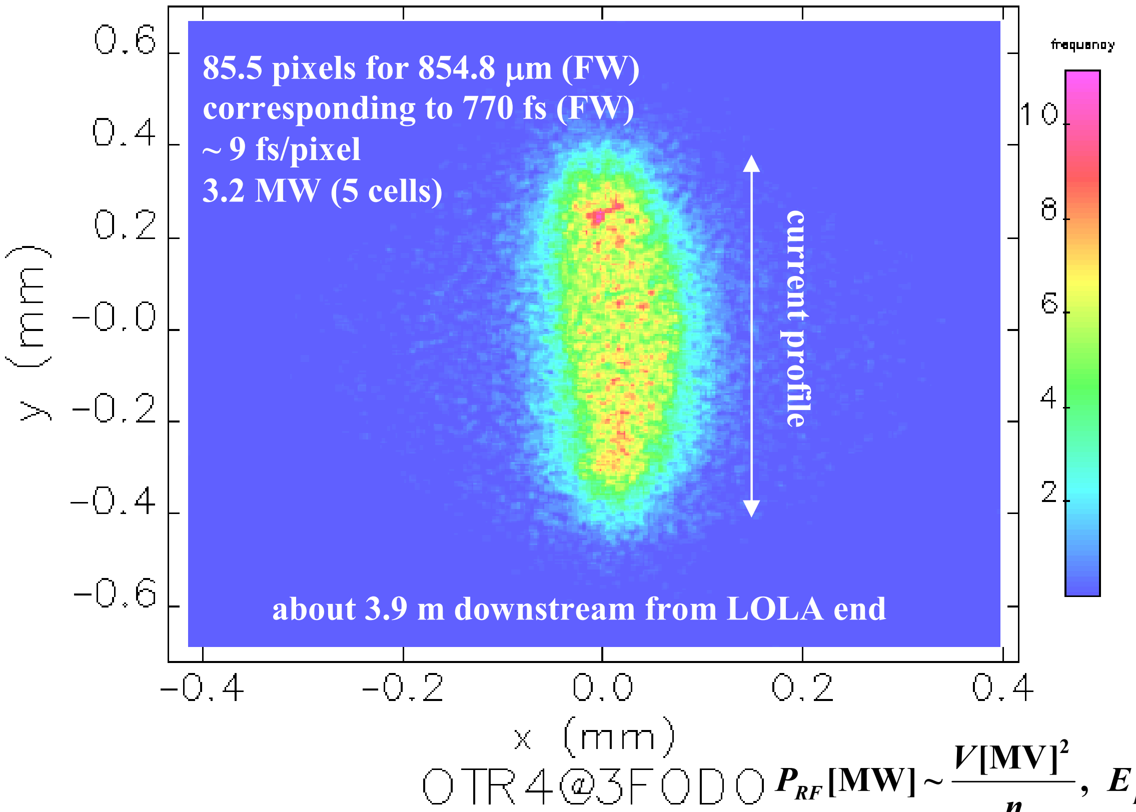
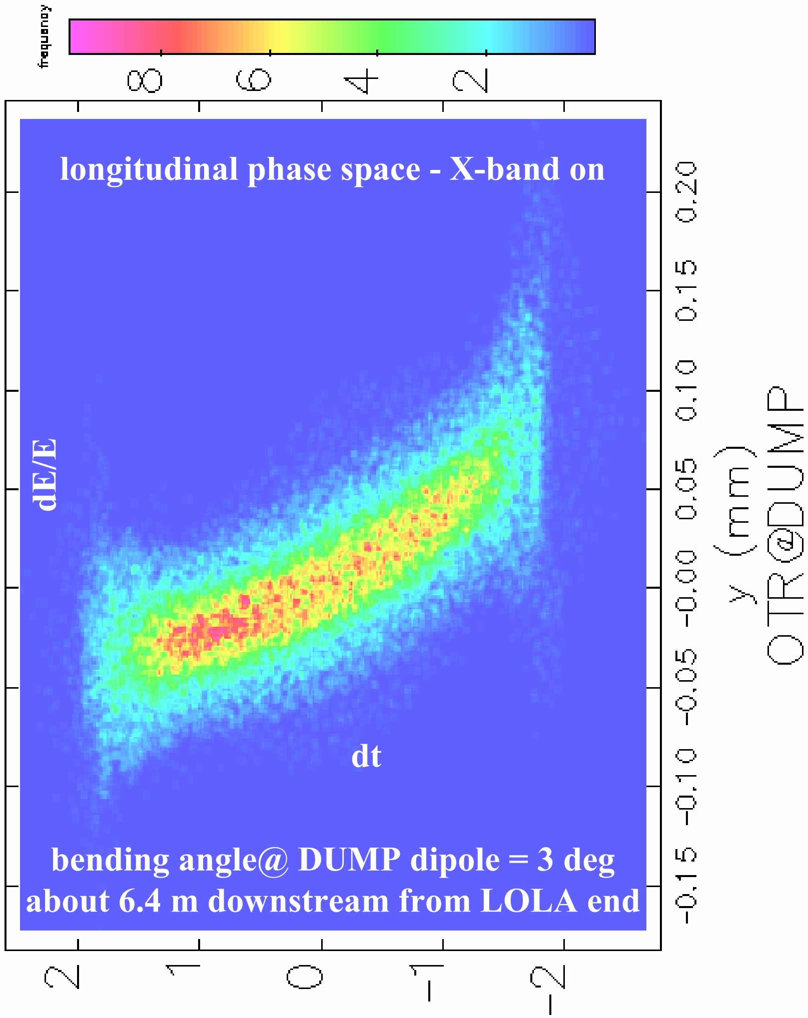


bunch length (rms) ~ 193 fs / 57.9 μm
bunch length (FWHM) ~ 455 fs
bunch length (FW) ~ 770 fs
σ_x= 60.2 μm @ OTR4
σ_y= 213.7 μm @ OTR4
σ_x= 1.015 mm @ DUMP
σ_y= 42.1 μm @ DUMP





$$P_{RF}[\mathrm{MW}] \sim \frac{V[\mathrm{MV}]^2}{n}, \quad E_{peak,surf}[\mathrm{MV/m}] \sim 90\sqrt{\frac{P_{RF}[\mathrm{MW}]}{n}}$$

Simulation on LOLA - 8 MV & 3 deg

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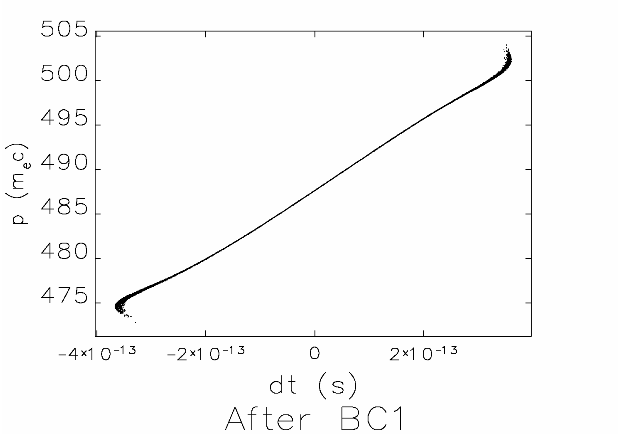
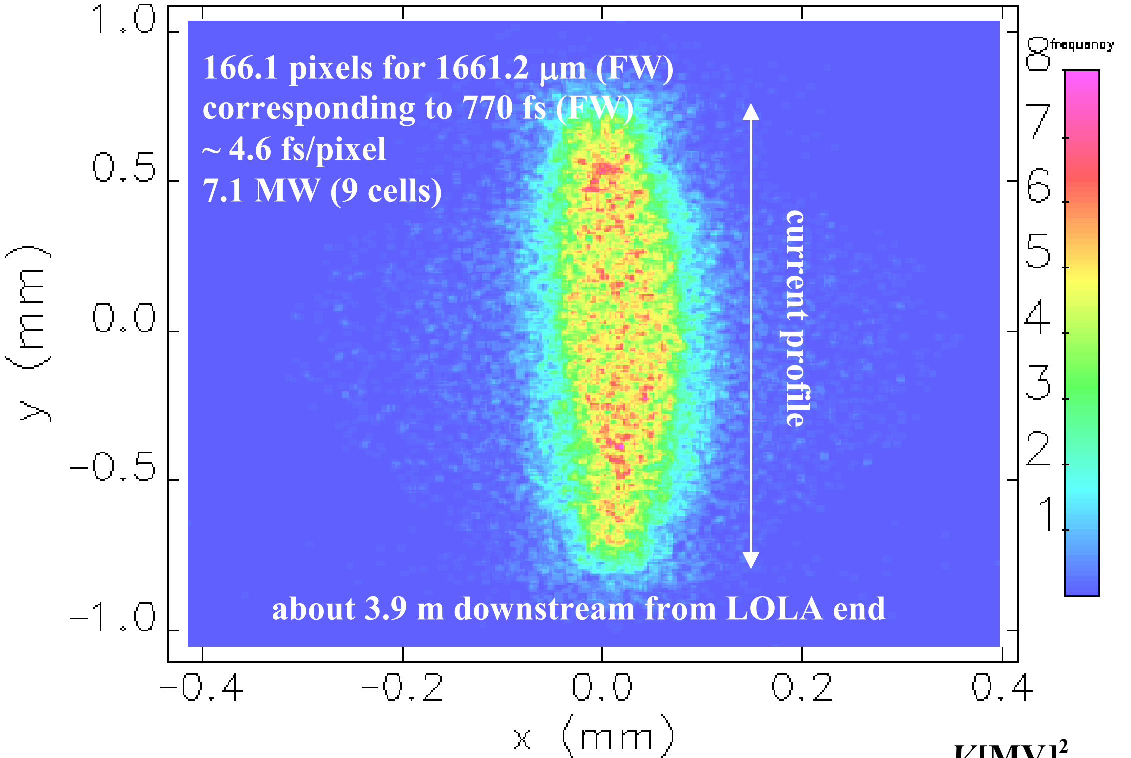
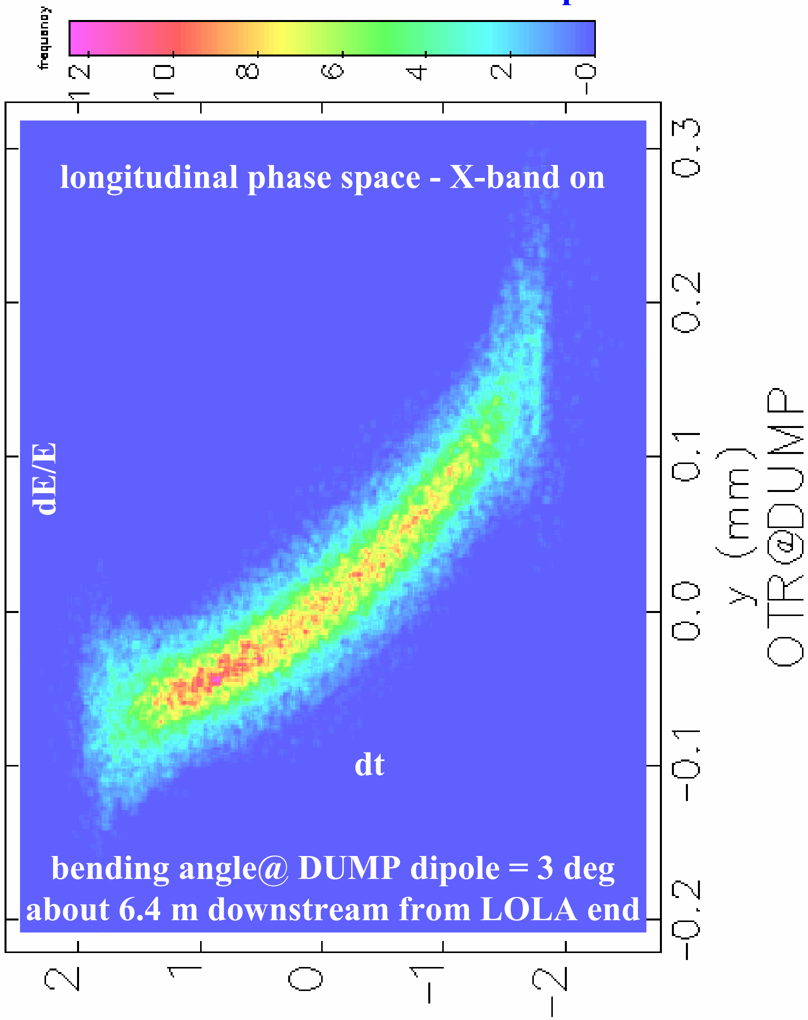


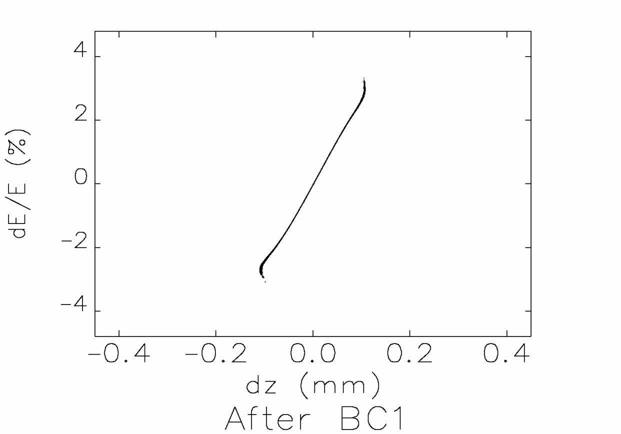
bunch length (rms) ~ 193 fs / 57.9 μm
bunch length (FWHM) ~ 455 fs
bunch length (FW) ~ 770 fs
σ_x = 60.2 μm @ OTR4
σ_y = 415.3 μm @ OTR4
σ_x = 1.014 mm @ DUMP
σ_y = 71.4 μm @ DUMP



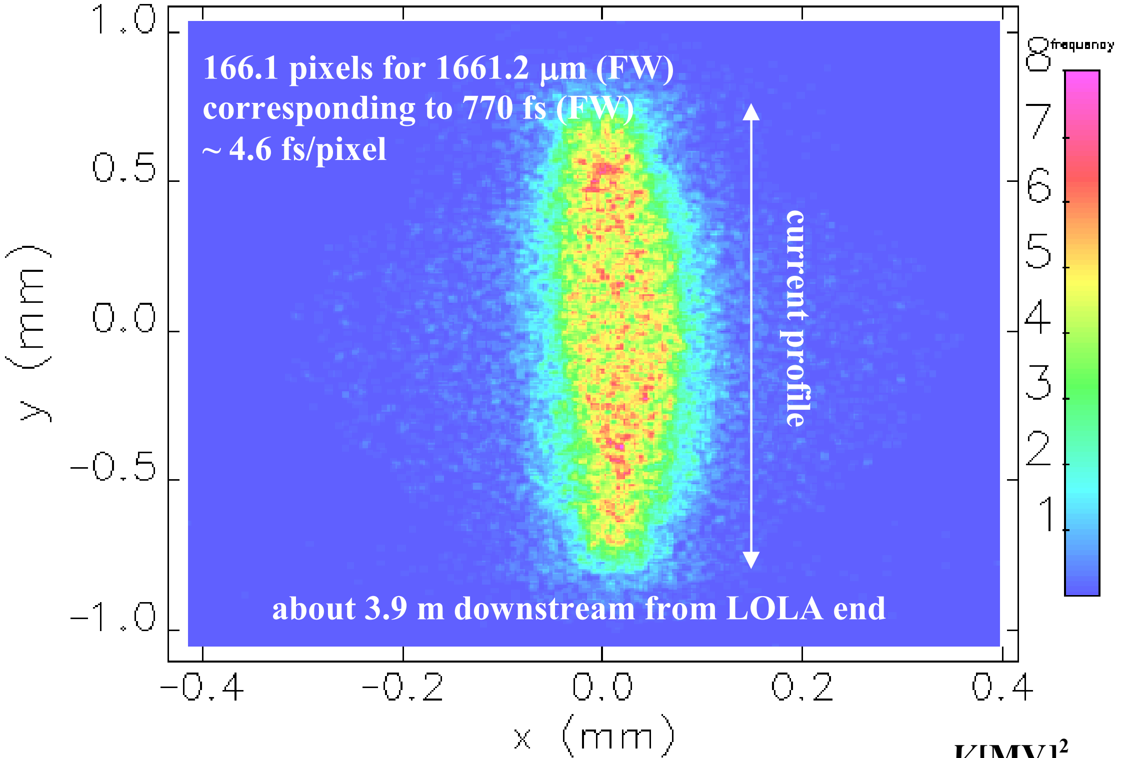


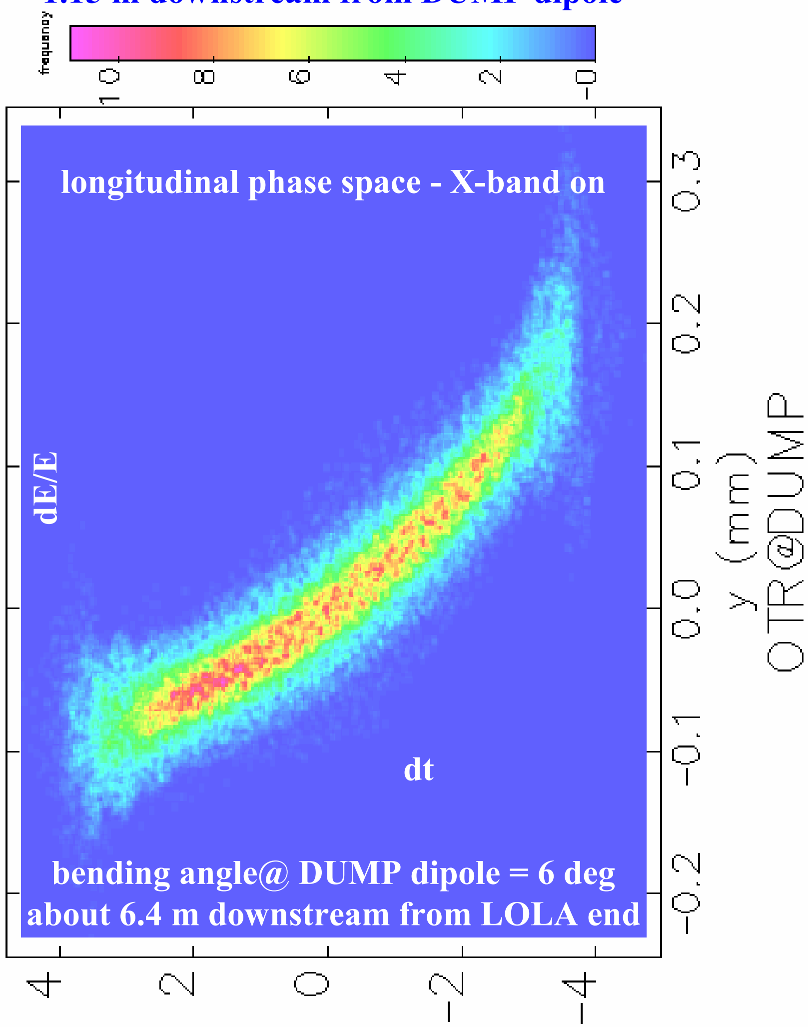
$$P_{RF}\,[\mathrm{MW}] \sim \frac{V[\mathrm{MV}]^2}{n}, \quad E_{peak,surf}\,[\mathrm{MV/m}] \sim 90\sqrt{\frac{P_{RF}\,[\mathrm{MW}]}{n}}$$

Simulation on LOLA - 8 MV & 6 deg



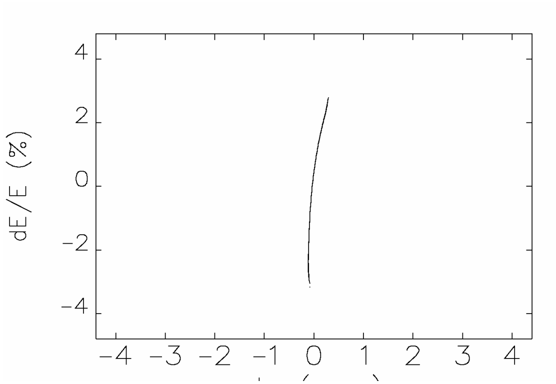
bunch length (rms) ~ 193 fs / 57.9 μm
bunch length (FWHM) ~ 455 fs
bunch length (FW) ~ 770 fs
σ_x= 60.2 μm @ OTR4
σ_y= 415.3 μm @ OTR4
σ_x= 1.014 mm @ DUMP
σ_y= 71.4 μm @ DUMP



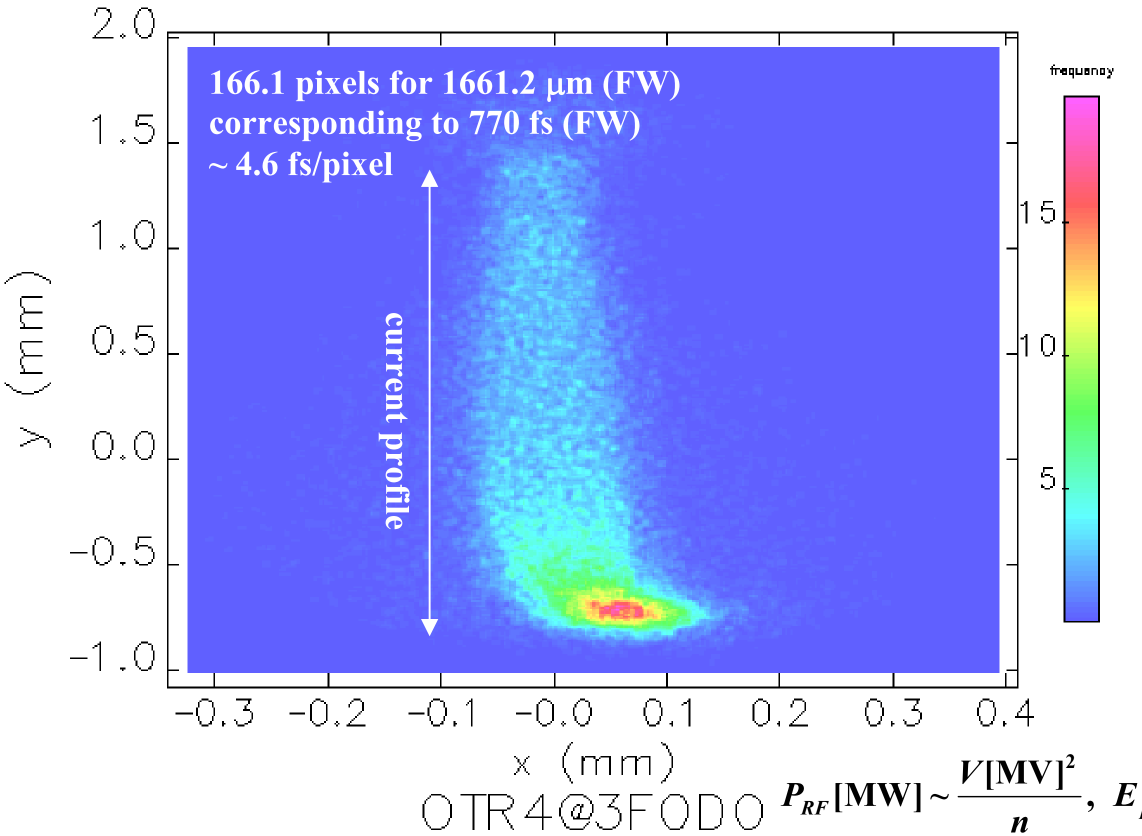


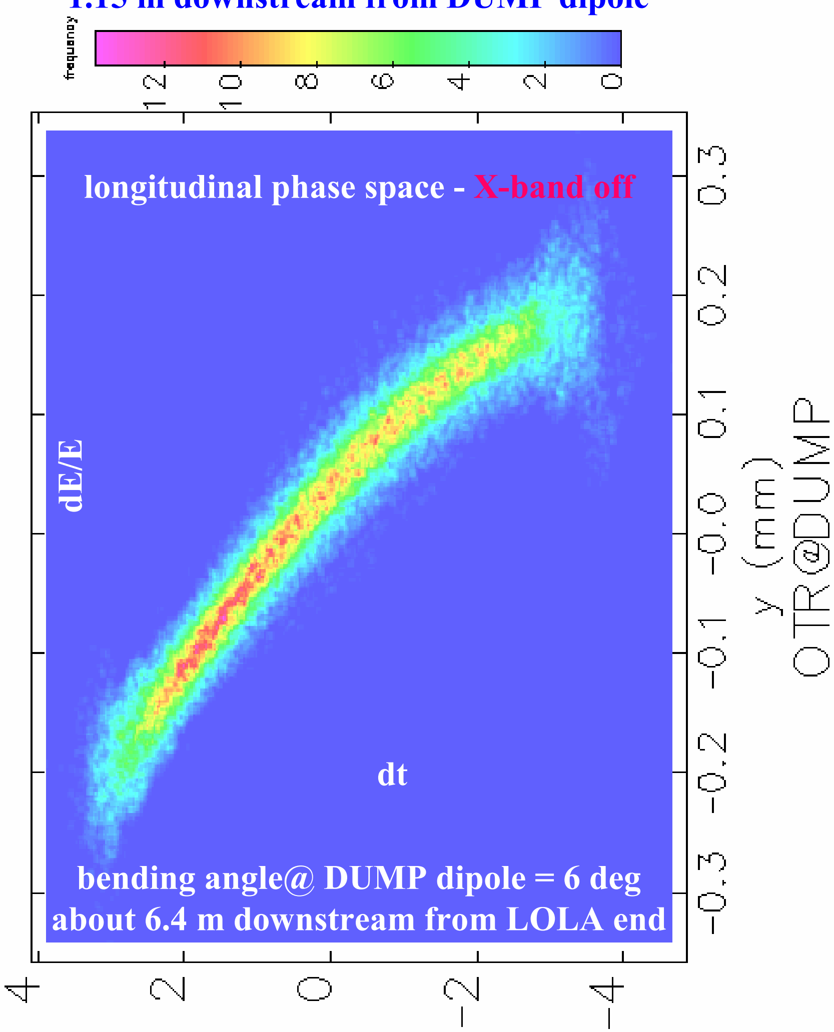
$P_{RF}[\mathrm{MW}] \sim \dfrac{V[\mathrm{MV}]^2}{n}$, $E_{peak,surf}[\mathrm{MV/m}] \sim 90\sqrt{\dfrac{P_{RF}[\mathrm{MW}]}{n}}$

Simulation on LOLA - 8 MV & 6 deg



bunch length (rms) ~ 342.7 fs / 102.8 μm
bunch length (FWHM) ~ 67 fs
bunch length (FW) ~ 1.4 ps
σ_x= 64.2 μm @ OTR4
σ_y= 684.7 μm @ OTR4
σ_x= 1.845 mm @ DUMP
σ_y= 118.1 μm @ DUMP





$$P_{RF}[\mathrm{MW}] \sim \frac{V[\mathrm{MV}]^2}{n}, \quad E_{peak,surf}[\mathrm{MV/m}] \sim 90\sqrt{\frac{P_{RF}[\mathrm{MW}]}{n}}$$

Simulation on LOLA - 8 MV & 6 deg

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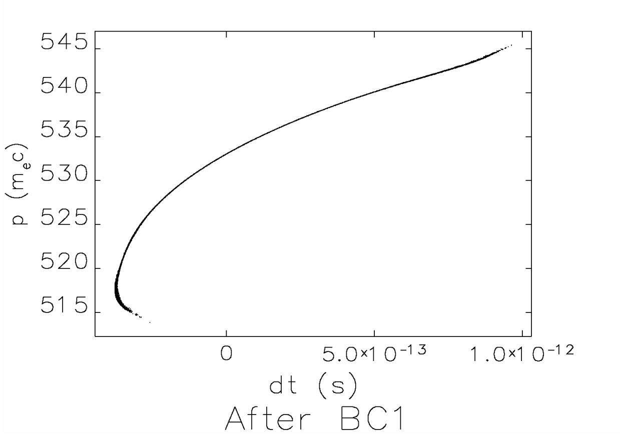


unch length (rms) ~ 342.7 fs / 102.8 μm

unch length (FWHM) ~ 67 fs

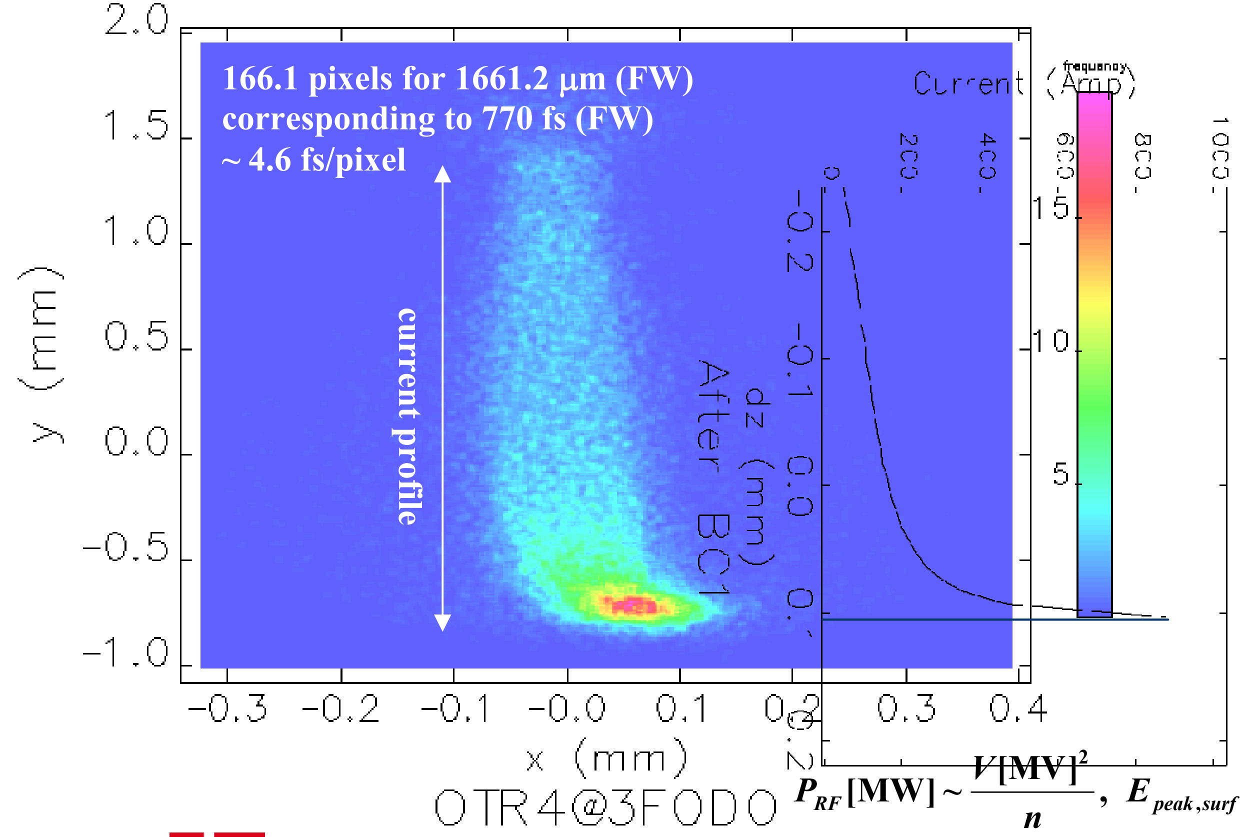
unch length (FW) ~ 1.4 ps

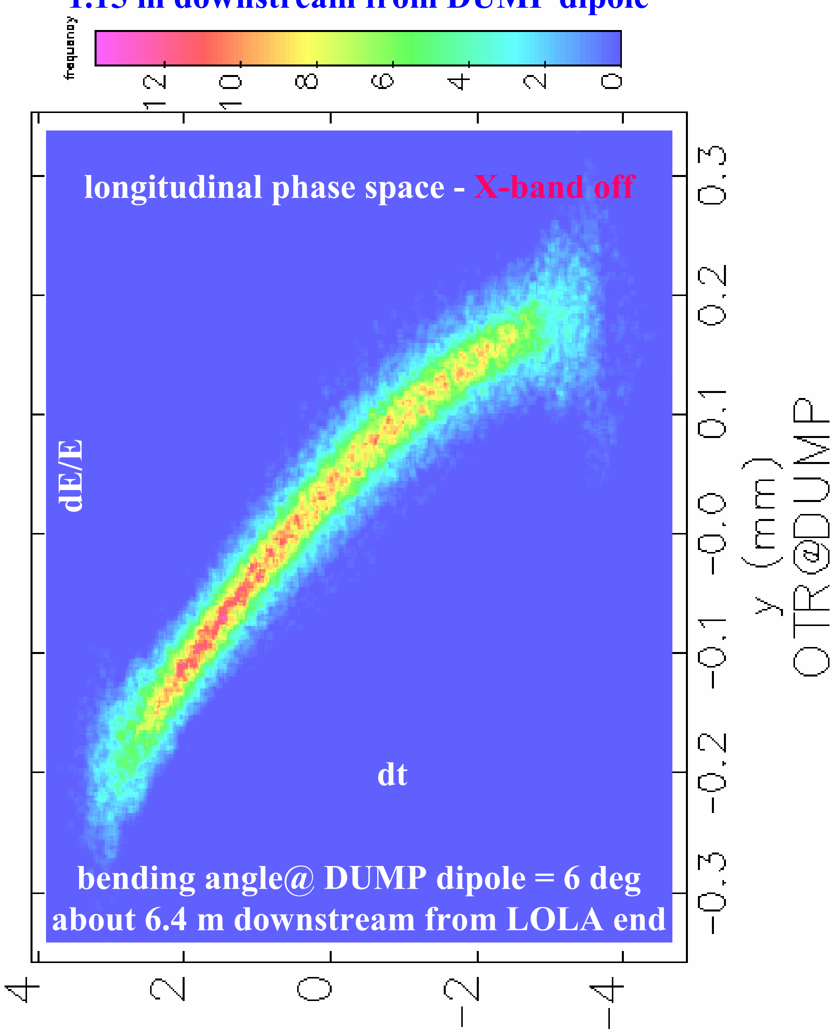
σ_x= 64.2 μm @ OTR4

σ_y= 684.7 μm @ OTR4

σ_x= 1.845 mm @ DUMP

σ_y= 118.1 μm @ DUMP





$P_{RF}[\text{MW}] \sim \frac{V[\text{MV}]^2}{n}$, $E_{peak,surf}[\text{MV/m}] \sim 90\sqrt{\frac{P_{RF}[\text{MW}]}{n}}$

Phase Advance for LOLA Operation

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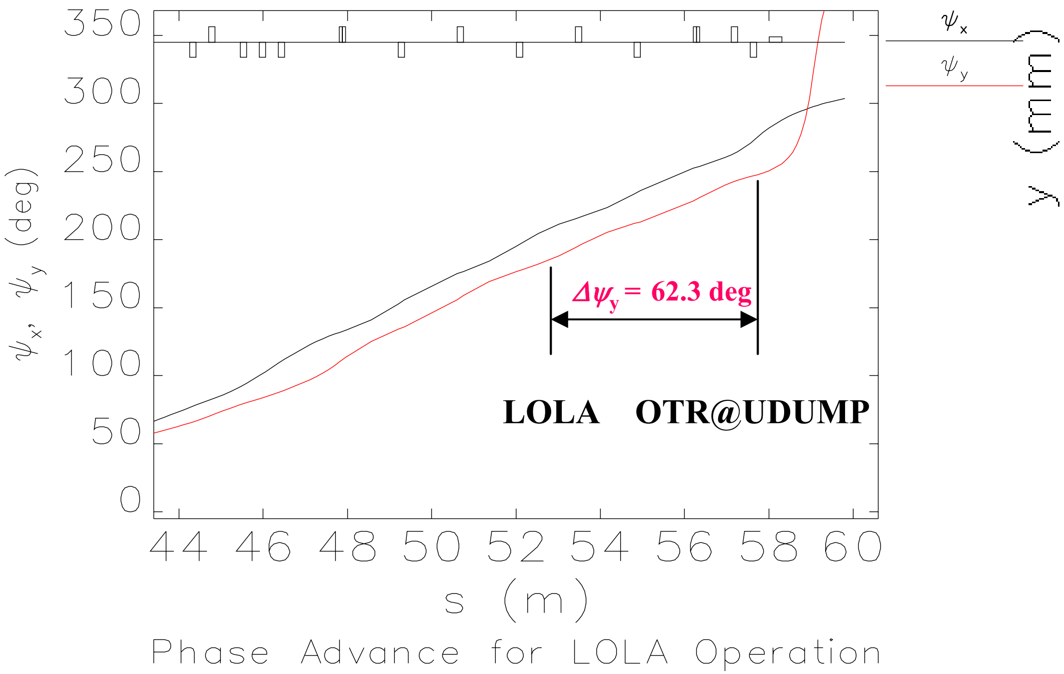
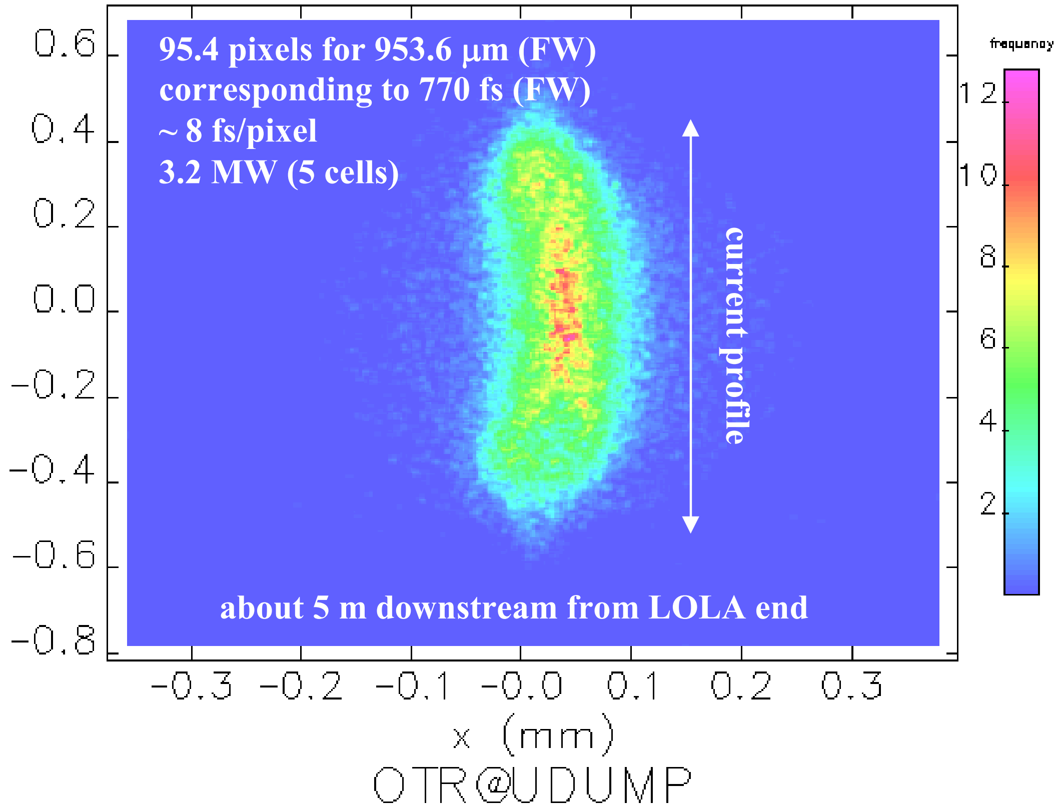
with 4 MV (5 cells) at OTR@UDUMP (just upstream of DUMP dipole)

σ_x= 59 µm @ LOLA
σ_y= 58 µm @ LOLA
σ_x= 47.3 µm @ UDUMP
σ_y= 238.4 µm @UDUMP
$\Delta\psi_y$ = 62.3 degree from center of LOLA
β_y @ LOLA ~ 4.0 m (~ 40 m with a changed optics)
β_y @ UDUMP ~ 4.5 m





Possibility of New Layout for Diagnostics

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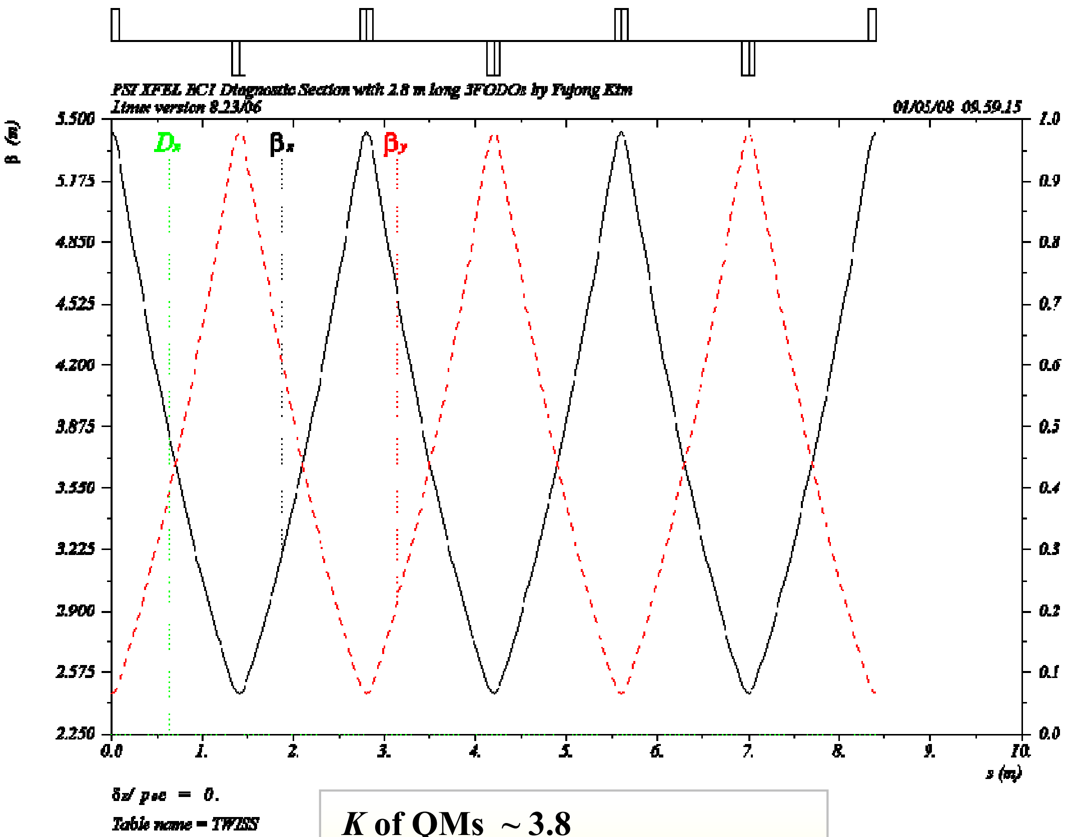
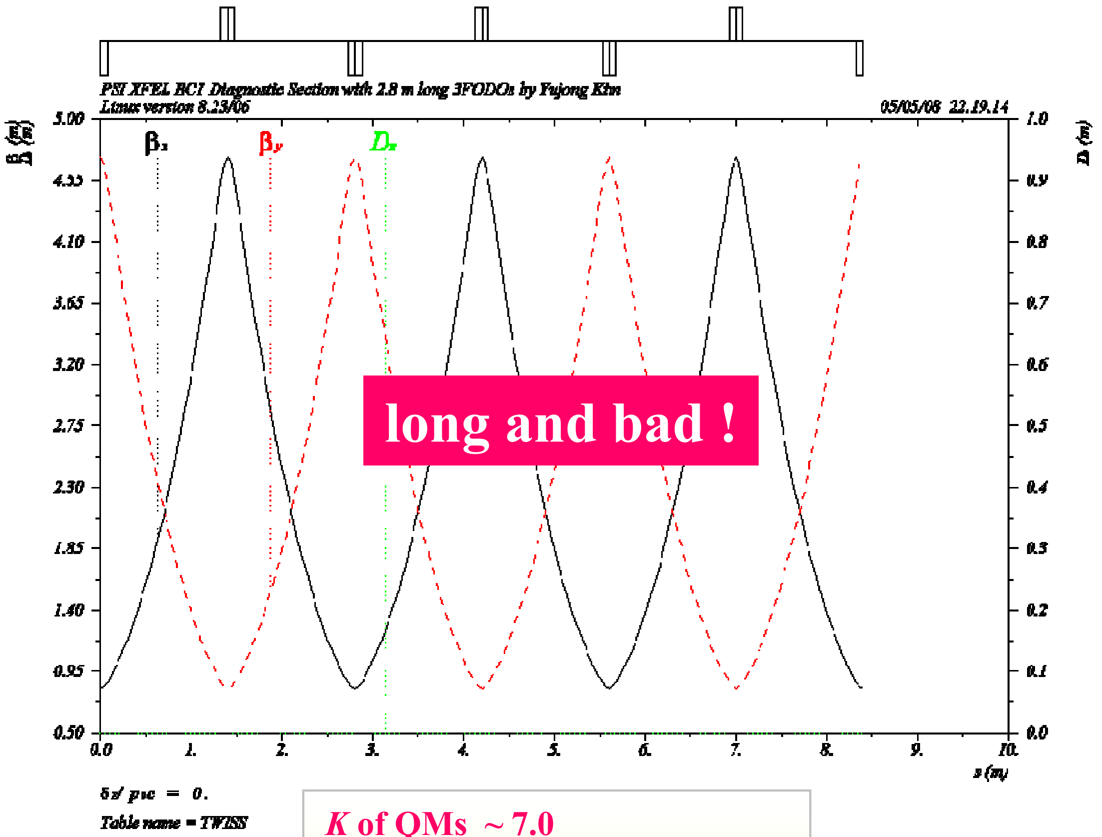
current 2.8 m long FODO



K of QMs ~ 3.8
max beta-function ~ 5.4 m
min beta-function ~ 2.4 m
phase advance per cell = 45 deg
one cell length = 2.8 m
3 cell length = 8.4 m
space between QMs = 1.25 m

current layout + 90 deg phase advance



long and bad !

K of QMs ~ 7.0
max beta-function ~ 4.7 m
min beta-function ~ 0.8 m
phase advance per cell = 90 deg
one cell length = 2.8 m
3 cell length = 8.4 m
space between QMs = 1.25 m

Possibility of New Layout for Diagnostics

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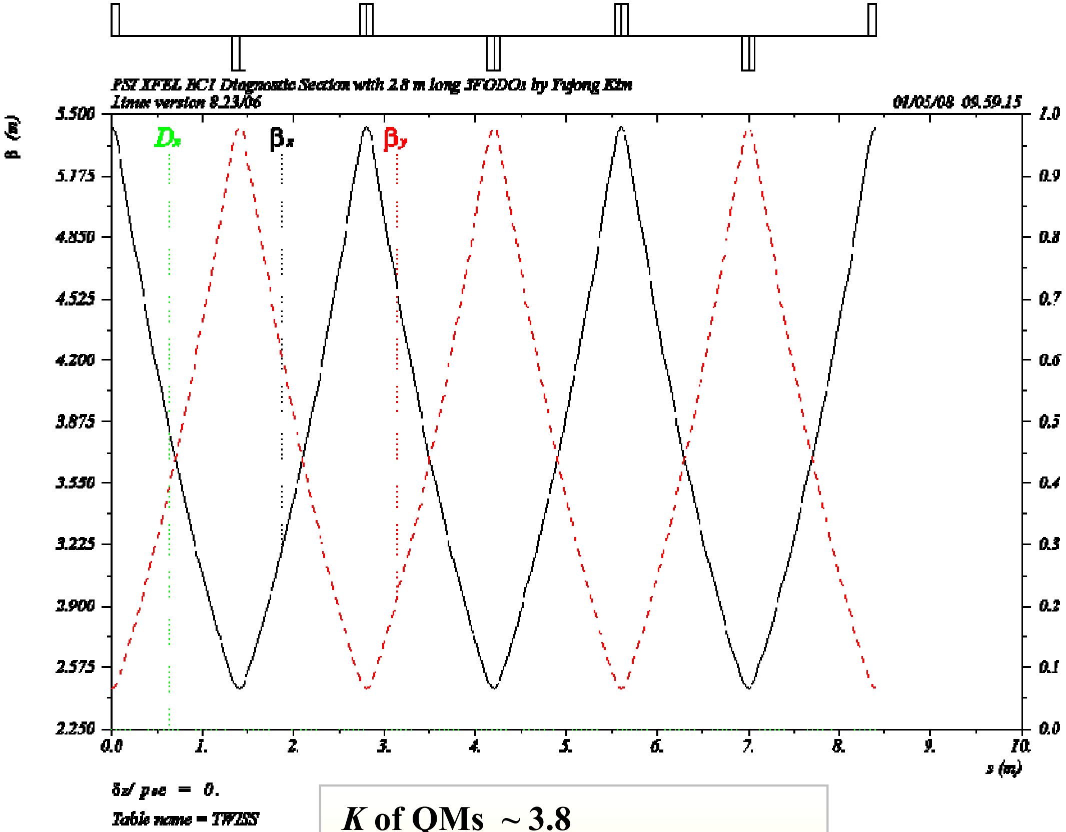
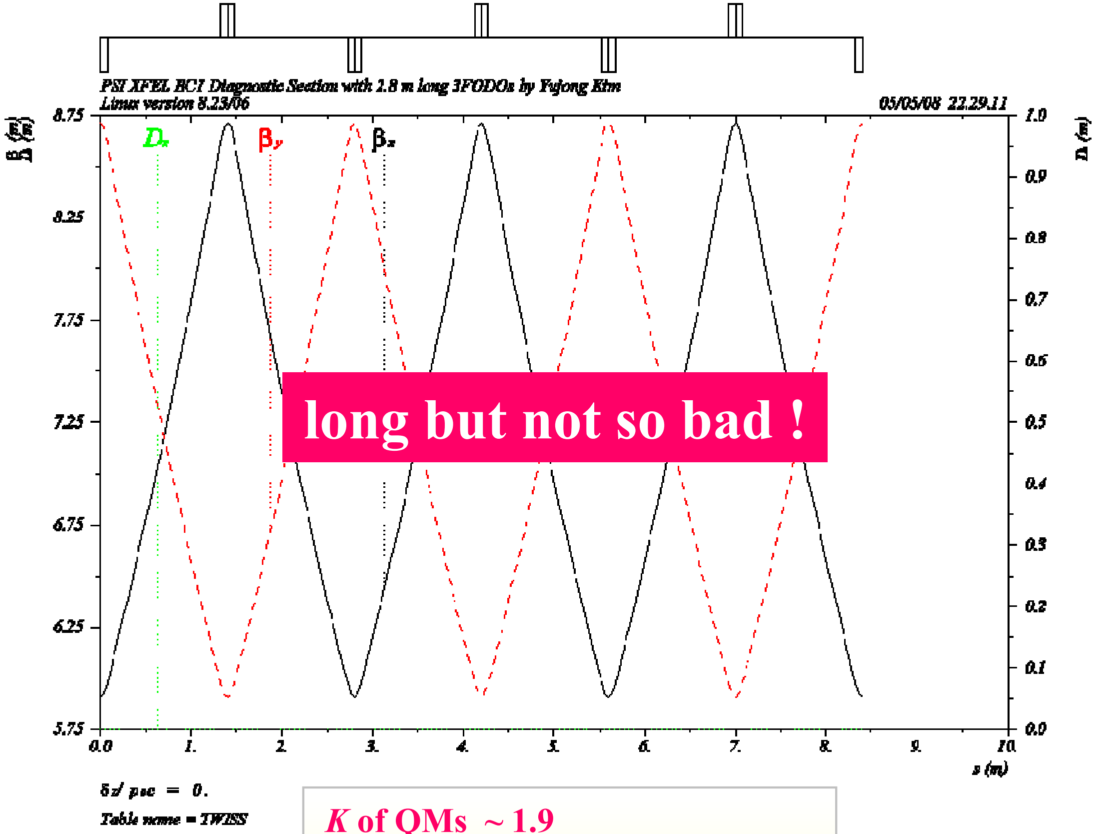
current 2.8 m long FODO



K of QMs ~ 3.8
max beta-function ~ 5.4 m
min beta-function ~ 2.4 m
phase advance per cell = 45 deg
one cell length = 2.8 m
3 cell length = 8.4 m
space between QMs = 1.25 m

current layout + 22.5 deg phase advance



long but not so bad !

K of QMs ~ 1.9
max beta-function ~ 8.7 m
min beta-function ~ 5.9 m
phase advance per cell = 22.5 deg
one cell length = 2.8 m
3 cell length = 8.4 m
space between QMs = 1.25 m

Possibility of New Layout for Diagnostics

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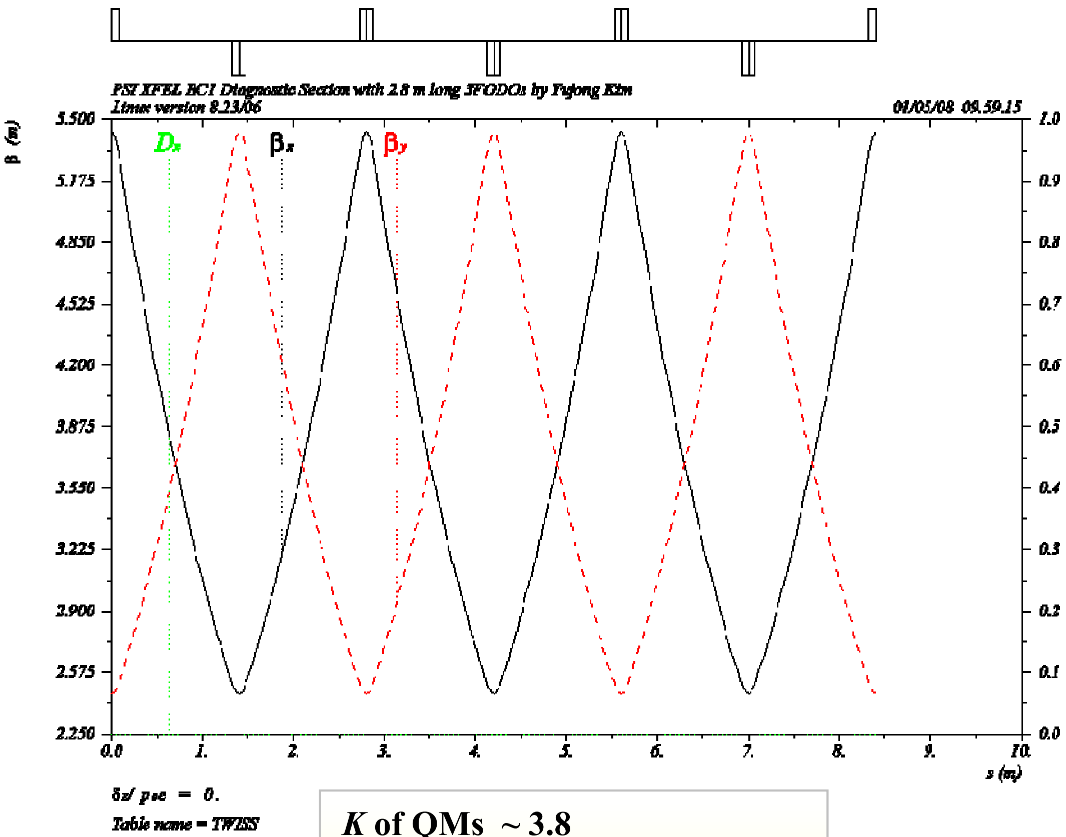
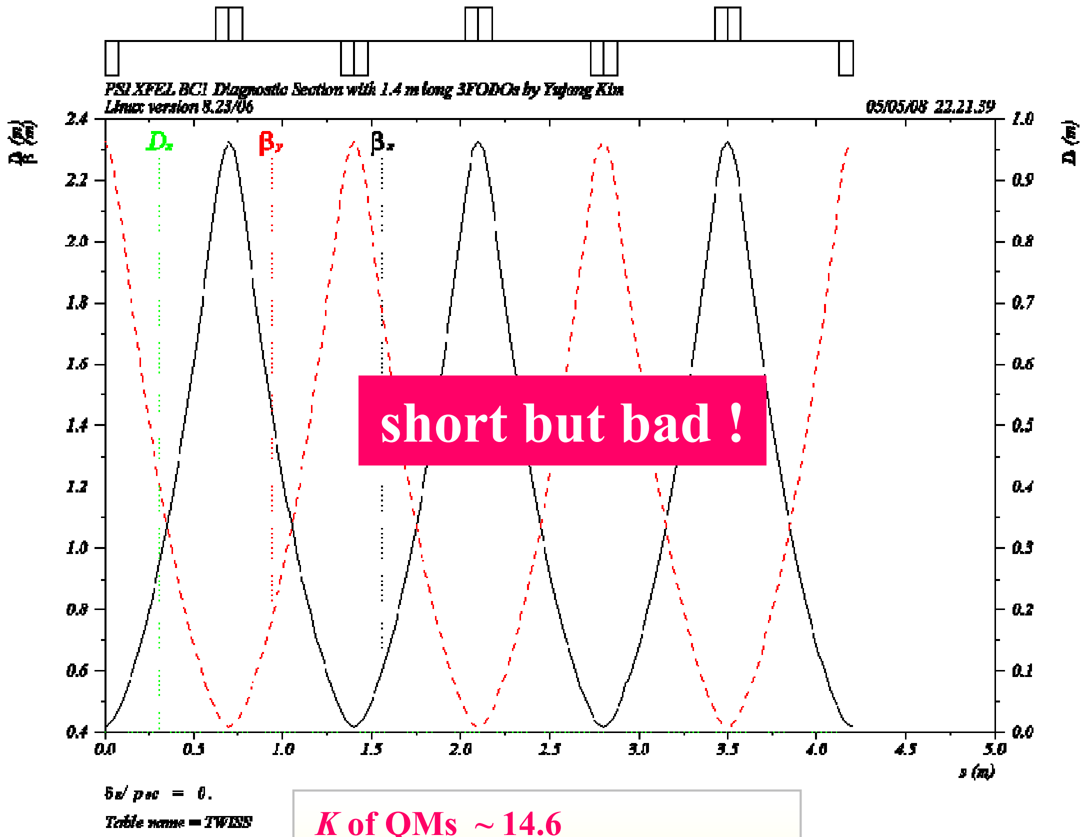
current 2.8 m long FODO



K of QMs ~ 3.8
max beta-function ~ 5.4 m
min beta-function ~ 2.4 m
phase advance per cell = 45 deg
one cell length = 2.8 m
3 cell length = 8.4 m
space between QMs = 1.25 m

1.4 m long FODO + 90 deg phase advance



short but bad !

K of QMs ~ 14.6
max beta-function ~ 2.3 m
min beta-function ~ 0.4 m
phase advance per cell = 90 deg
one cell length = 1.4 m
3 cell length = 4.2 m
space between QMs = 0.55 m

Possibility of New Layout for Diagnostics

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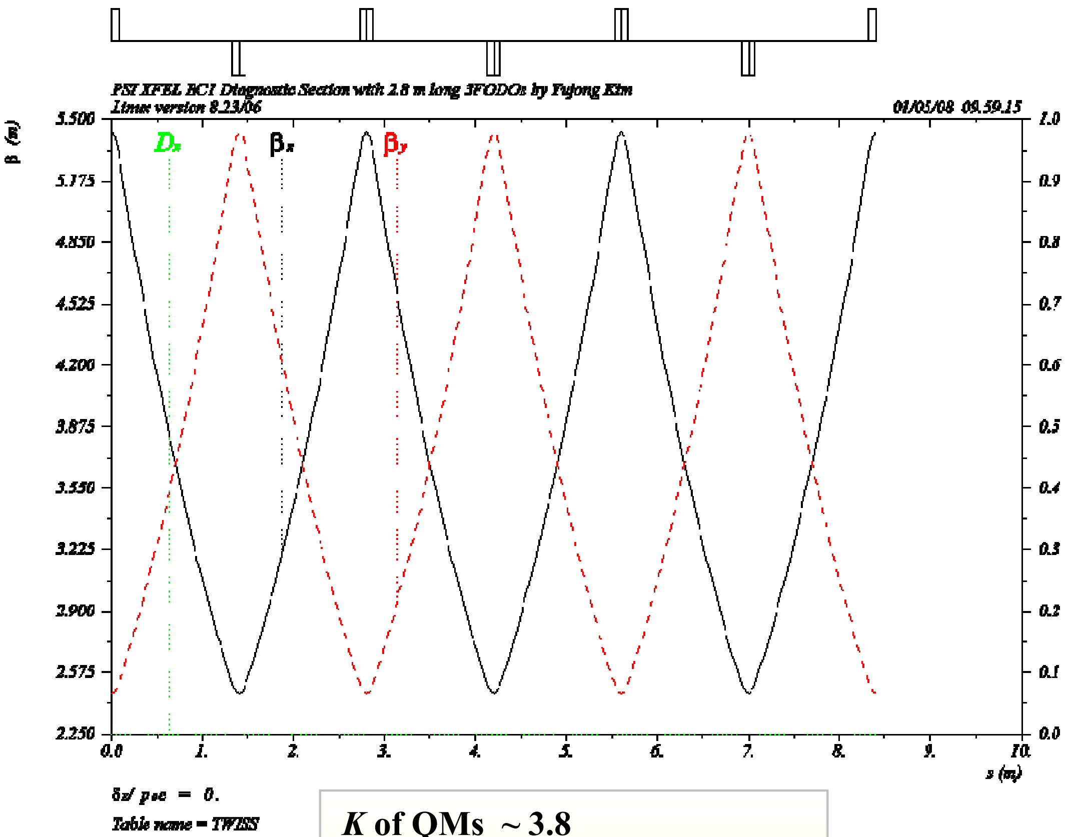
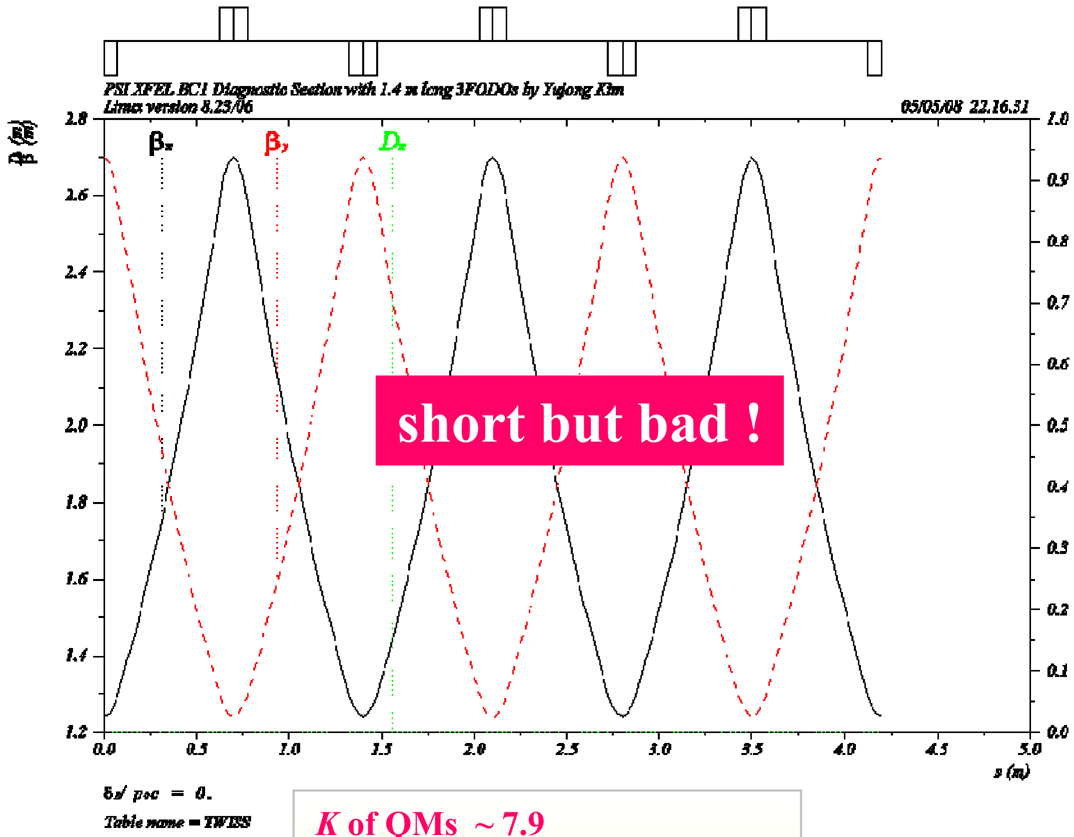
current 2.8 m long FODO



K of QMs ~ 3.8
max beta-function ~ 5.4 m
min beta-function ~ 2.4 m
phase advance per cell = 45 deg
one cell length = 2.8 m
3 cell length = 8.4 m
space between QMs = 1.25 m

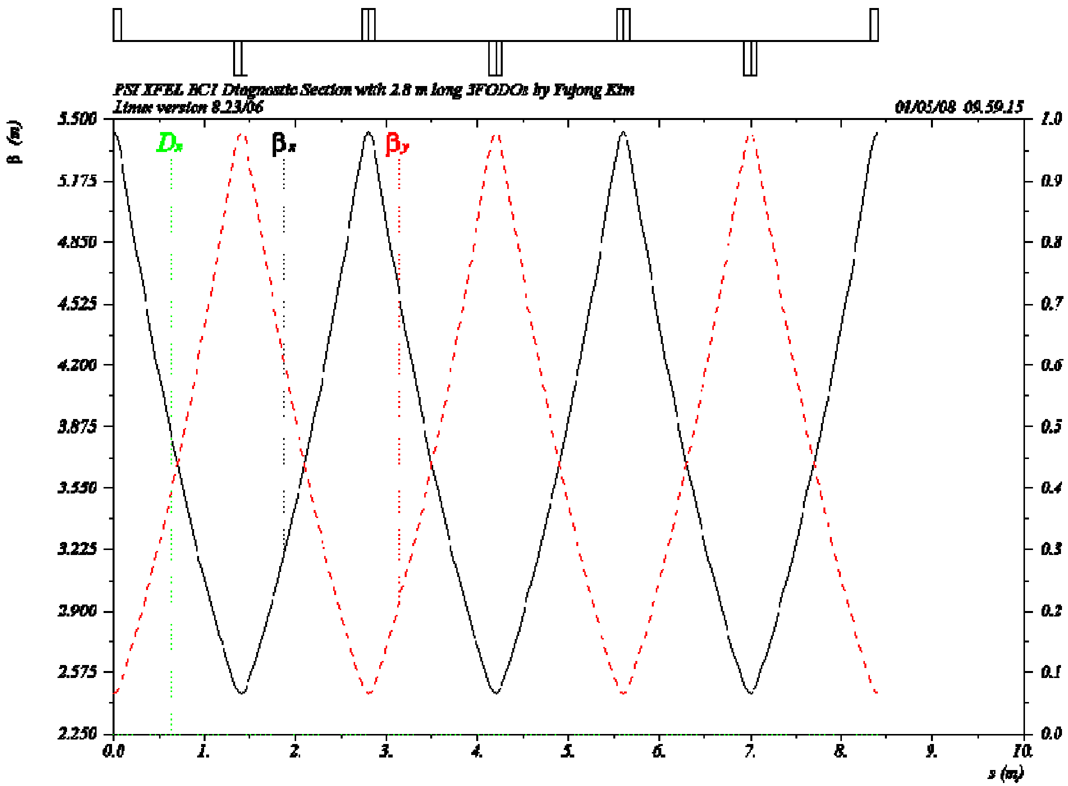
1.4 m long FODO + 45 deg phase advance



K of QMs ~ 7.9
max beta-function ~ 2.7 m
min beta-function ~ 1.2 m
phase advance per cell = 45 deg
one cell length = 1.4 m
3 cell length = 4.2 m
space between QMs = 0.55 m

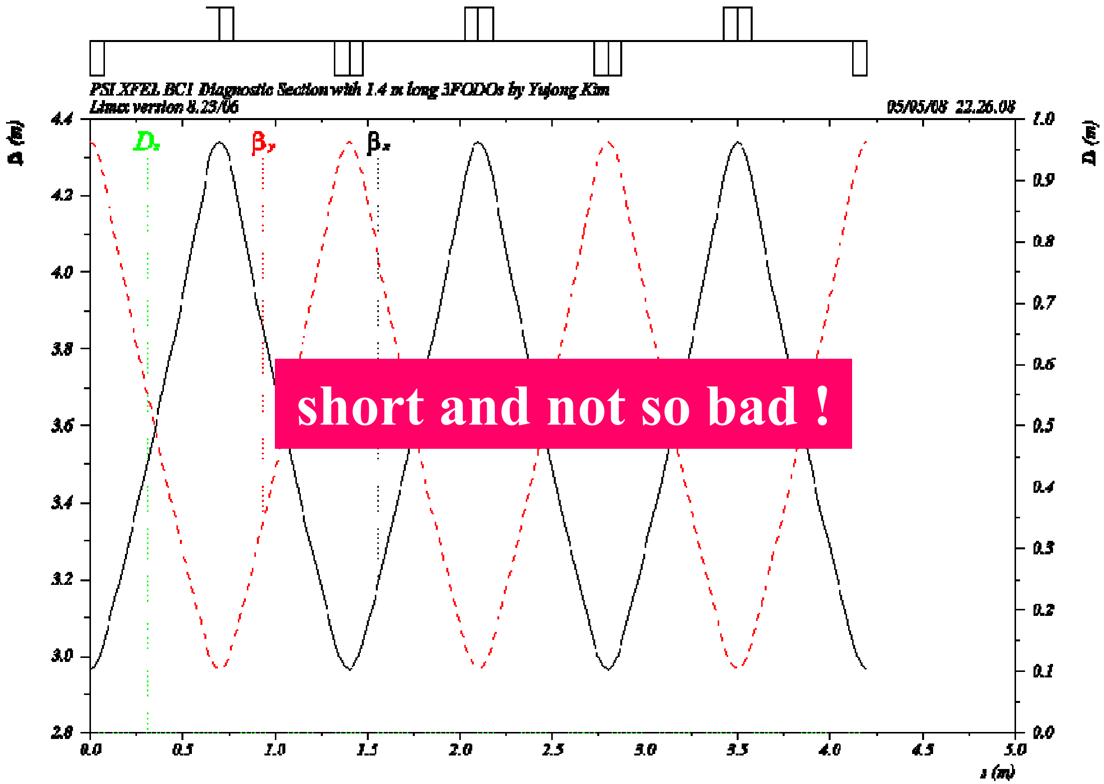
Possibility of New Layout for Diagnostics

current 2.8 m long FODO



K of QMs ~ 3.8
max beta-function ~ 5.4 m
min beta-function ~ 2.4 m
phase advance per cell = 45 deg
one cell length = 2.8 m
3 cell length = 8.4 m
space between QMs = 1.25 m

1.4 m long FODO + 22.5 deg phase advance



K of QMs ~ 4.0
max beta-function ~ 4.3 m
min beta-function ~ 3.0 m
phase advance per cell = 22.5 deg
one cell length = 1.4 m
3 cell length = 4.2 m
space between QMs = 0.55 m

Possibility of New Layout for Diagnostics

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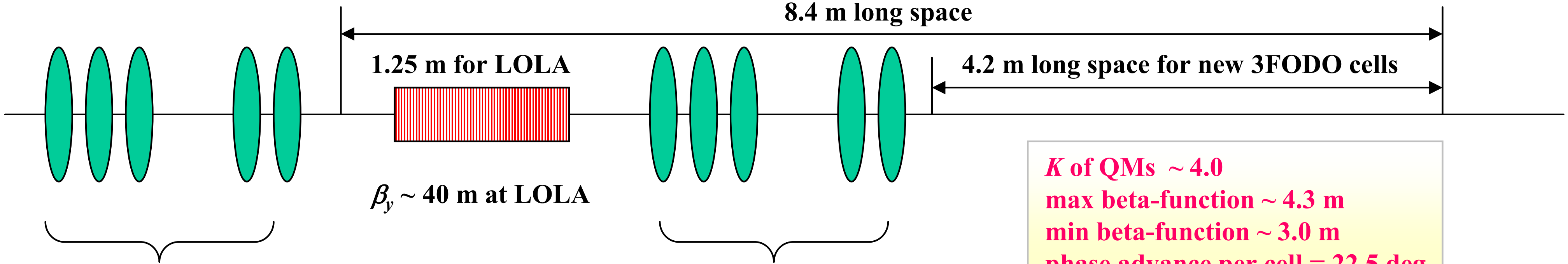
1.4 m long FODO + 22.5 deg phase advance



4.75 m long space
5 QMs for Matching
from BC to LOLA

2.95 m long space
Can we host
5 QMs for Matching
from LOLA to FODO ?

***K* of QMs ~ 4.0**
max beta-function ~ 4.3 m
min beta-function ~ 3.0 m
phase advance per cell = 22.5 deg
one cell length = 1.4 m
3 cell length = 4.2 m
space between QMs = 0.55 m

We have to check with simulations.
But at the moment, it seems that we need a longer space to choose this layout.

Summary & Acknowledgement

We checked performance of CTF3 gun type V with a gradient of 120 MV/m. It seems that it can supply a good projected (slice) emittance of around 0.4 μm (0.33 μm), which is sufficient for our soft X-ray FEL beamline (FEL3). But we may need a much better injector for the hard X-ray FEL beamlines (FEL1 & FEL2).

In case of LCLS type backup injector, we can get more flat slice parameters. But in case of CTF3 gun type V, there is some weak nonlinearity along bunch.

As the first time, we have performed a full start-to-end simulation from the cathode to dump for 250 MeV injector with CTF3 GUN type V. Here, we consider space charge effects from cathode to 150 MeV, and wakefields for whole machine, and CSR and ISR in BC and DUMP. Now a layout of full diagnostic section is ready.

Due to CSR and ISR at BC dipoles, the horizontal projected emittance was increased by about 6%. But in case of slice emittance, it is almost unchanged.

Slice energy spread after BC1 is about 100 keV, and peak current is about 350 A.

For pulser system, the total machine length will be about 60 m from the cathode to dump. For CTF3 gun type injector, the total machine length will be about 55 m.

Summary & Acknowledgement

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Current optics is adaptable even incoming Twiss parameters are somewhat different from design ones.

Optics of pulser based Injector has a positive alpha-function along linac, which induces a stronger CSR and a large emittance growth in BC. This poor optics in pulser based injector should be improved in the near future.

If there is a longer available space, we can move out LOLA from 3FODO cells.

Resolution of LOLA is about 9 fs/pixel (4.6 fs/pixel) for 5 cell (9 cell) LOLA cavity.

Y. Kim sincerely thank to Dr. R. Ganter, Dr. M. Dehler, Dr. A. Adelmann, Dr. A. Streun, Dr. T. Garvey, Dr. V. Schlott, Prof. L. Rivkin, Dr. R. Bakker, Dr. M. Pedrozzi, and Prof. A. Wrulich for their interests and encouragements for this work.