Status of the SPARC Working Point

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On behalf of the SPARC Beam Dynamics Group
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SPARC Review Committee

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Outline

* Previous Working point
* Strategy for the parameters optimization studies
* Optimized working point
* Implications of this variation
* High bunch current with velocity bunching
* Conclusions

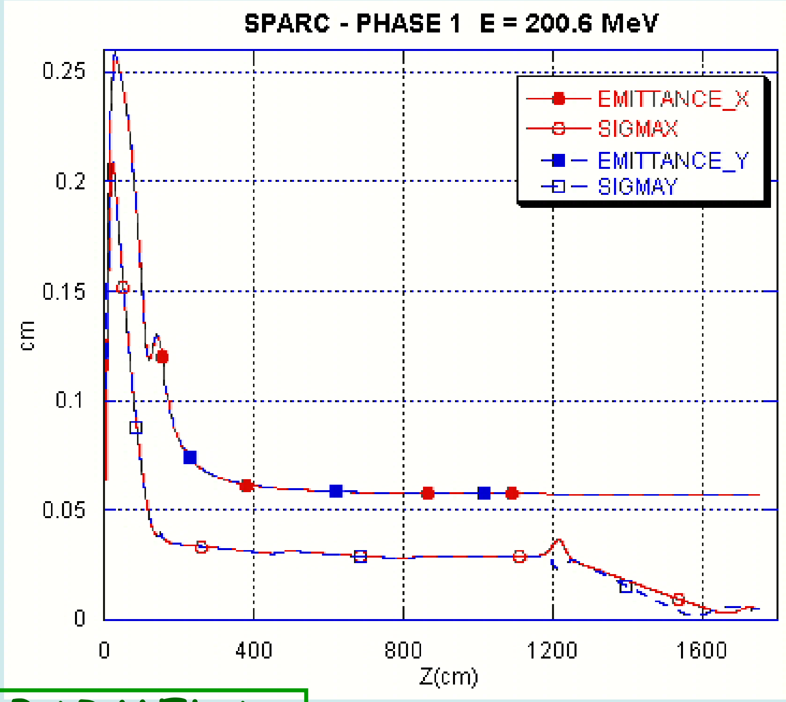
PARMELA Start-to-End Simulation

(Previous working point: Q=1nC; L=11.7ps; R=1mm)

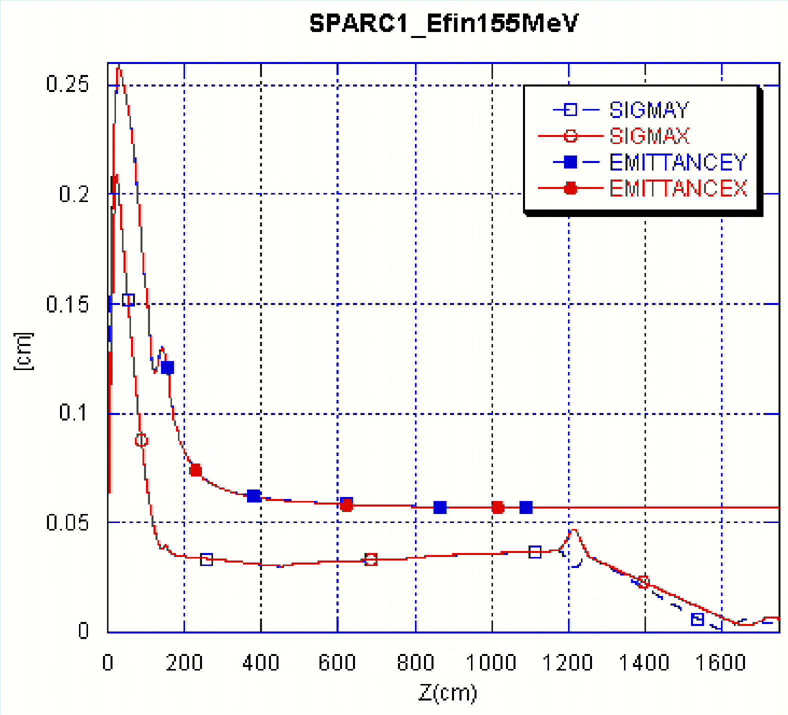
3 RF str.: 25+12.5+12.5 MV/m

B(solenoid) = 750G

E = 200 MeV



E = 155 MeV



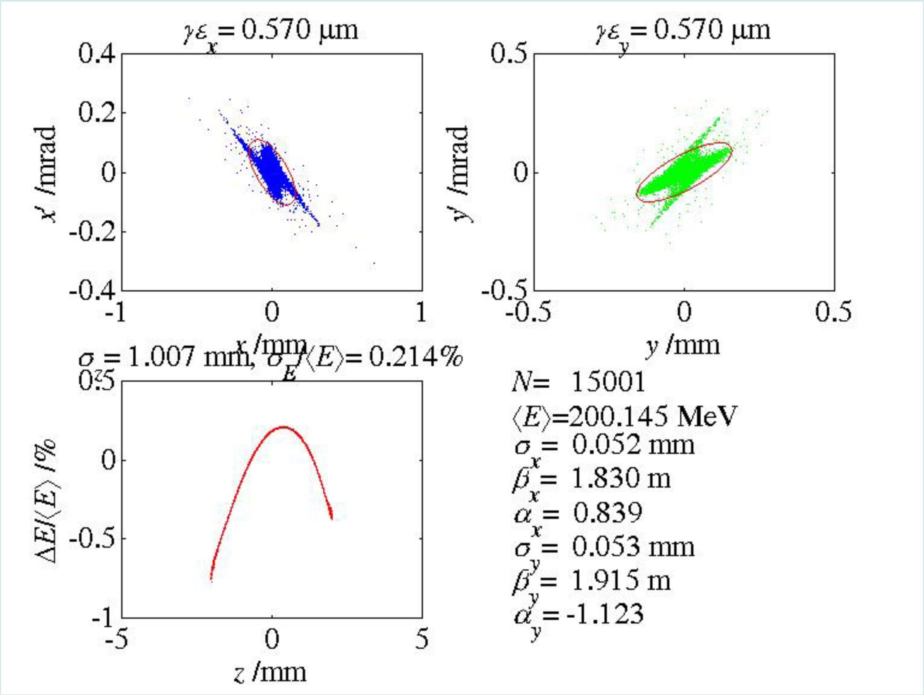
PARMELA simulations **rms values**: @undulator entrance :

$\langle \varepsilon_x \rangle$ = **0.57 mm mrad**

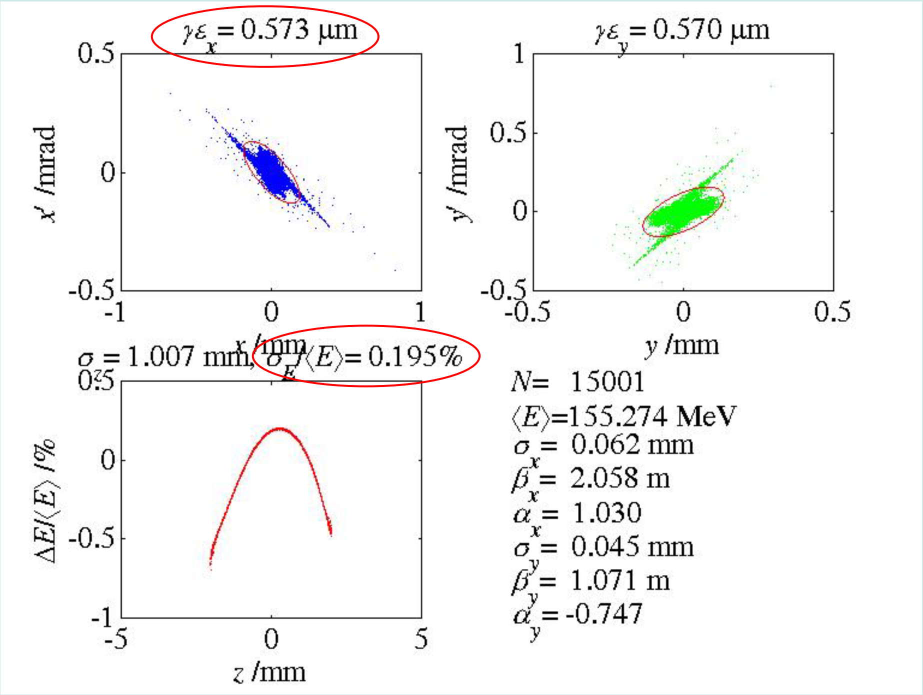
$\langle \sigma_E/E \rangle = 2 \cdot 10^{-3}$

Beam characterization @undulator entrance:

E = 200 MeV



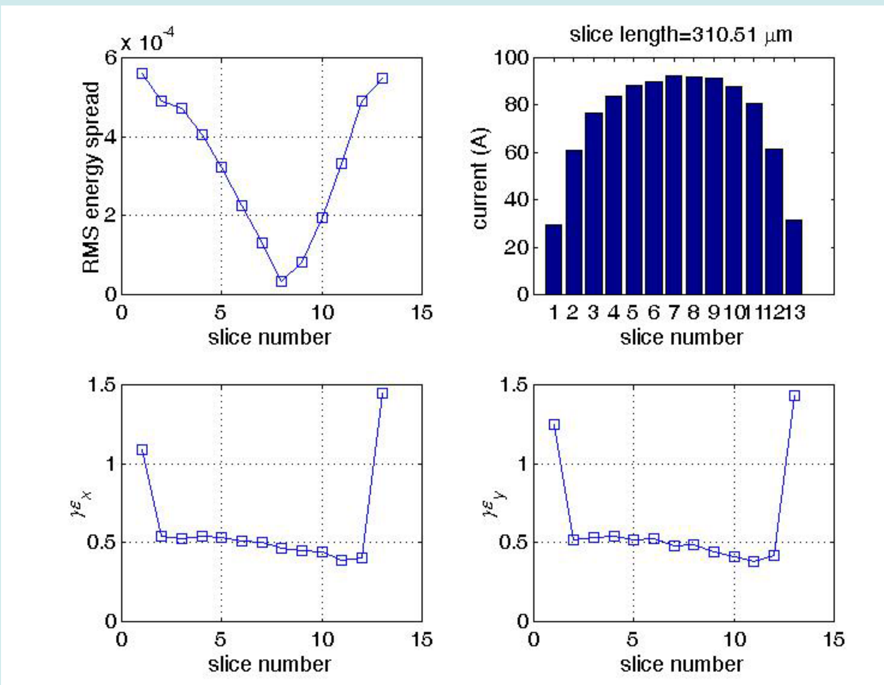
E = 155 MeV



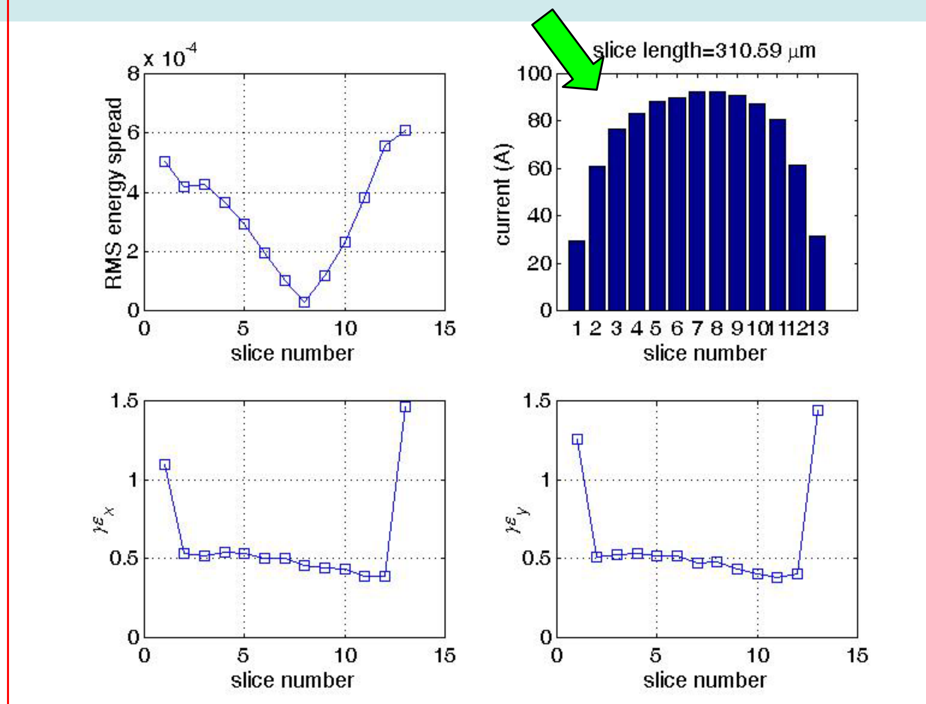
Slice analysis @undulator entrance (PARMELA output)

previous working point:
Q=1nC;L=11.7ps; R=1mm

E = 200 MeV



E = 155 MeV



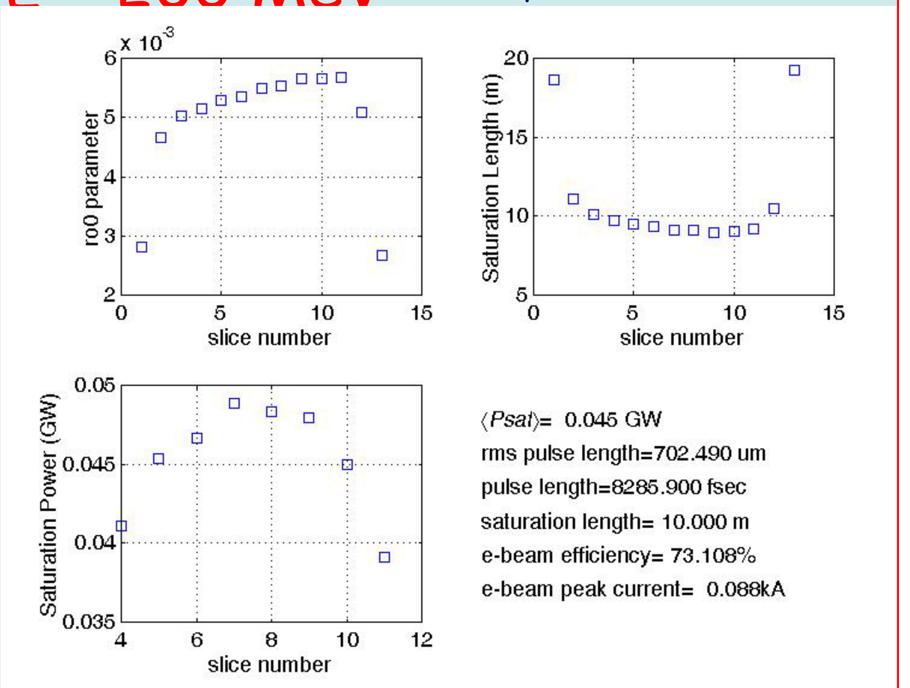
Slice analysis @undulator entrance (PARMELA output)

13 slices

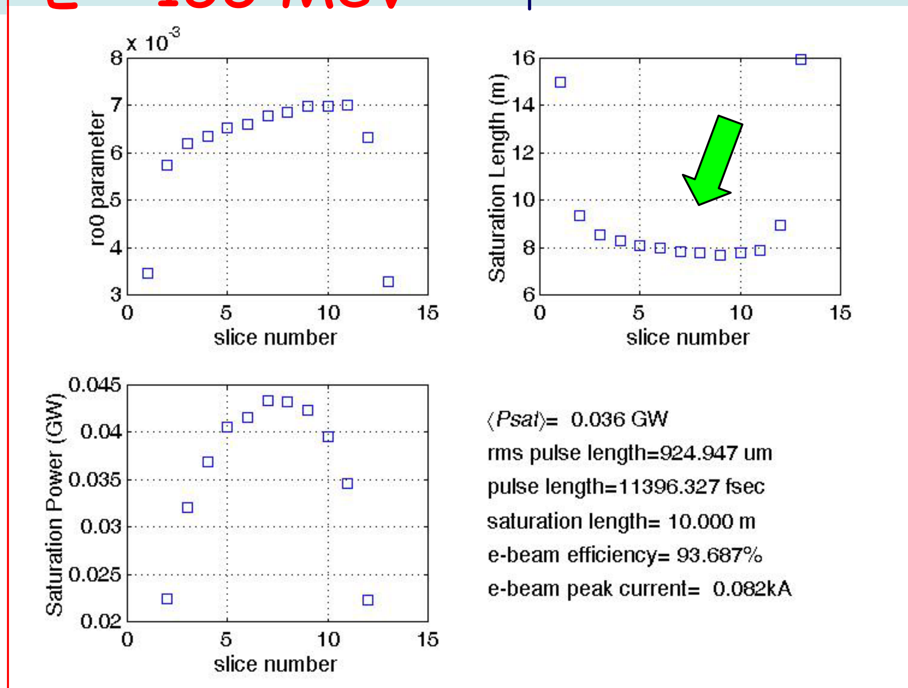
λ_u=3 cm

$\langle\beta\rangle_{und}$=1.6m

E = 200 MeV λ_r=290 nm



E = 155 MeV λ_r=530 nm



We slightly moved some parameters to further optimize this WP

Saturation in the last undulator section

Result obtained using both
Ginger and ***Genesis***

λ_u=3cm

K=2

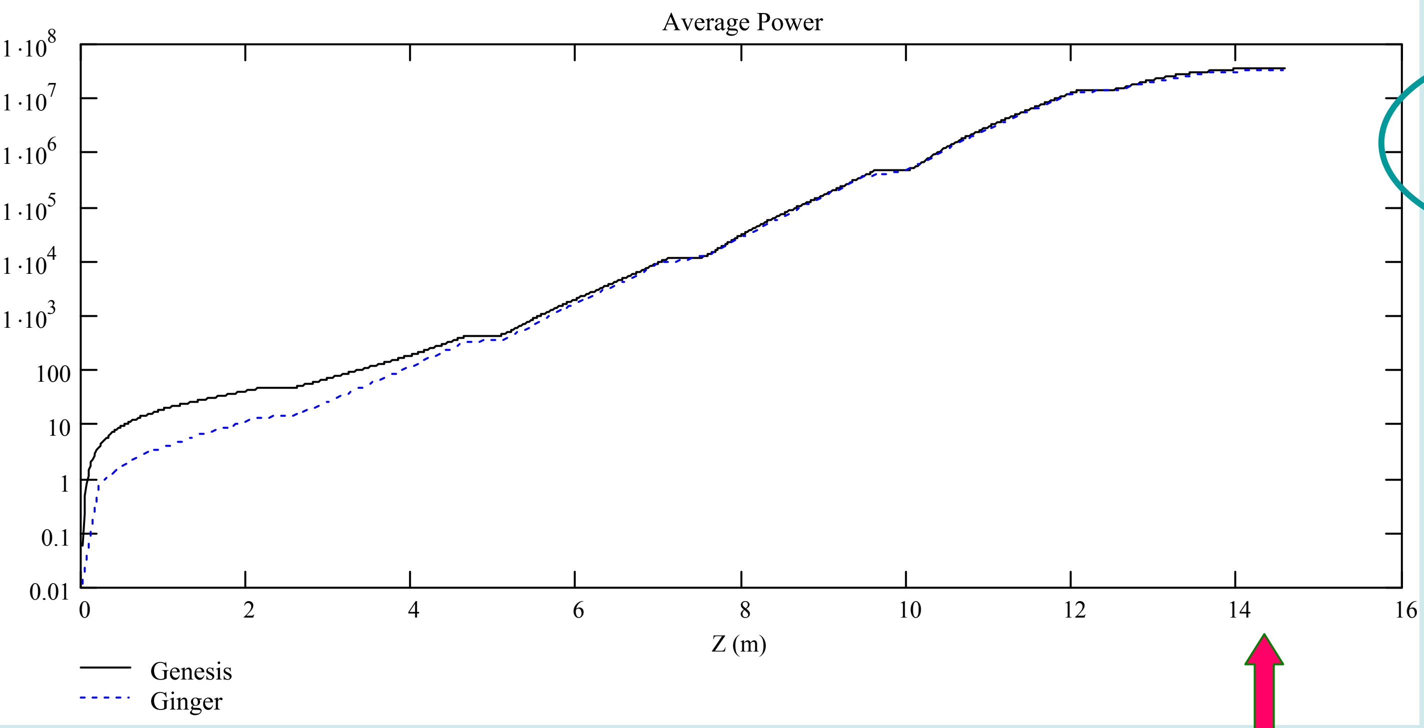
L_u=14.5 m

I=85A

ε_{slice}=1 mm-mrad

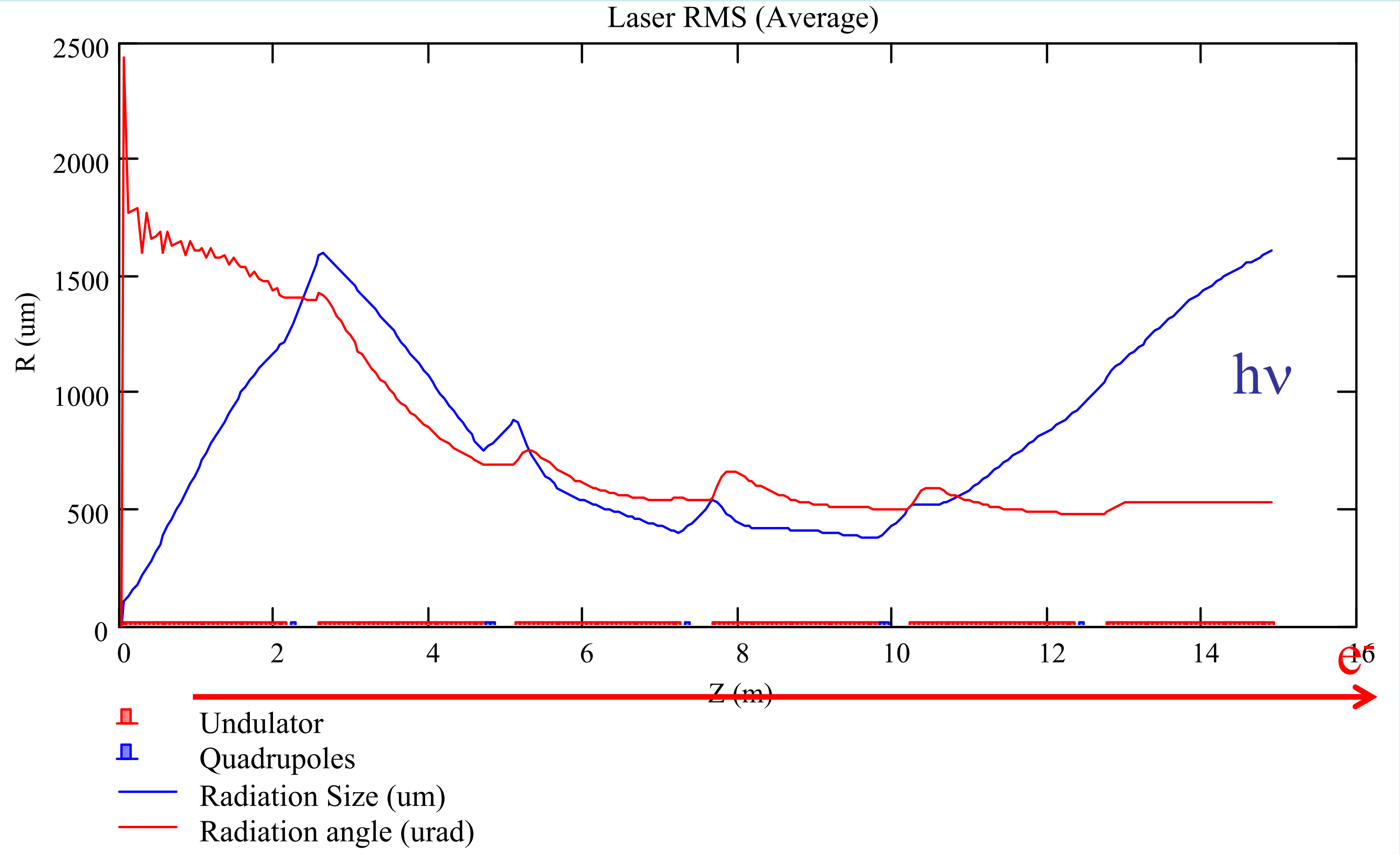
$(\sigma_E/E)_{slice}=6\cdot10^{-4}$

Taking into account tolerances, misalignments, errors,...



L_{sat} ~ 14.2 m

SPARC-FEL is dominated by Diffraction



the photon beam is not overlapped to the electron beam

through all the undulator

the photon beam is not focussed as the electron beam

Motivations and Strategies

(JBR et al. SPARC-BD-03-004)

$$L_g \cong L_{1D}\left(1+0.45\left(\frac{L_{1D}}{Z_R}\right)^{0.57}+\ldots\right)$$

Xie scaling accounts for diffraction effects

+ ......

$$L_{1D} \propto \frac{\lambda_u}{\rho} \propto \left(\frac{\lambda_u \varepsilon_n}{I}\right)^{1/3}$$

$$Z_R \propto \frac{\varepsilon_n}{\lambda_u}$$

$$\frac{L_{1D}}{Z_R} \propto \frac{\lambda_u^{4/3}}{I^{1/3}\varepsilon_n^{2/3}}$$

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

What about the undulator gap?

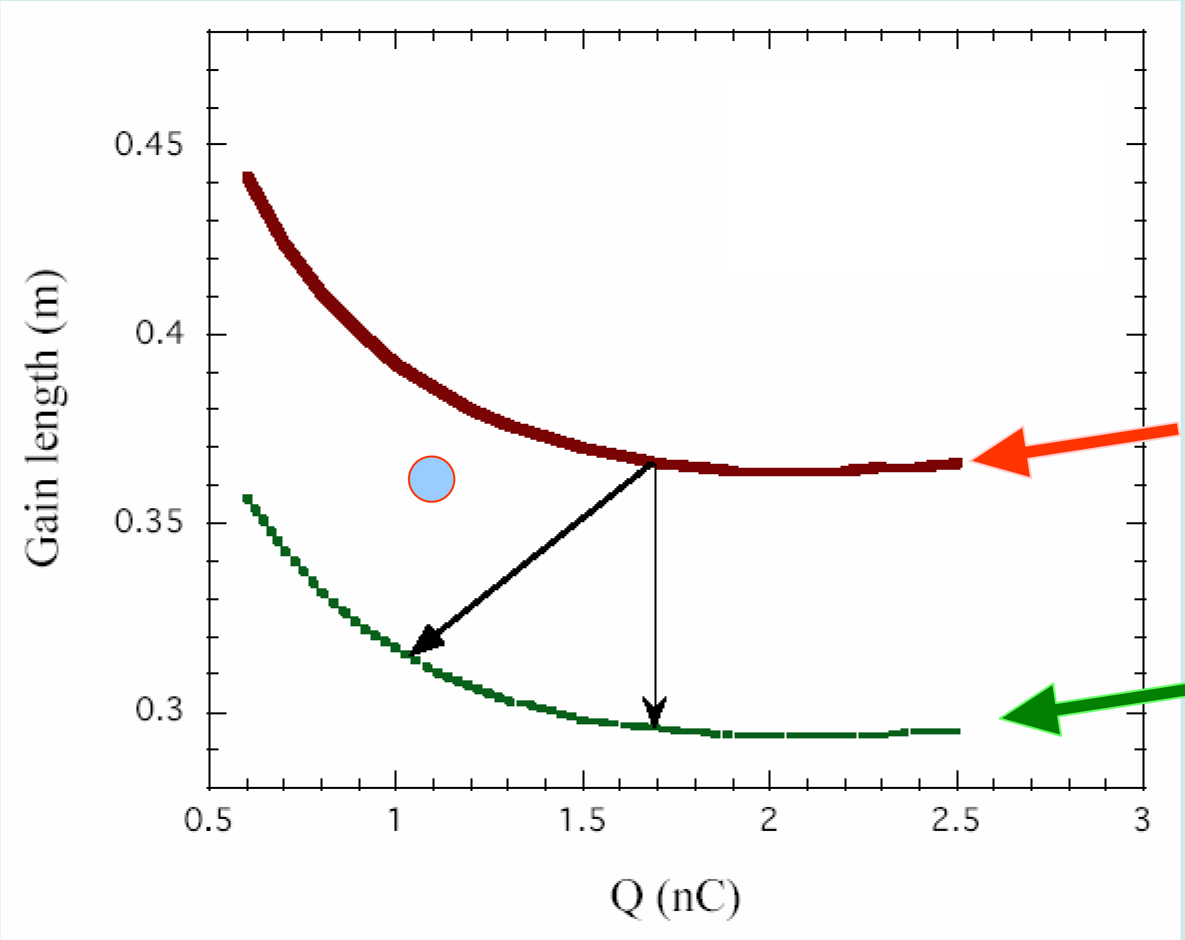
$$K \approx \lambda_u \exp\left[-5.08\, g/\lambda_u - 1.54\left(g/\lambda_u\right)^2\right]$$

$\downarrow \lambda_u \Rightarrow g \downarrow$

Gain length vs bunch charge for the SPARC FEL

previous WP:
gap=9mm
λ_u=3cm

NEW WP:
gap=9mm
λ_u=2.8cm



gap=10mm
λ_u=3cm

gap=6.6mm
λ_u=2.5cm

Adopted strategy
to decrease the saturation length:

↓

* Increase the slice current up to 100A

  for at least 50% of the bunch

* Reduce the undulator period λ_u

There are different possibilities to increase the bunch current while keeping the bunch density constant

1. Keep constant the longitudinal length ⇨ Increase transverse area

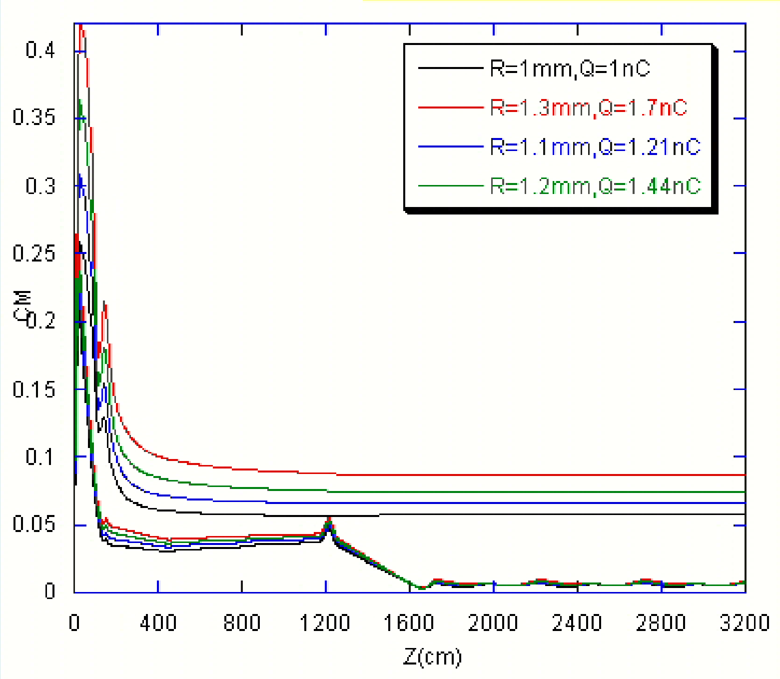
$$\sigma_z = \text{const.} \Rightarrow \sigma_x \propto \sqrt{Q} \Rightarrow I \propto Q$$

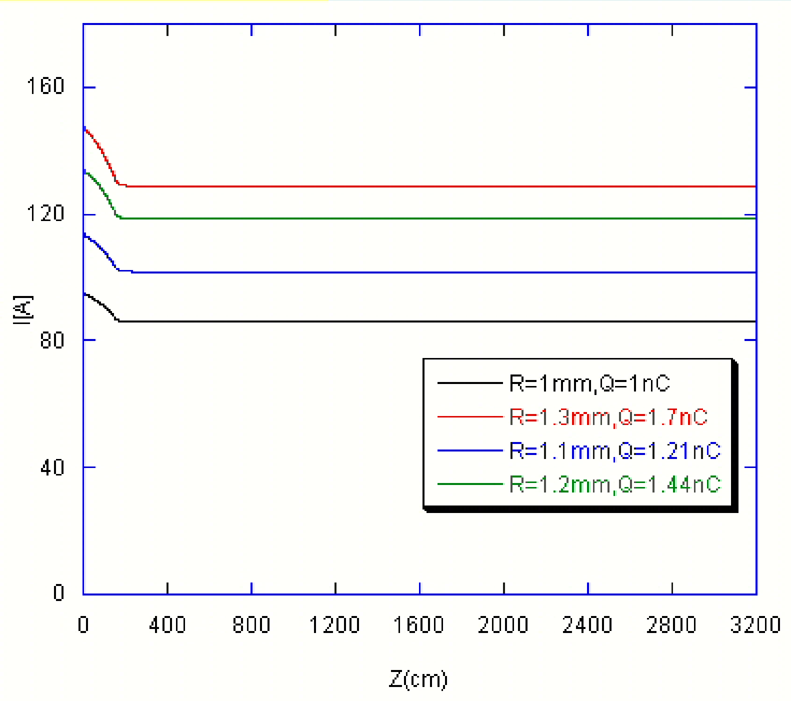
2. Keep constant the linear charge density ⇨ Bunch length is shortened (and tranverse size slightly increased)

$$\frac{Q}{\sigma_z} = \text{const.} \Rightarrow \sigma_x \propto \sqrt{\frac{Q}{\sigma_z}}$$

PARMELA Start-to-End Simulation

$\sigma_z = \text{const.} \Rightarrow \sigma_x \propto \sqrt{Q} \Rightarrow I \propto Q$





@ undulator entrance: (z=18m)

Q=1nC; R=1mm	εx=0.570μm	<I>= 82A
Q=1.21nC; R=1.1mm	εx=0.665μm	<I>~ 102A
Q=1.44nC; R=1.2mm	εx=0.746μm	<I>~ 118.5A
Q=1.7 nC; R=1.3mm	εx=0.869μm	<I>~ 128A

Slice Analysis at the undulator entrance

13 slices

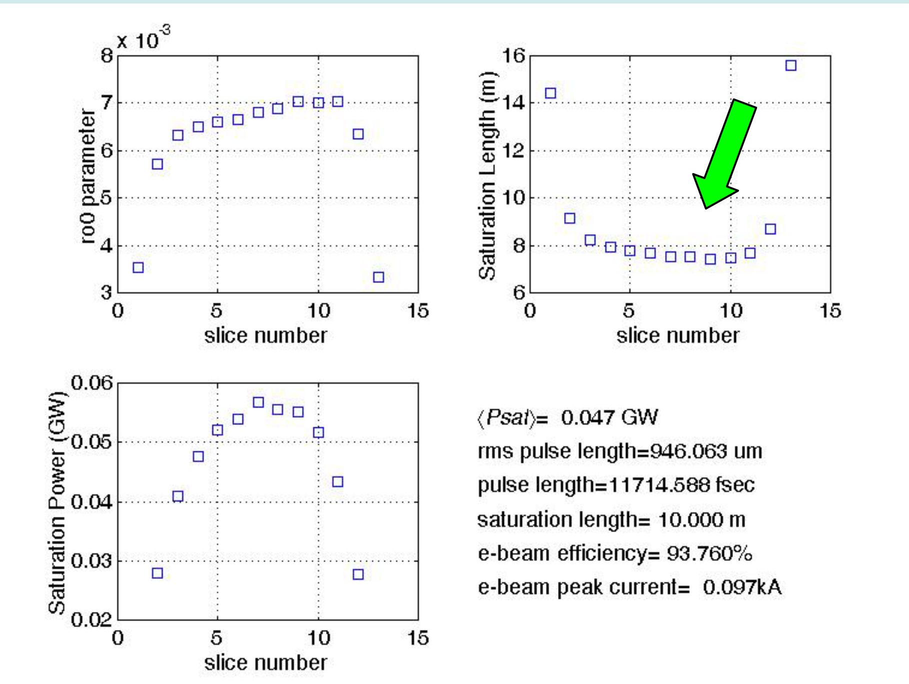
λ=0.03 cm

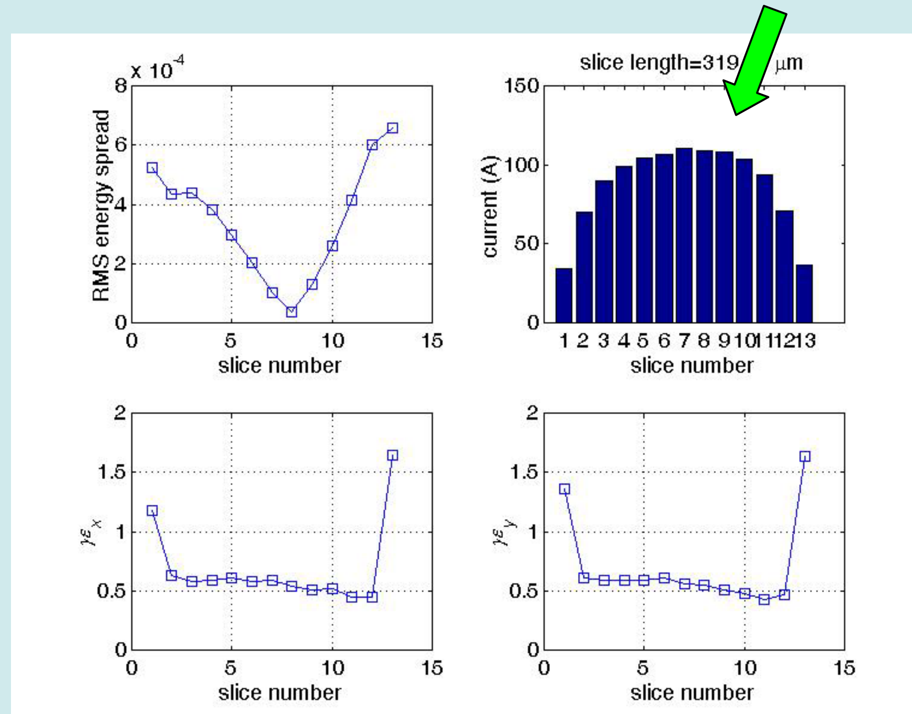
$\langle\beta\rangle_{und}$=1.6m

λ_{rad}=530 nm

Q=1.2nC; R=1.1mm;

pulse length=11.7ps



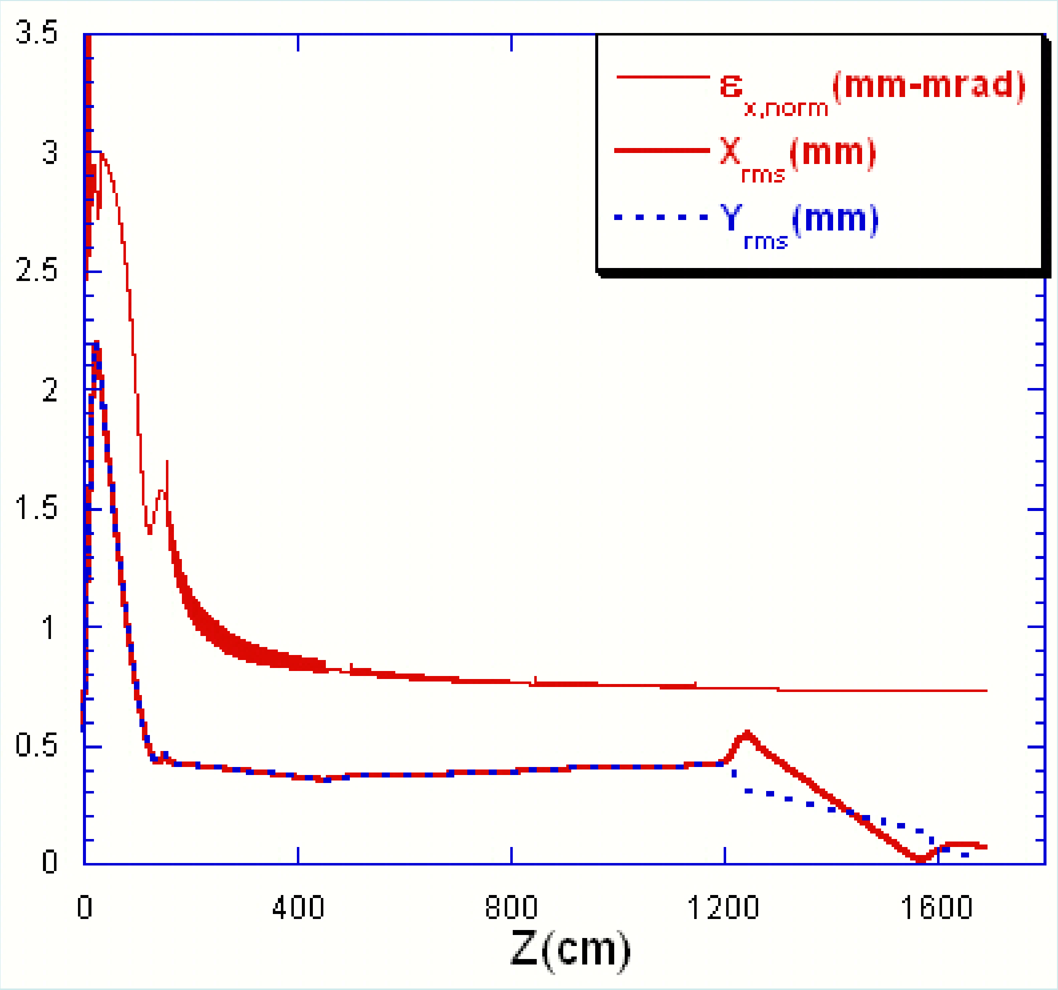


I_{slice}>110A in >60% beam

L_{SAT}~7m

$$\frac{Q}{\sigma_z} = \text{const.} \Rightarrow \sigma_x \propto \sqrt{\frac{Q}{\sigma_z}}$$

PARMELA simulation up to the entrance of the undulator



ε_{th} = 0.34 mm mrad

Q = 1.1nC ; R=1.13mm

Pulse length(FWHM) = 10ps

Rise time = 1ps

Gun peak field = 120MV/m

Injection phase = 33°

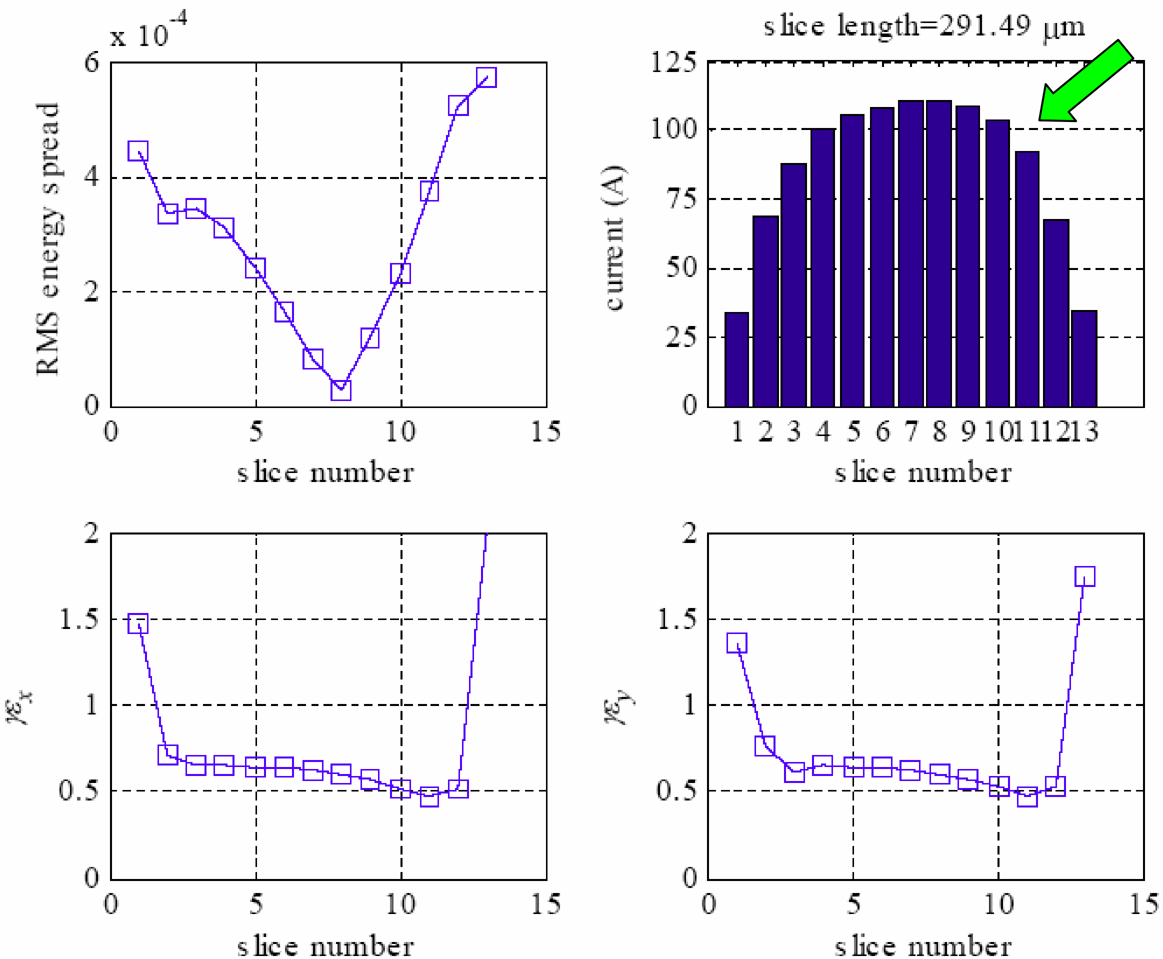
Bsol(gun) = 2.73KGauss

Bsol(1TW) = 750 Gauss

$\varepsilon_{x,rms}$=0.74 mm mrad

$$\frac{Q}{\sigma_z} = \text{const.} \Rightarrow \sigma_x \propto \sqrt{\frac{Q}{\sigma_z}}$$

Q=1.1 nC, pulse length (FWHM) = 10 psec, rise time=1 psec

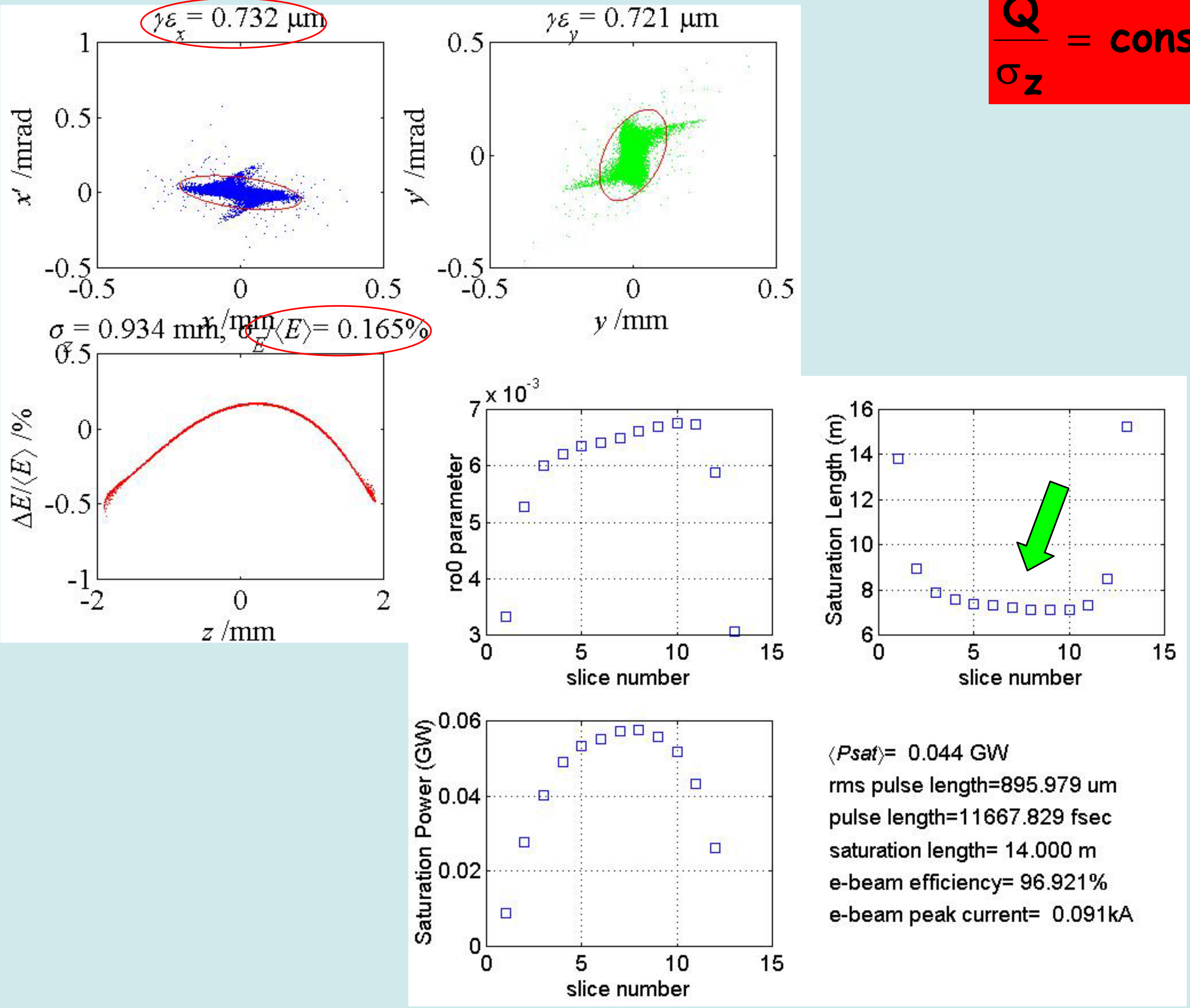


Max. slice current=110 A

Current ≥ 100 A in 54% beam

Projected emittance= 0.75 mm mrad

$$\frac{Q}{\sigma_z} = \text{const.} \Rightarrow \sigma_x \propto \sqrt{\frac{Q}{\sigma_z}}$$



L_{SAT}<8m

in >60% beam

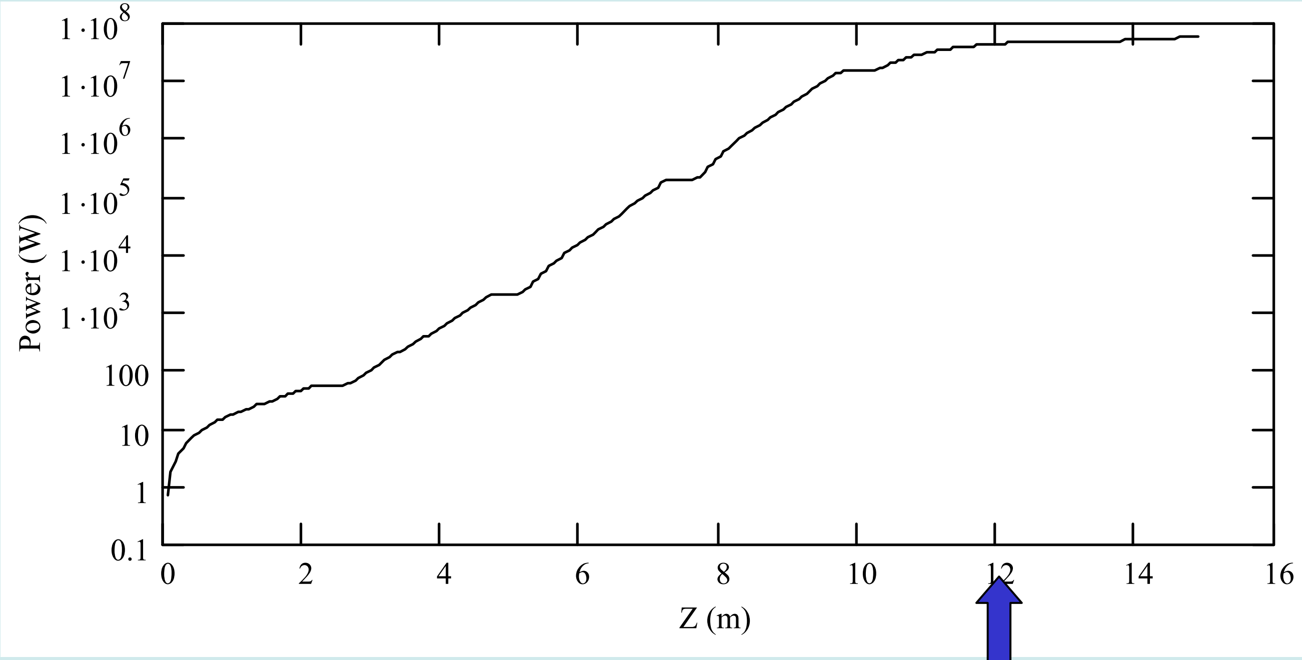
We gained ~15% in the saturation length

λ_u=2.8cm; gap=9mm

I_{peak}=110A/ 100A (50% bunch)

ε_{slice}=1 mm-mrad

$(\sigma_E/E)_{slice}=6\cdot10^{-4}$



L_{sat} ~ 12 m

(it was 14.2m)

to summarize: last Parameter List

Red: modified parameters
Blue: confirmed old relevant parameters
Black: no change

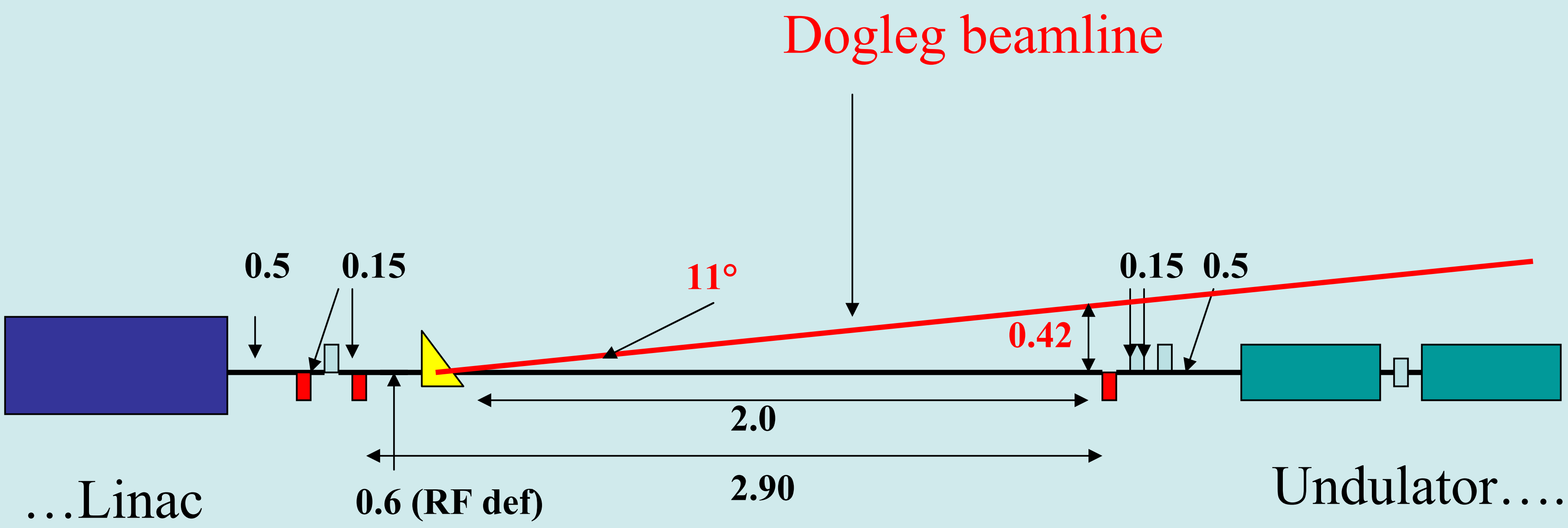
Electron Beam Energy (MeV)	155	
Bunch charge (nC)	**1.1**	(1)
Repetition rate (Hz)	1-10	
Cathode peak field (MV/m)	120	
Peak solenoid field @ 0.19 m (T)	0.273	
Photocathode spot size (mm, hard edge radius)	**1.13**	(1)
Central RF launch phase (RF deg)	**33**	
Laser pulse duration, flat top (ps)	**10**	(12)
Laser pulse rise time (ps) 10%→90%	1	
Bunch energy @ gun exit (MeV)	5.6	
Bunch peak current @ linac exit (A)	**100**	(85)
Rms normalized transverse emittance @ lin ac exit (mm-mrad); includes thermal comp. (0.3)	**< 2**	
Rms slice norm. emittance (300 μm slice)	**< 1**	
Rms longitudinal emittance (deg.keV)	1000	
Rms total correlated energy spread (%)	**0.2**	
Rms incorrelated energy spread (%)	**0.06**	(0.05)
Rms beam spot size @ linac exit (mm)	0.4	
Rms bunch length @ linac exit (mm)	1	

last FEL Parameter List

Undulator period [cm]	2.8
Undulator parameter K	2.143
Undulator gap [mm]	9.25
# Undulator sections	6
# Undulator periods per section	78
Drift length between undulator sections [cm]	36.5
Additional quadrupole gradient [T/m]	5.438
Additional quadrupole length [cm]	8.4
FEL radiation wavelength (fundamental) [nm]	499.6
Average beta function [m]	1.516
Expected saturation length [m]	< 12

Transfer Line sketch

- Total TL length = 5.4 m **(it was 6 m)** ➡ Some space is gained
- RF deflector included



Transfer Line for SPARC @150 MeV with 3 SLAC sections

- Total TL length = 5.4 m, 6 quadrupoles (2 triplets)
- Beam characteristics at end of Linac (HOMDYN):
  - $z = 11.58$ m
  - $\beta_x = 68.761$ m, $\beta_y = 69.799$ m
  - $\alpha_x = -3.547$, $\alpha_y = -3.602$
  - $E = 155.32$ MeV
  - $\varepsilon_x = \varepsilon_y = 0.7\ \mu m$ (normalized, slice)
- Opt. Functions at the undulator entrance:
  - $\beta_x = 1.999$ m, $\beta_y = 0.677$ m, $\alpha_x = 0.878$, $\alpha_y = -0.787$

SPARC RF compressor studies:

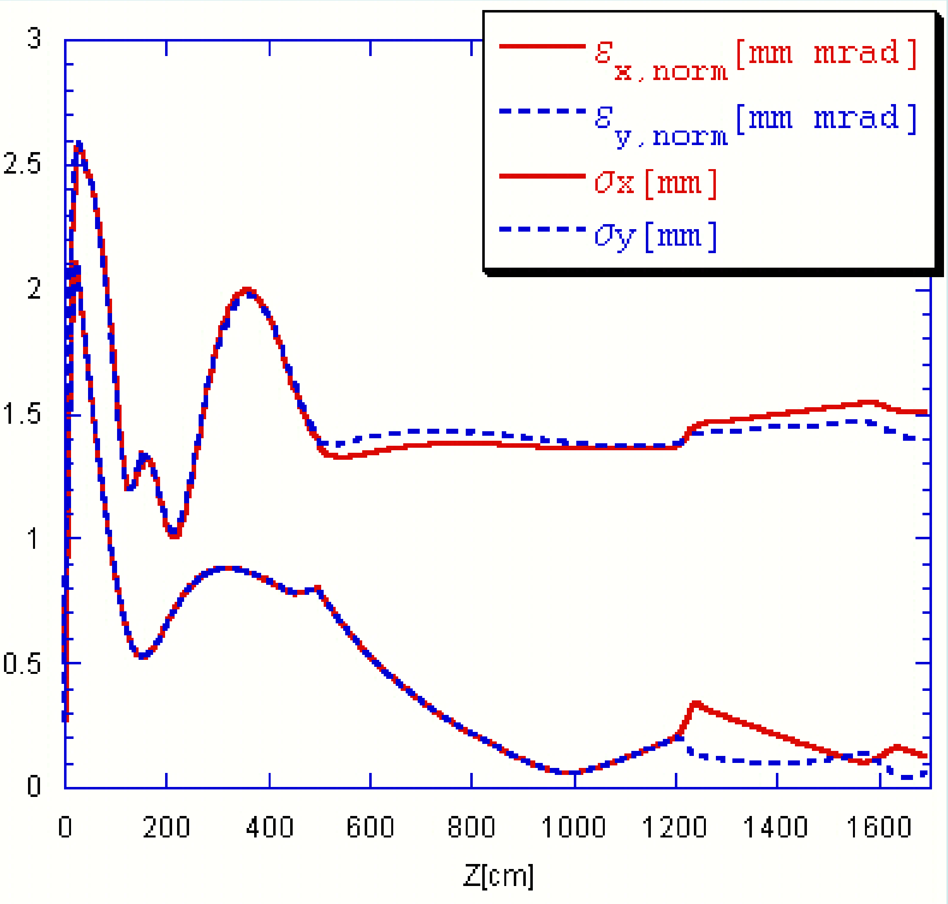
parameters for E~155MeV and
3 TRW structures

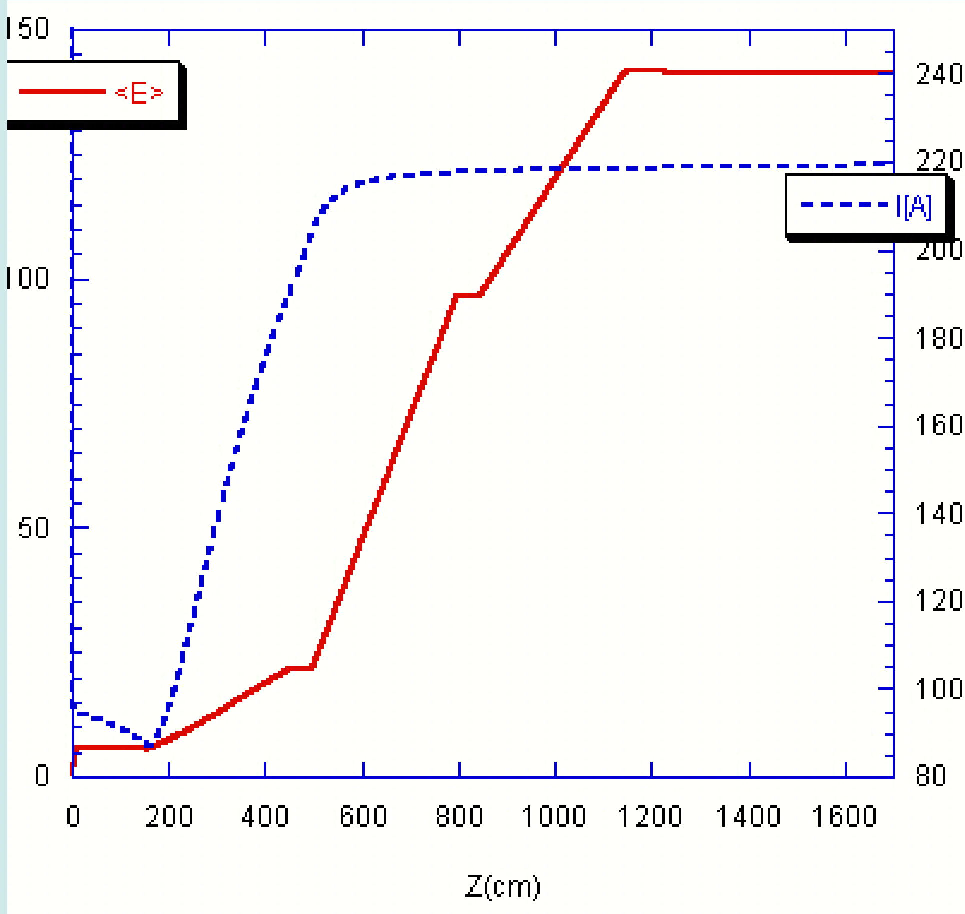
...BUT WITH

velocity bunching

E(gun) =120 MV/m
Q=1 nC
R= 1 mm
Δt=11.65 ps
phi_inj=33deg

B(gun) =2730 G
B(I TRW) =650 G phi=-83 deg
B(II TRW) =950 G on crest
B(III TRW) =1000G on crest





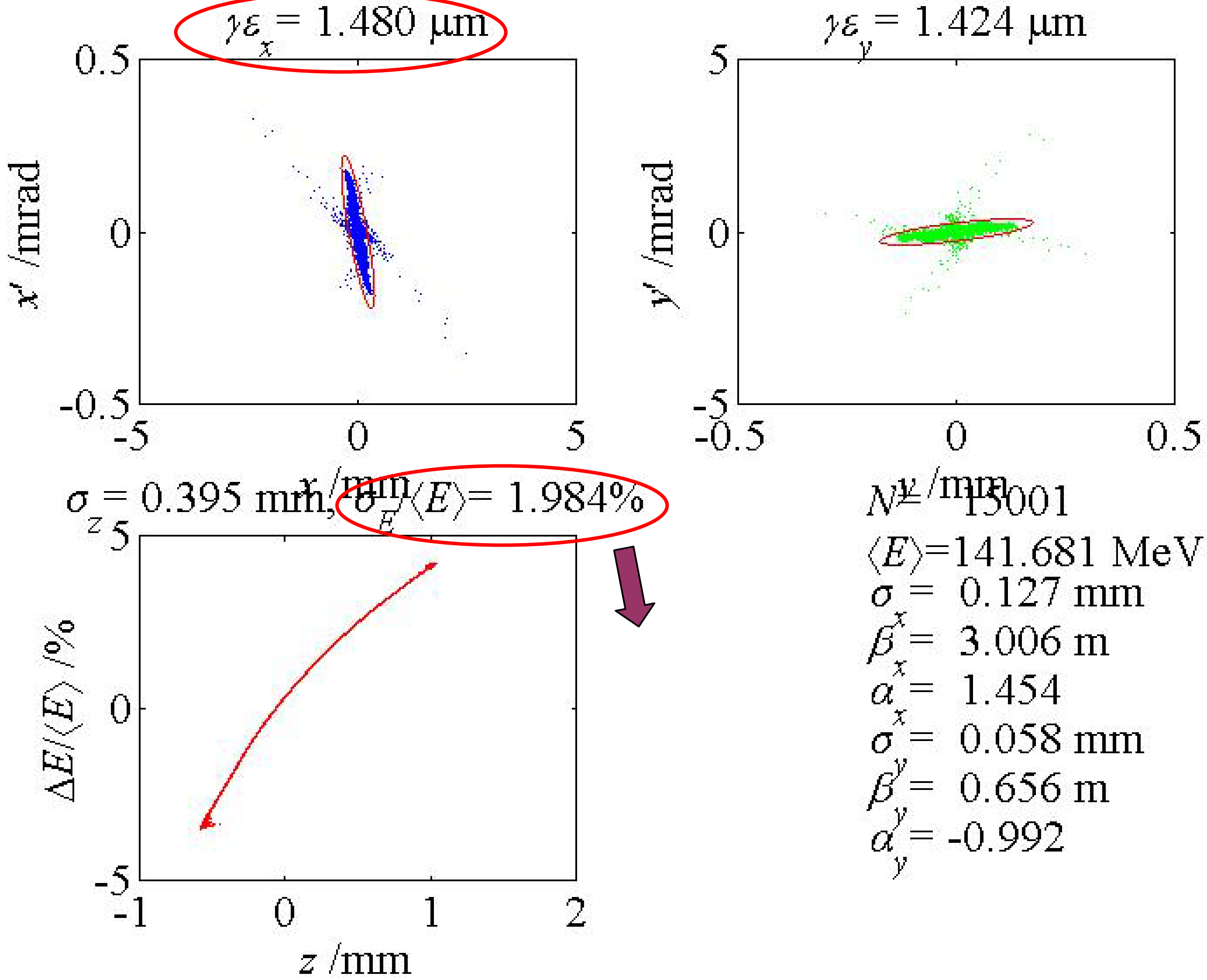
$\langle\varepsilon_x\rangle$=1.506 μm

$\langle\varepsilon_y\rangle$=1.391 μm

I=219 A

$\langle E\rangle$=141.6 MeV

AT UNDULATOR ENTRANCE



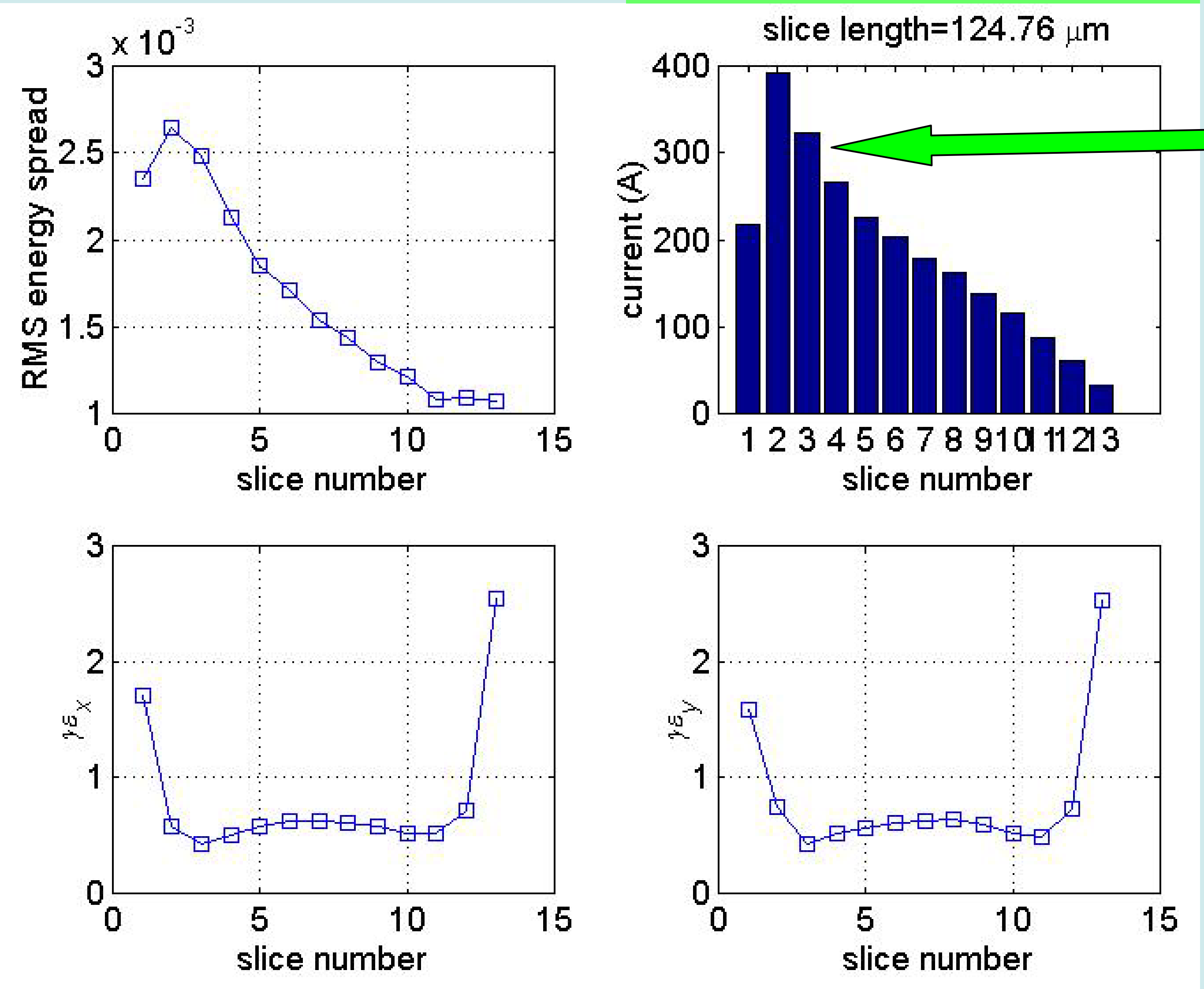
Electron beam at undulator entrance

No attempt to minimize the energy spread

(II and III TRW phase on crest)

Slice Analysis at undulator entrance

Very large slice current



I_{slice}>200A
~50% of beam

3rd slice:

ε_n=0.43μm

I=323A

L_{sat}=6.5m

Small slice emittance

Conclusions for the RF compressor studies

→ Parameters have been optimized for RF compression at ~155MeV and 3 TRW to have I~200A @undulator entrance.

→ The beam energy spread is ~2%, BUT the slice energy spread is small (in the range between $1\cdot10^{-3}$ and $3\cdot10^{-3}$)

→Each slice has a LARGE current (~50% of the beam has I_{slice}>200A!)

⇓

Every slice will saturate

it is also possible to select one particular slice

Conclusions

* Optimized the working point :it is very close to previous one BUT now: $\langle I_{slice} \rangle$~100A (instead of ~85A)

* The strategy has been to increase a bit the bunch charge while shortening the bunch length

* The gain is essentially in the calculated saturation length: it is reduced by ~15%.

Best experimental results at high charge: εn≈1.2 mm mrad at Q=1 nC, pulse length=9 psec FWHM, εn≈1.5 mm mrad at Q=1.2 nC

EXPERIMENTAL STUDIES OF PHOTOCATHODE RF GUN WITH LASER PULSE SHAPING

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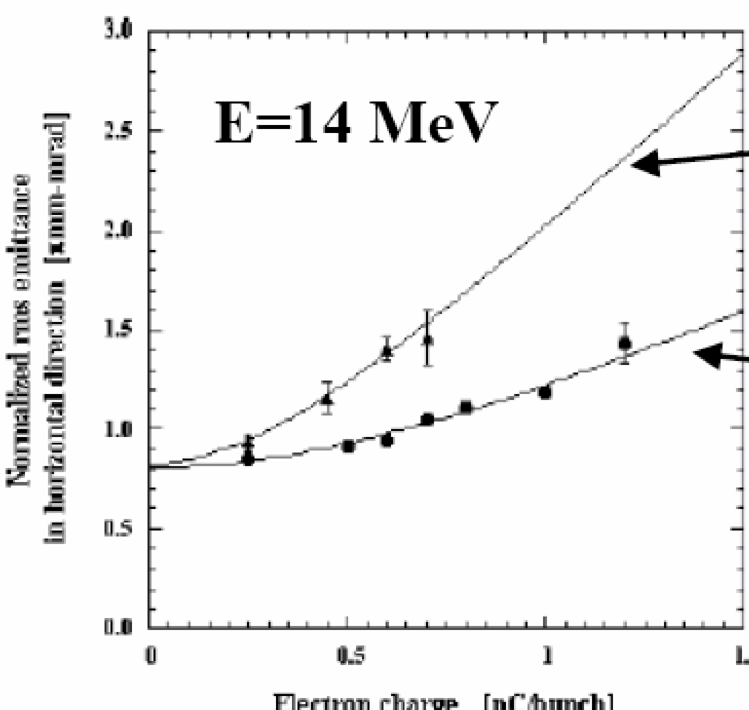
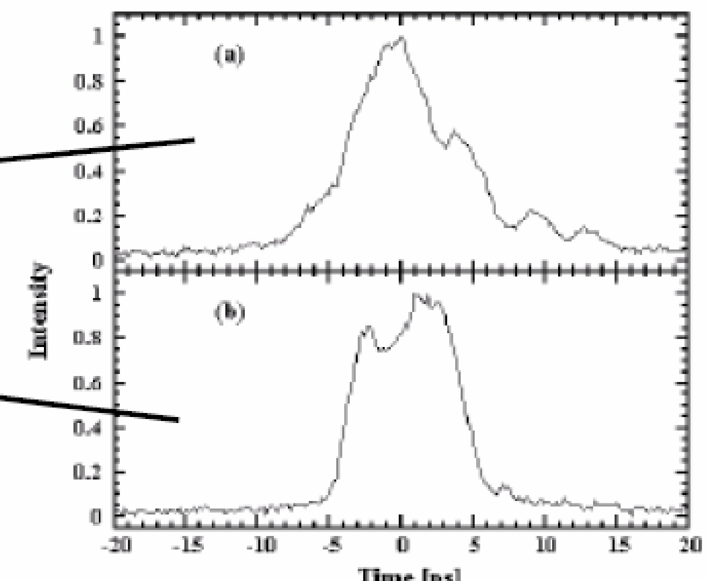
K. Takasago, A. Endo, Femtosecond Technology Research Association, 5-5 Tokodai, Tsukuba, Ibaraki 300-2635, Japan





igure 2: Temporal distributions of the Gaussian (a) nd square (b) laser pulse shapes with a pulse length f 9 ps FWHM.

current vs beam density: scaling laws (JBR et al.)

$$\sigma_x'' + \frac{(\beta\gamma)'}{\beta\gamma}\sigma_x' + k_{sol}\sigma_x - \frac{2I_{slice}(\sigma_x/\sigma_z)}{I_o(\beta\gamma)^3\sigma_x} = 0$$

$$= k_{sc}\cdot\sigma_x$$

beamline unchanged

if k_{sc} constant

$$k_{sc} \propto \frac{Q}{V} \propto \frac{Q}{\sigma_z}\cdot\frac{1}{\sigma_x^2}\cdot g\left(\frac{\sigma_x}{\sigma_z}\right) \equiv \text{const.}$$

Constant aspect ratio

$$\sigma_x \propto \sigma_z \Rightarrow$$

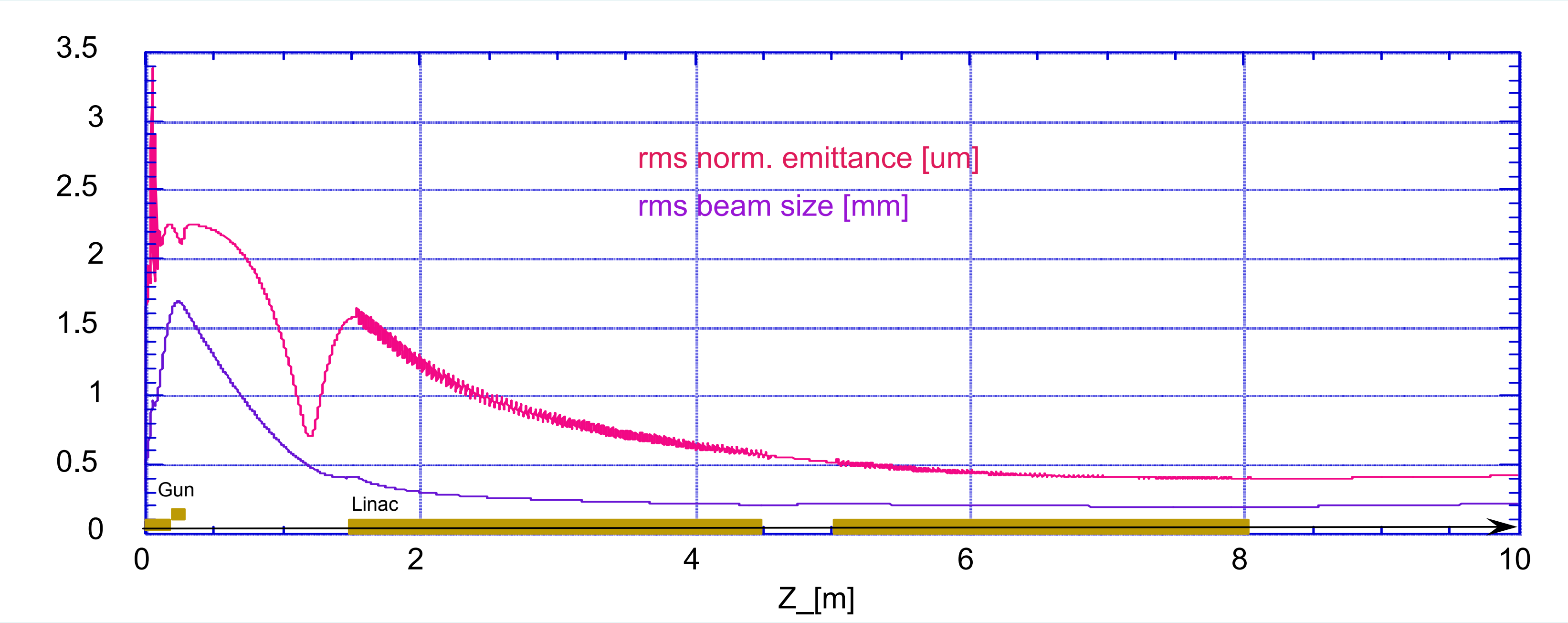
$$Q \propto \sigma_z^3 \Rightarrow I \propto \sigma_z^2$$

1. $\sigma_z = \text{const.} \Rightarrow \sigma_x \propto \sqrt{Q} \Rightarrow I \propto Q$
2. $\frac{Q}{\sigma_z} = \text{const.} \Rightarrow \sigma_x \propto \sqrt{\frac{Q}{\sigma_z}}$
3. $Q = \text{const.} \Rightarrow \sigma_x \propto \frac{1}{\sqrt{\sigma_z}} \Rightarrow I \propto \frac{1}{\sigma_z}$

Maintenance of emittance compensation requires keeping the beam plasma frequency constant

⇩

Beam density constant



$$\frac{Q}{\sigma_z} = \text{const.} \Rightarrow \sigma_x \propto \sqrt{\frac{Q}{\sigma_z}}$$

SUMMARY OF RESULTS

Q (nC)	τ = FWHM pulse duration (psec)*	Beam fraction with ≥ 100 A	Projected rms norm. Emittance (mm-mrad)	Max. Slice rms norm. emittance (mm-mrad)**	Total RMS energy spread	Max. Slice RMS energy spread**
1	11.7	**0 %** (max. curr. Slice ~**92 A**) (average bunch current ~**86A**)	0.6	**0.5**	2e-3	**5e-4**
1	10	**23%** (max. curr. Slice ~**102 A**) (average bunch current ~**94A**)	0.67	**0.6**	1.62e-3	**5e-4**
1.1	10	**54 %** (max. curr. Slice~**110 A**) (average bunch current ~**102A**)	0.75	**0.71**	1.65e-3	**5.2 e-4**
1.2	10	**60 %** (max. curr. Slice ~**120 A**) (average bunch current ~**110A**)	0.81	**0.79**	1.66e-3	**5.4e-4**
1	9	**50%** (max. curr. Slice ~**110 A**) (average bunch current ~**101A**)	0.8	**0.73**	1.67e-3	**4.2e-4**
1.1	9	**58 %** (max.curr Slice~**120 A**) (average bunch current ~**110A**)	0.86	**0.82**	1.67e-3	**4.3e-4**

*** Rise time=1 psec, ** 85% beam**

Slice length ≅ 300 μm

1.1 nC, 10 psec meet the requirement on current with the minimum emittance