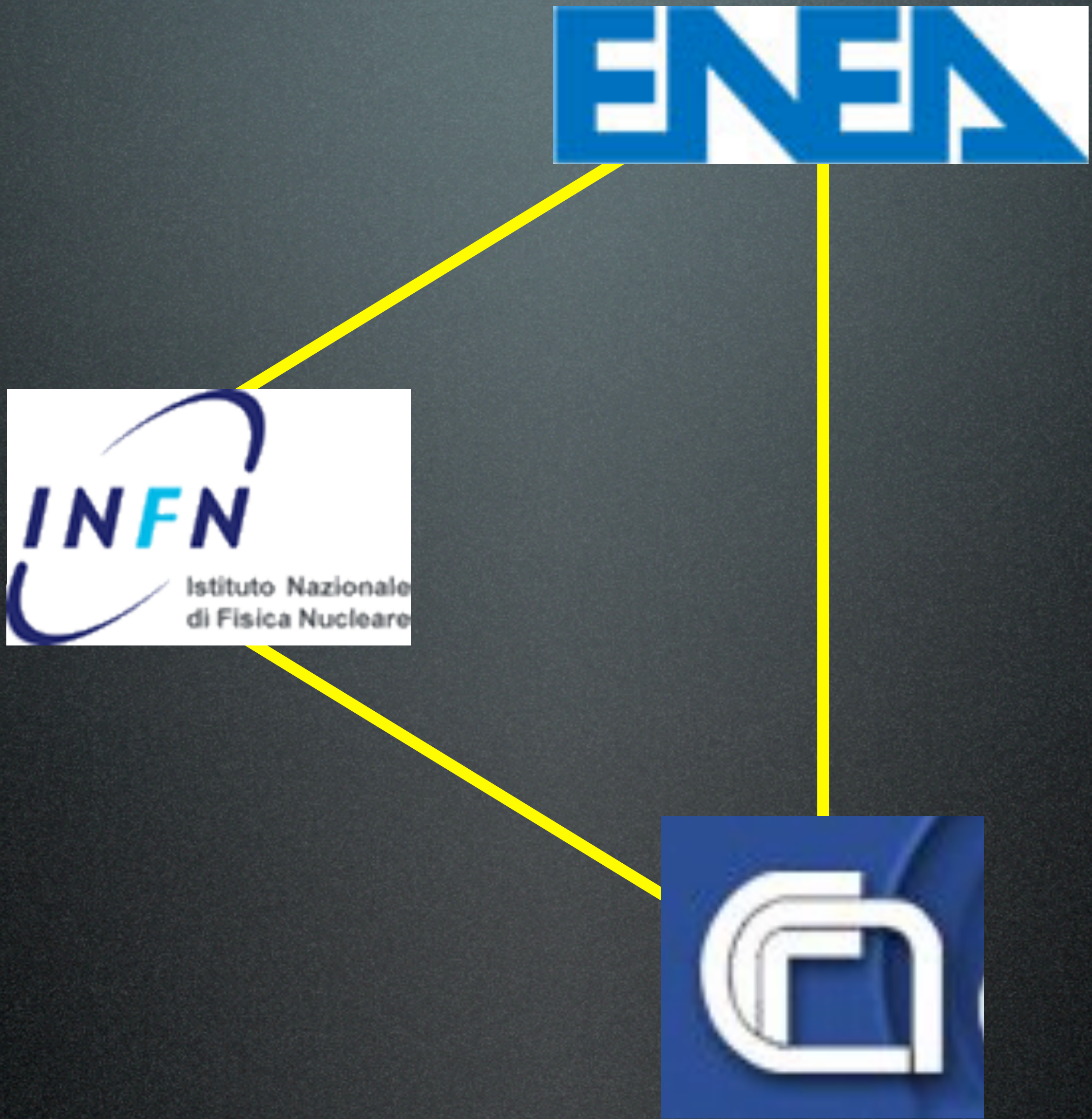
Advanced Accelerator Activities at SPARC_LAB

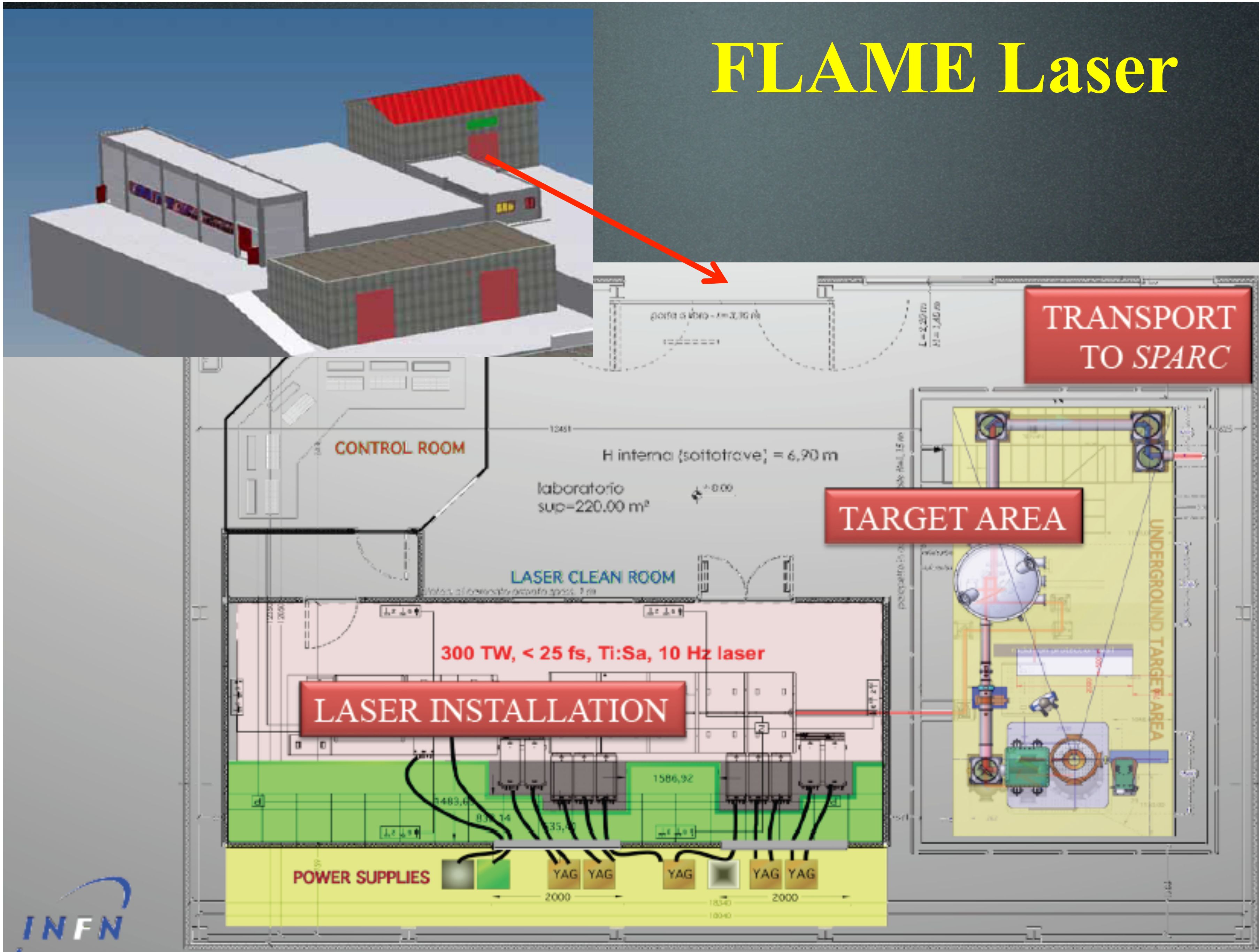
(Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams)

Massimo Ferrario
INFN-LNF

John Adams Institute for Accelerator Science - Oxford - June 21, 2012

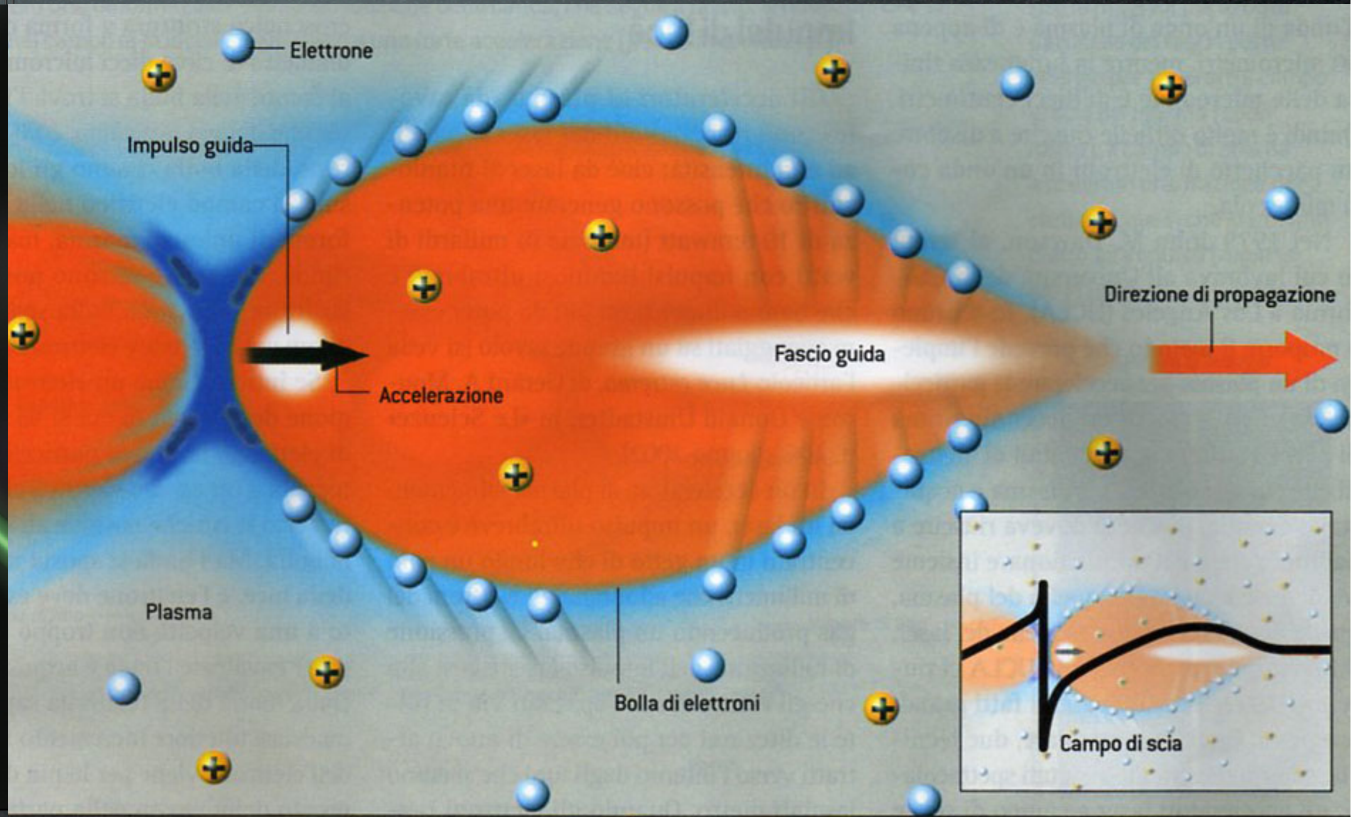

ENEA
INFN
Istituto Nazionale
di Fisica Nucleare

FLAME Laser



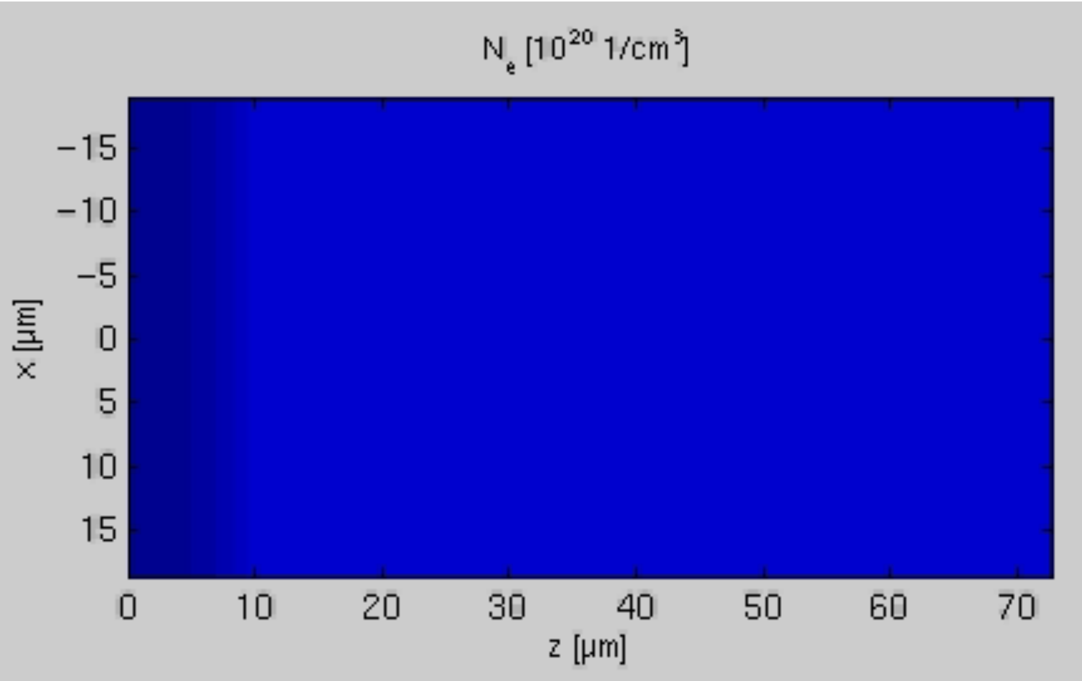
TRANSPORT TO *SPARC*
CONTROL ROOM
H interna (sottotrave) = 6,90 m
laboratorio
sup=220.00 m²
TARGET AREA
LASER CLEAN ROOM
UNDERGROUND TARGET AREA
300 TW, < 25 fs, Ti:Sa, 10 Hz laser
LASER INSTALLATION
POWER SUPPLIES
YAG
YAG
YAG
YAG
YAG
2000
2000

FLAME Target Area



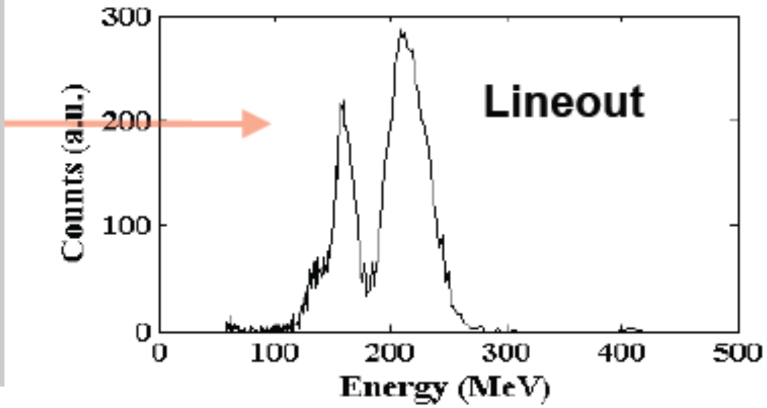
Self Injection:
spectrum of the accelerated electrons

Recent spectra acquired at 1 J laser energy on gas-jet target and 35 fs: expected intensity at focus: 7E18 W/cm2



Energy dispersion with a 0.9 T magnetic dipole

Electrons at lanex screen

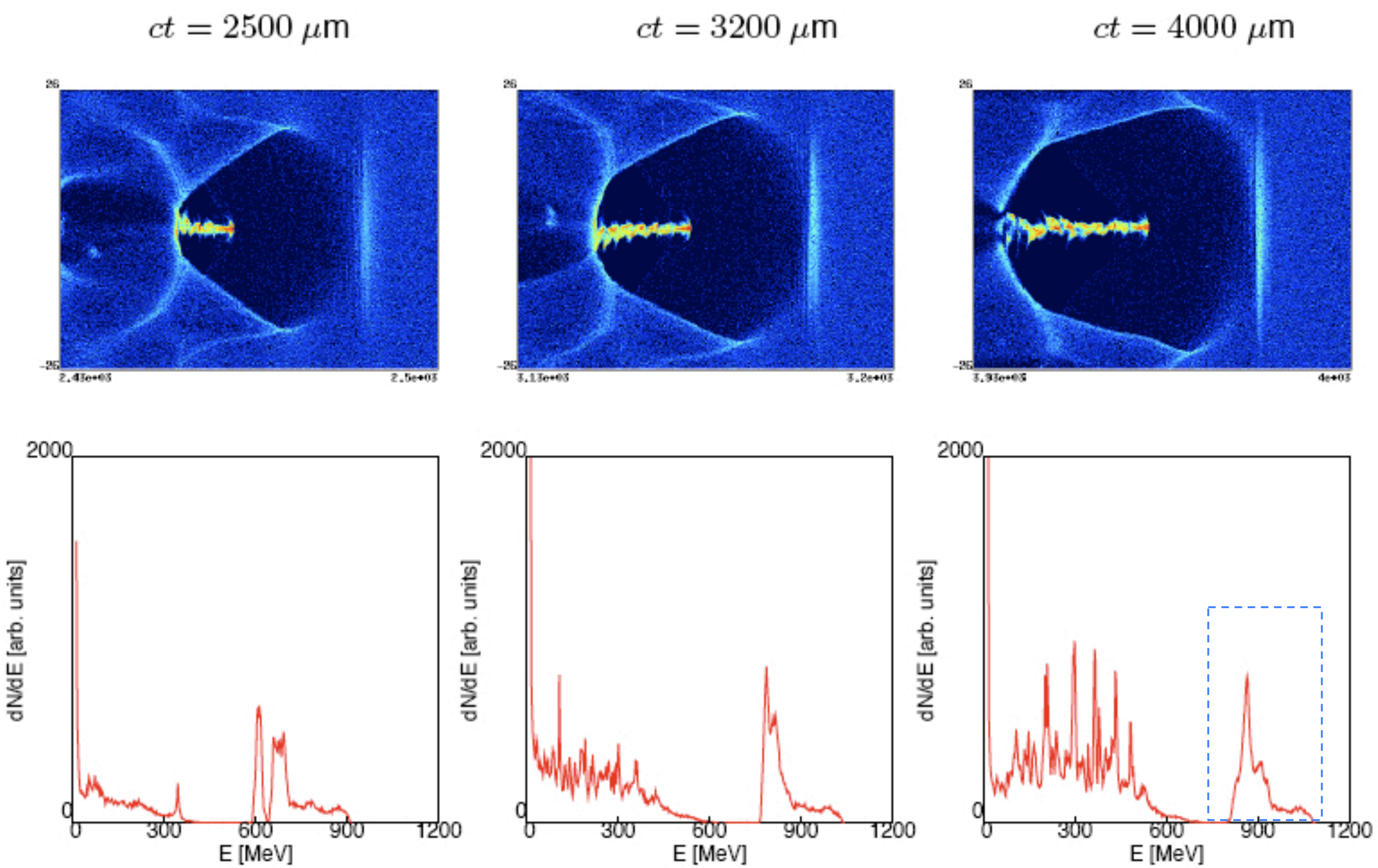


Energy of LPA electrons entering the multi 100 MeV range

T. Levato et al., EPS Conference in Plasma Physics, 2011

Studies for the SITE

- 3D sim. "GeV-class" ($L_{gasjet} = 4$ mm)



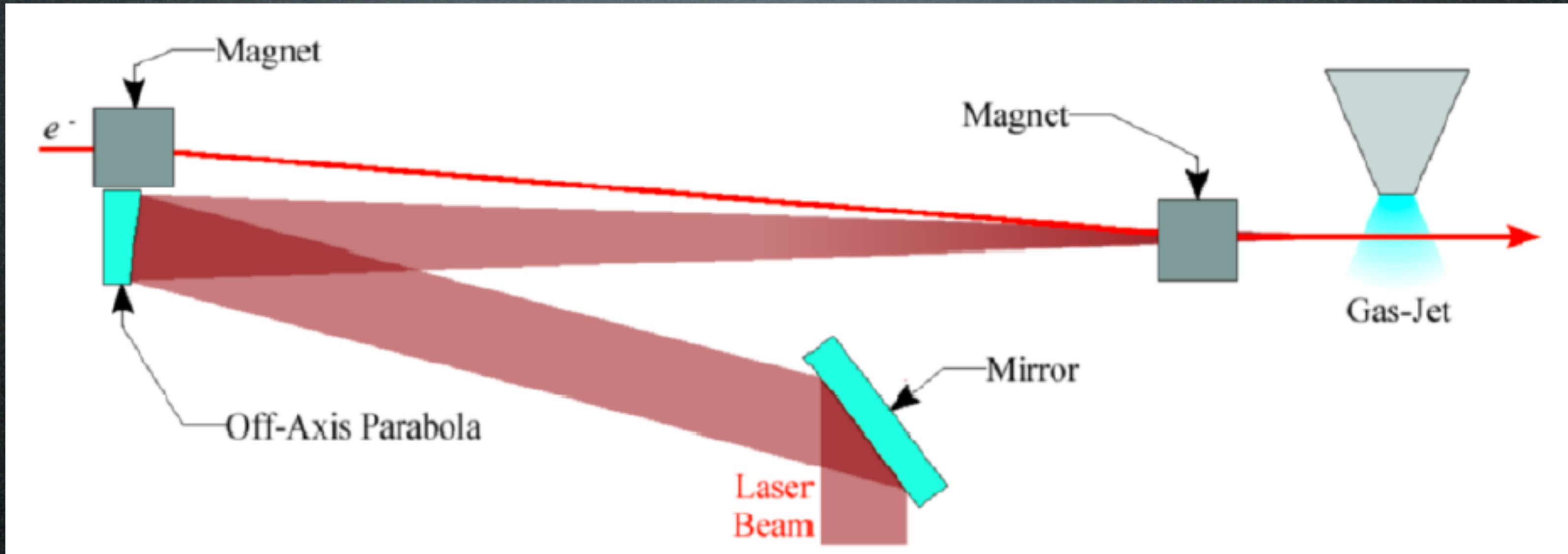
$Q \cong 0.6\ nC$

$\sigma_z \cong 1.8\ \mu m\ (I \cong 45\ kA)$

$\sigma_x \cong 0.5\ \mu m\ \varepsilon_n \cong 2\ \mu m$

Courtesy C. Benedetti

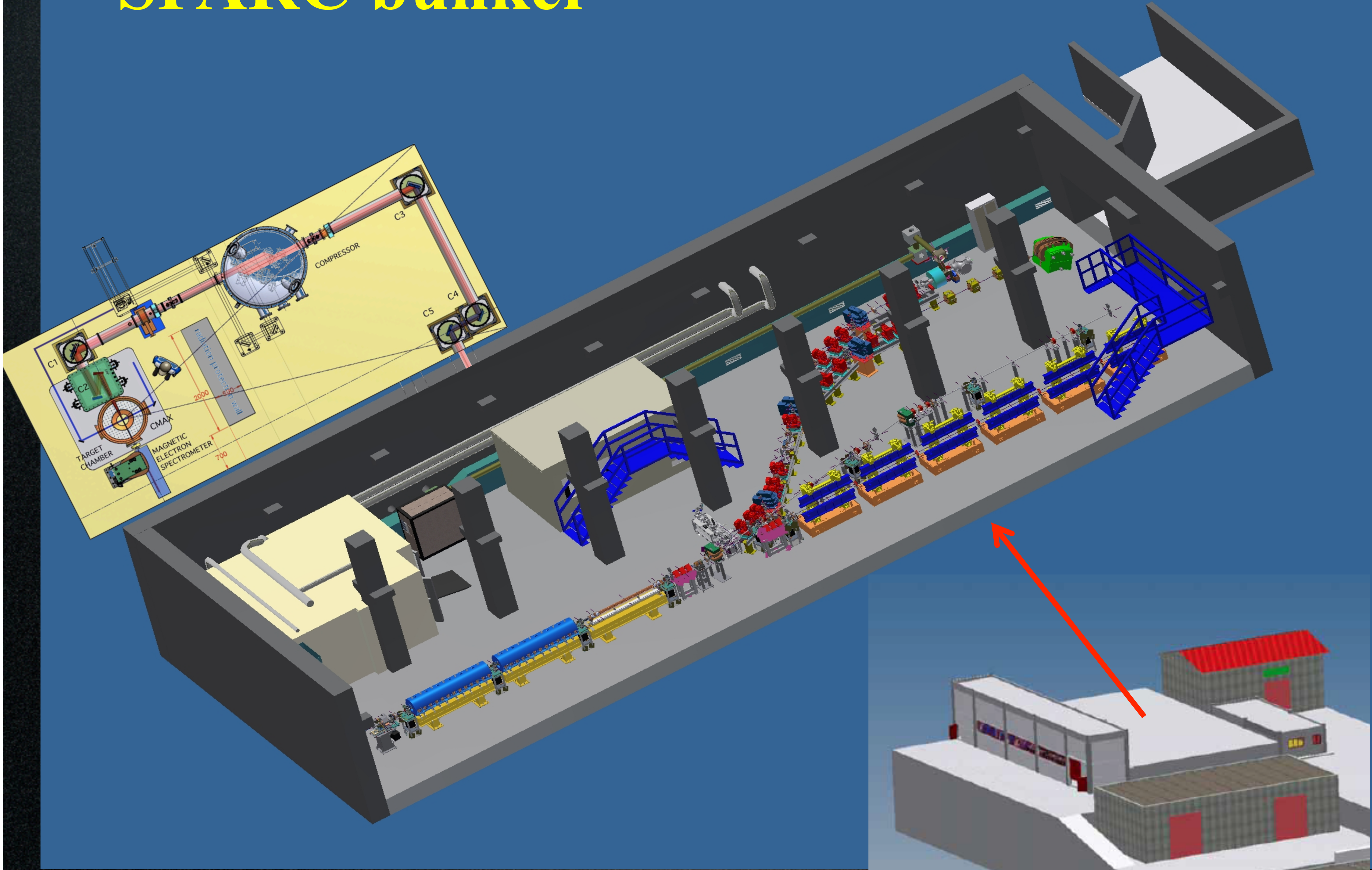
EXIN (EXternal INjection)

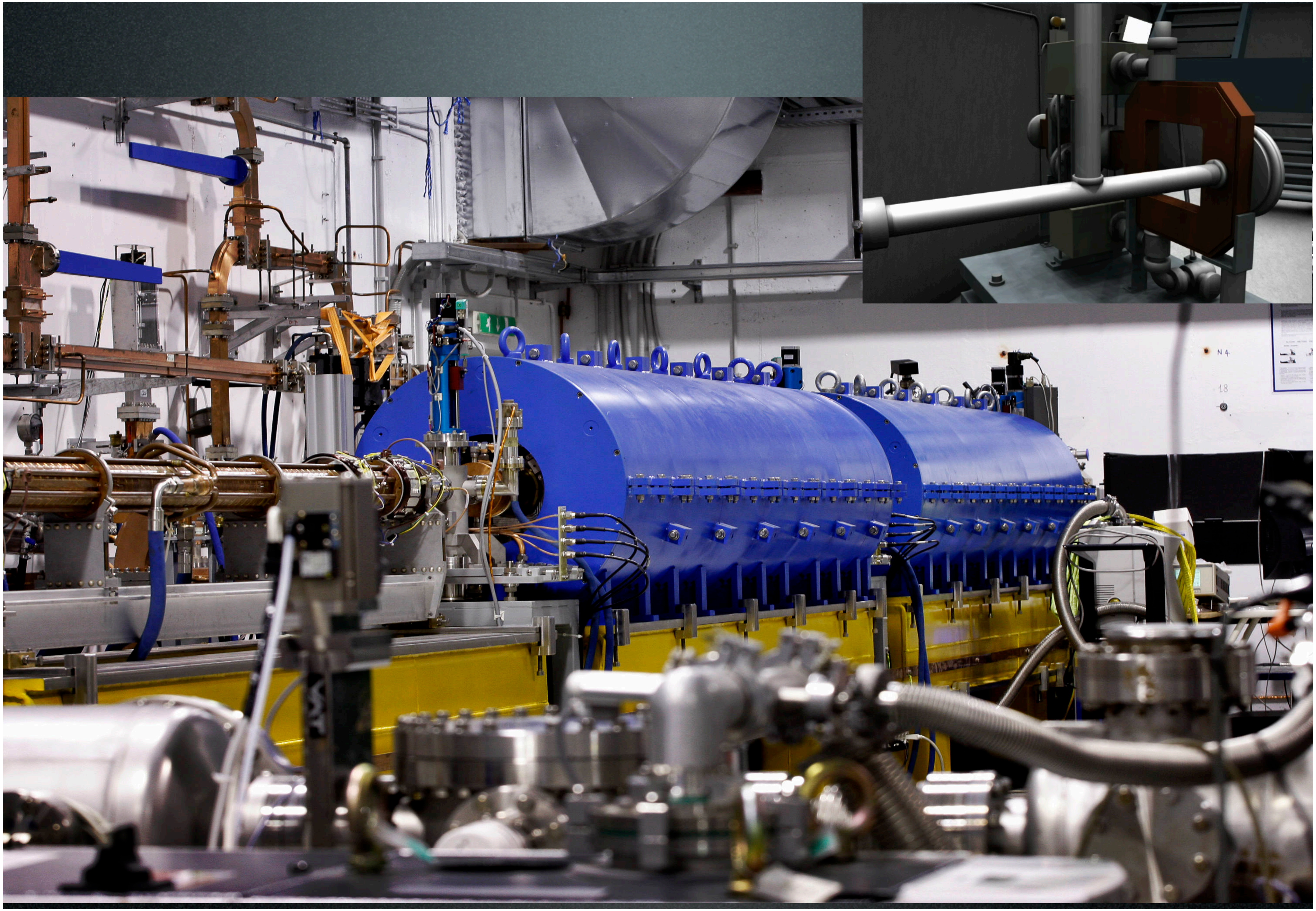


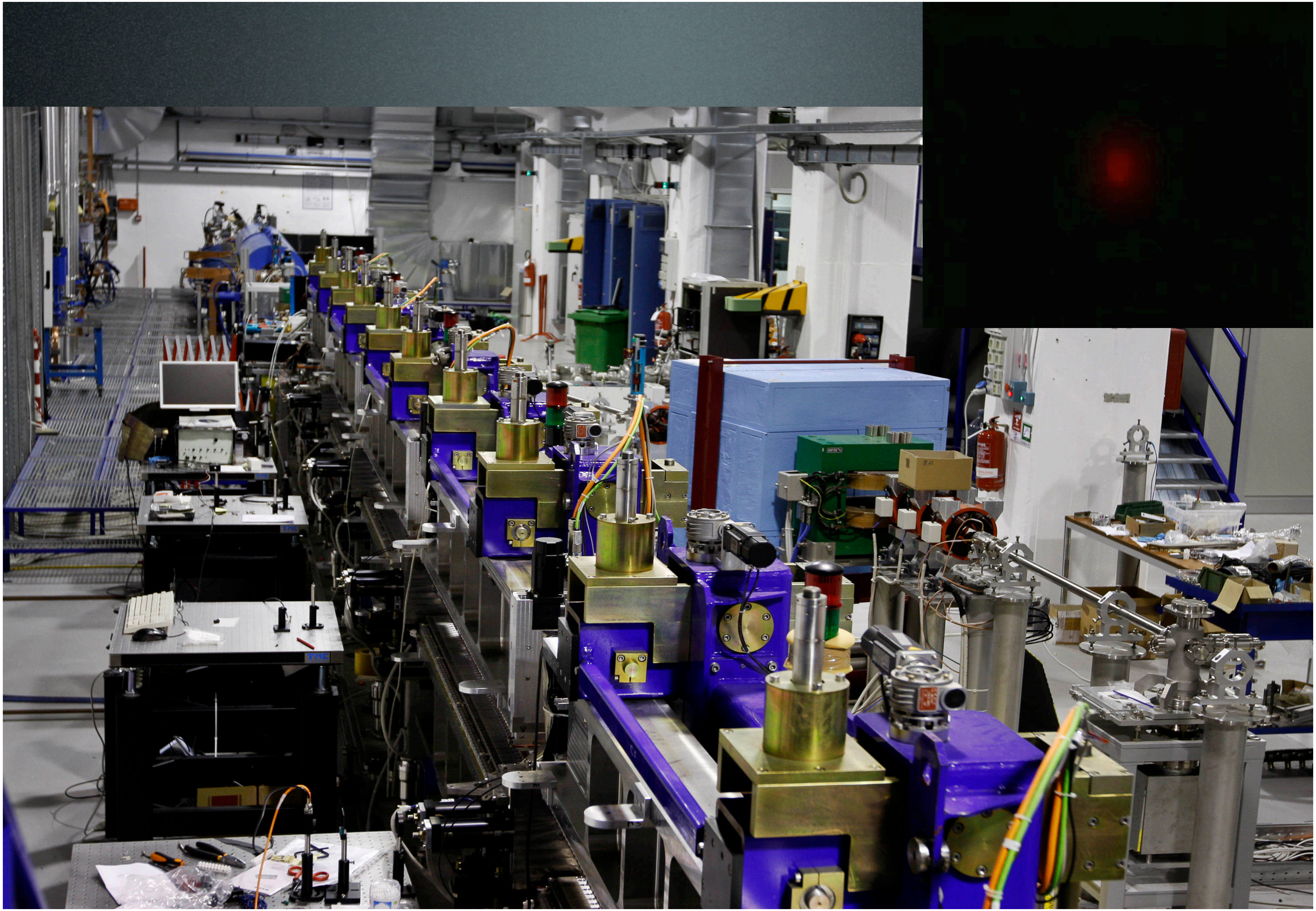
n_e [cm^{-3}]	E_{max} [GV/m]	λ_p [μm]	Ldeph [m]	Energy gain over L = 2cm [MeV]	Energy gain over L = 10cm [MeV]
1e16	0.2	330	400	<4	<20
5e16	1	150	5	<20	<100
2.5e17	3.8	66	0.45	<76	<380
7.5e17	7.5	39	0.1	<150	<750
2.5e18	8.5	30	0.04	<190	-

Courtesy L. Serafini

SPARC bunker







Modern accelerators require high quality beams: ==> High Luminosity & High Brightness

↑ $$L = \frac{N_{e+} N_{e-} f_r}{4\pi\sigma_x\sigma_y}$$

- –N of particles per pulse => 10^9
- –High rep. rate f_r=> bunch trains
- –Small spot size => low emittance

↑ $$B_n \approx \frac{2I}{\varepsilon_n^2}$$

- –Short pulse (ps to fs)
- –Little spread in transverse momentum and angle => low emittance

Velocity Bunching

Bunch length in the moving frame S'

More interesting is the bunch dynamics as seen by a moving reference frame S', that we assume it has a relative velocity V with respect to S such that at the end of the process the accelerated bunch will be at rest in the moving frame S'. It is actually a deceleration process as seen by S'

Inverse Lorentz transformations:

$$\begin{cases} ct' = \gamma\left(ct - \frac{V}{c}z\right) \\ z' = \gamma(z - Vt) \end{cases}$$

leading for the tail particle to:

$$\begin{cases} t'_{o,t} = t_o = 0 \\ z'_{o,t} = z_{o,t} = 0 \end{cases}$$

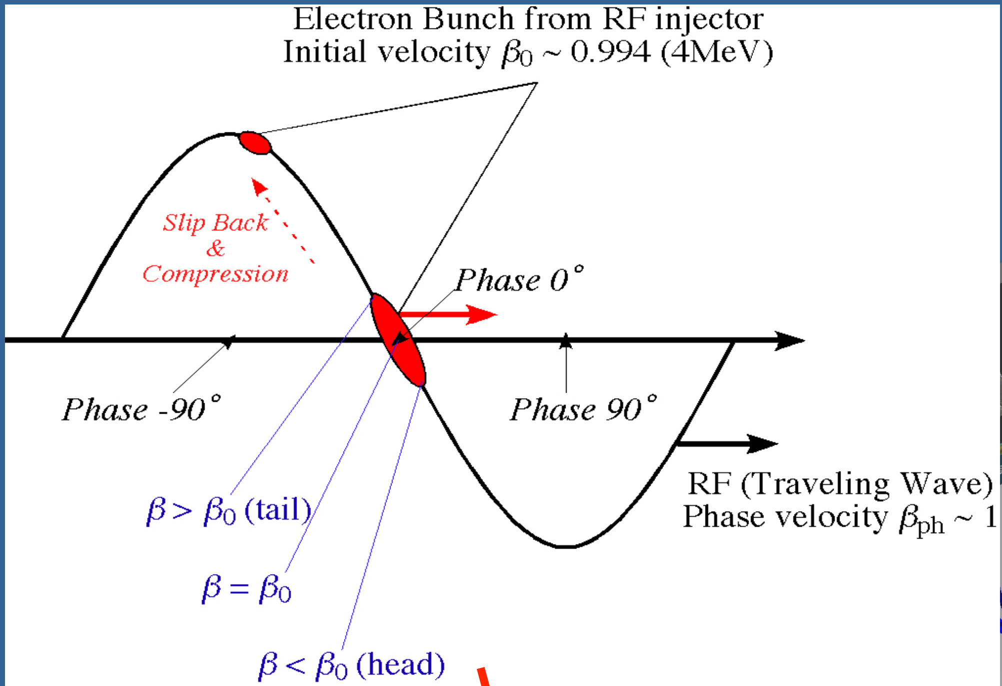
and for the head particle to:

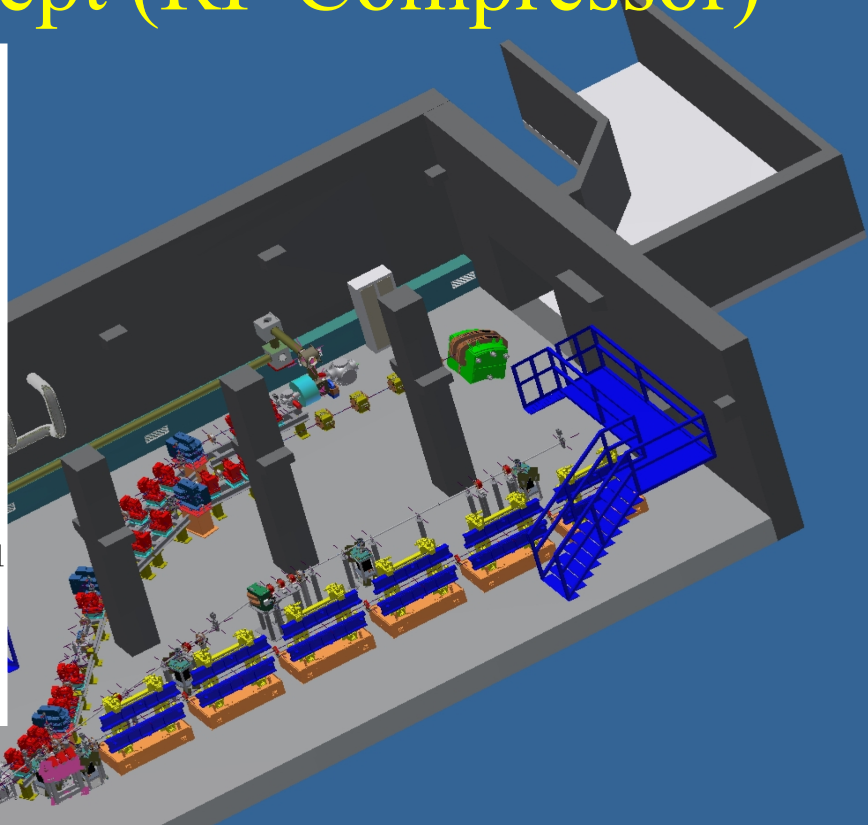
$$\begin{cases} t'_{o,h} = -\frac{V}{c}\gamma'_o L_o < t_o \\ z'_{o,h} = \gamma'_o L_o > z_{o,h} \end{cases}$$

The key point is that as seen from S' the decelerating force is not applied *simultaneously* along the bunch but with a *delay* given by:

$$\Delta t'_o = t'_{o,h} - t'_{o,t} = -\frac{V}{c}\gamma'_o L_o < 0$$

Velocity bunching concept (RF Compressor)



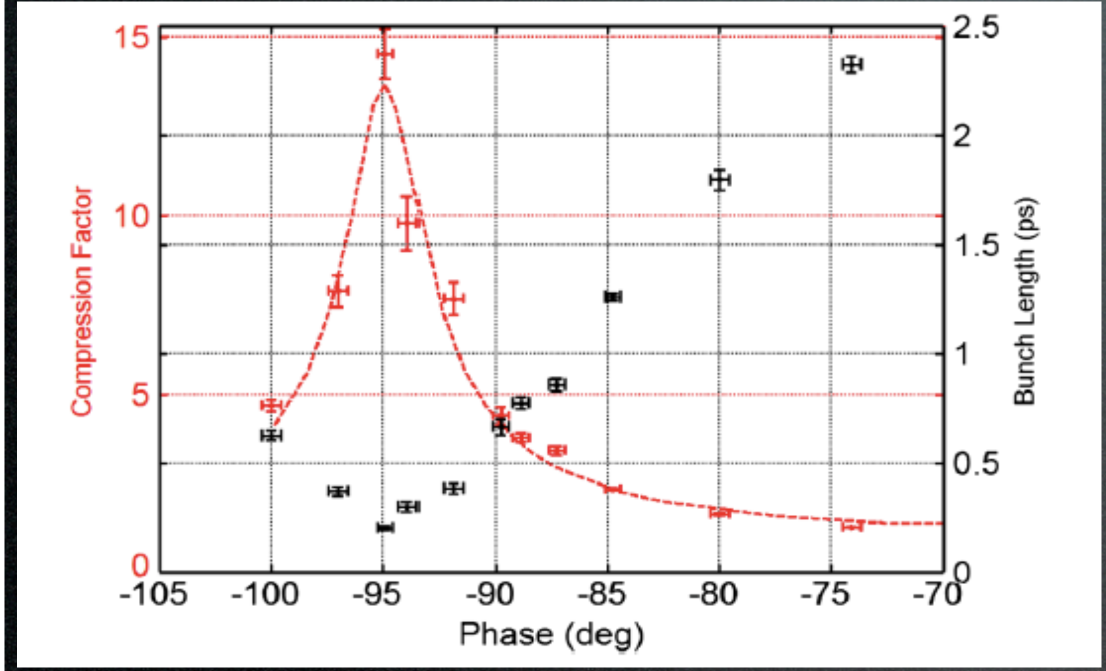


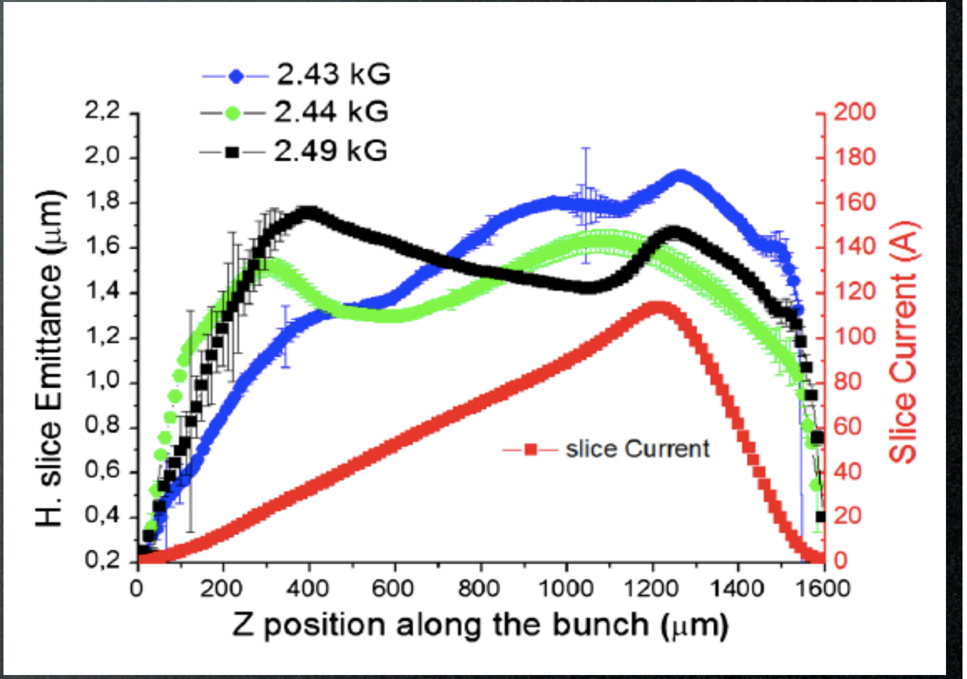
If the beam injected in a long accelerating structure at the crossing field phase and it is slightly slower than the phase velocity of the RF wave , it will slip back to phases where the field is accelerating, but at the same time it will be chirped and compressed.

PRL 104, 054801 (2010) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2010

Experimental Demonstration of Emittance Compensation with Velocity Bunching

M. Ferrario,[1] D. Alesini,[1] A. Bacci,[3] M. Bellaveglia,[1] R. Boni,[1] M. Boscolo,[1] M. Castellano,[1] E. Chiadroni,[1] A. Cianchi,[2] L. Cultrera,[1] G. Di Pirro,[1] L. Ficcadenti,[1] D. Filippetto,[1] V. Fusco,[1] A. Gallo,[1] G. Gatti,[1] L. Giannessi,[4] M. Labat,[4] B. Marchetti,[2] C. Marrelli,[1] M. Migliorati,[1] A. Mostacci,[1] E. Pace,[1] L. Palumbo,[1] M. Quattromini,[4] C. Ronsivalle,[4] A. R. Rossi,[3] J. Rosenzweig,[5] L. Serafini,[3] M. Serluca,[6] B. Spataro,[1] C. Vaccarezza,[1] and C. Vicario[1]



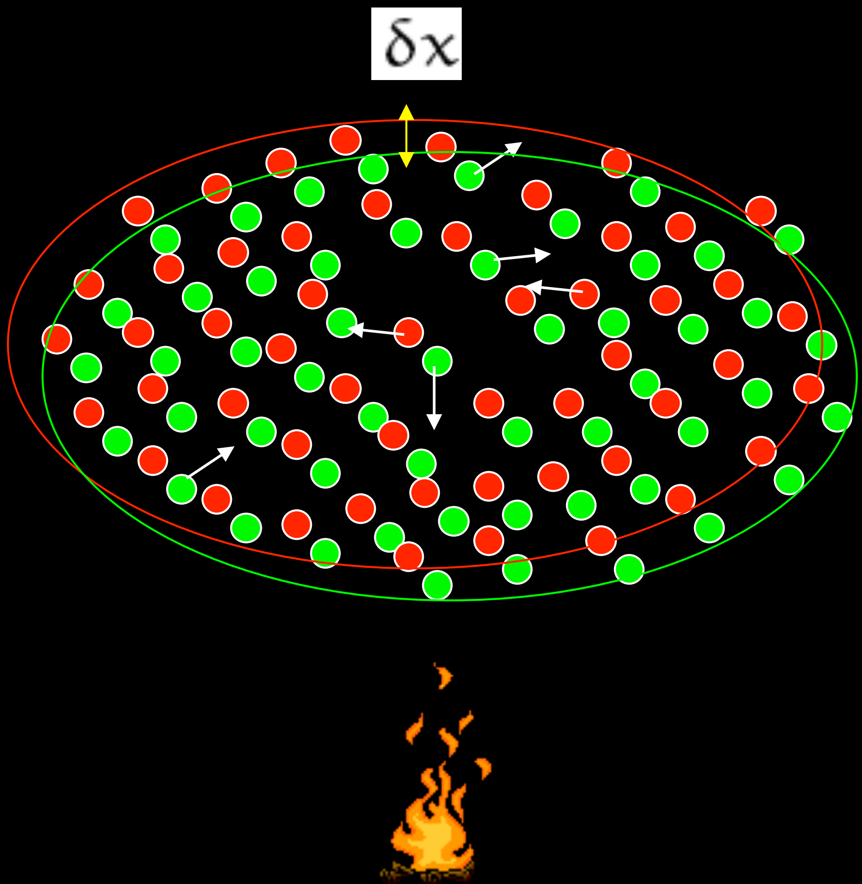


Space Charge induced emittance oscillations in a laminar beam

Neutral Plasma

Surface charge density

$$\sigma = e\, n\, \delta x$$



Surface electric field

$$E_x = -\sigma/\epsilon_0 = -e\, n\, \delta x/\epsilon_0$$

Restoring force

$$m \frac{d^2 \delta x}{dt^2} = e\, E_x = -m\, \omega_p^{\,2}\, \delta x$$

Plasma frequency

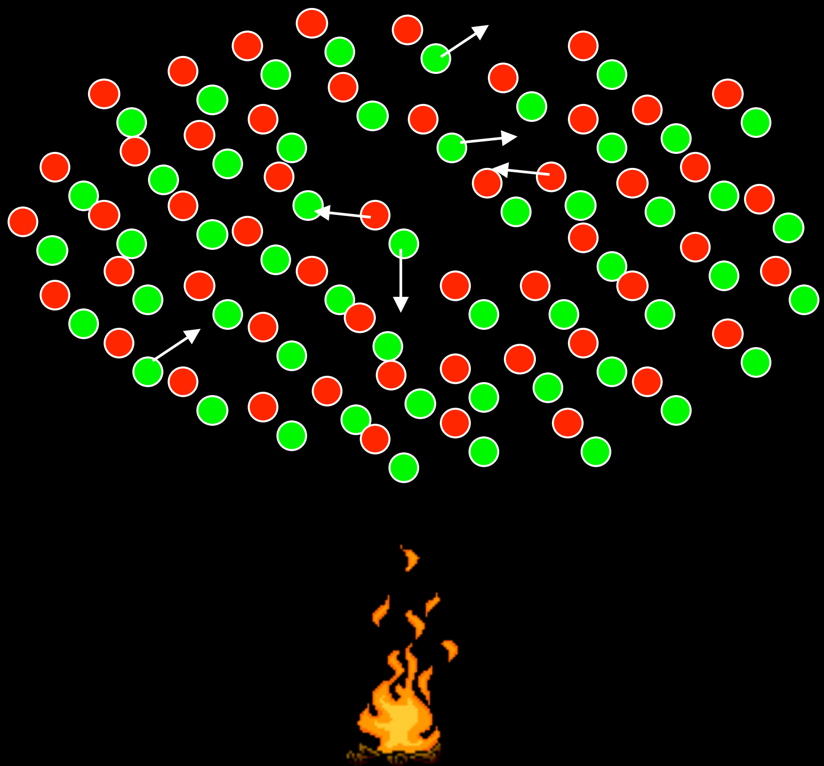
$$\omega_p^{\,2} = \frac{n\, e^2}{\epsilon_0\, m}$$

Plasma oscillations

$$\delta x = (\delta x)_0 \cos(\omega_p\, t)$$

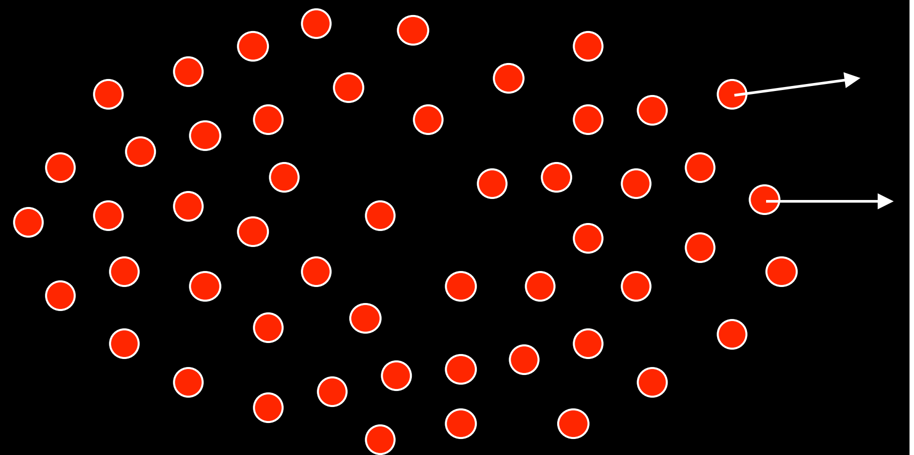
Neutral Plasma

- Oscillations
- Instabilities
- EM Wave propagation



Single Component Cold Relativistic Plasma

Magnetic focusing



Magnetic focusing

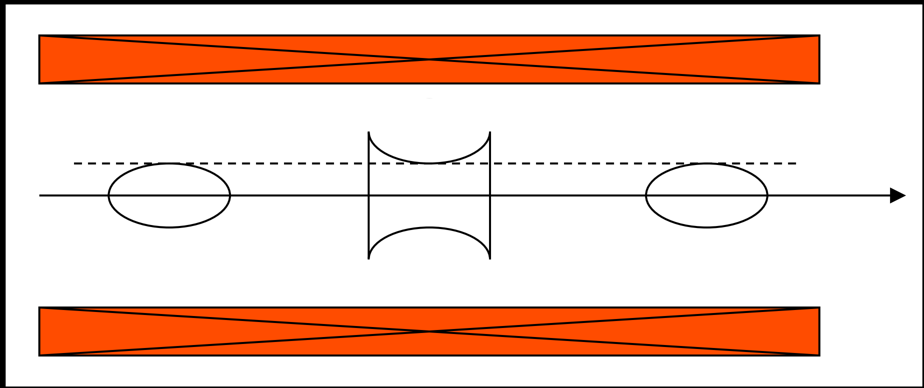
Single Component Relativistic Plasma

$$\sigma'' + k_s^2 \sigma = \frac{k_{sc}(s,\gamma)}{\sigma}$$

$$k_s = \frac{qB}{2mc\beta\gamma}$$

Equilibrium solution:

$$\sigma_{eq}(s,\gamma) = \frac{\sqrt{k_{sc}(s,\gamma)}}{k_s}$$



Small perturbation:

$$\sigma(\zeta) = \sigma_{eq}(s) + \delta\sigma(s)$$

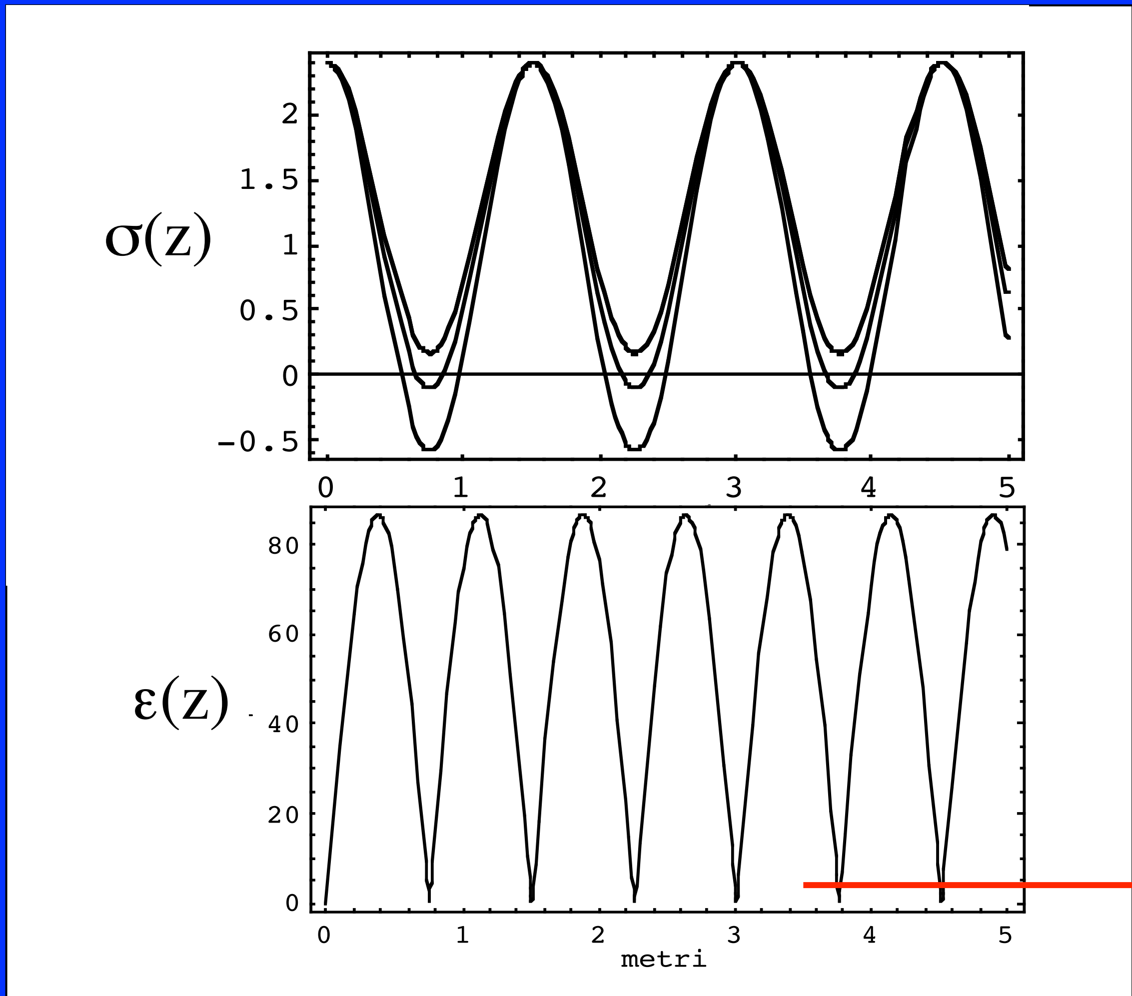
$$\delta\sigma''(s) + 2k_s^2 \delta\sigma(s) = 0$$

$$\delta\sigma(s) = \delta\sigma_o(s)\cos\left(\sqrt{2}k_s z\right)$$

Perturbed trajectories oscillate around the equilibrium with the same frequency but with different amplitudes:

$$\sigma(s) = \sigma_{eq}(s) + \delta\sigma_o(s)\cos\left(\sqrt{2}k_s z\right)$$

Envelope oscillations drive Emittance oscillations



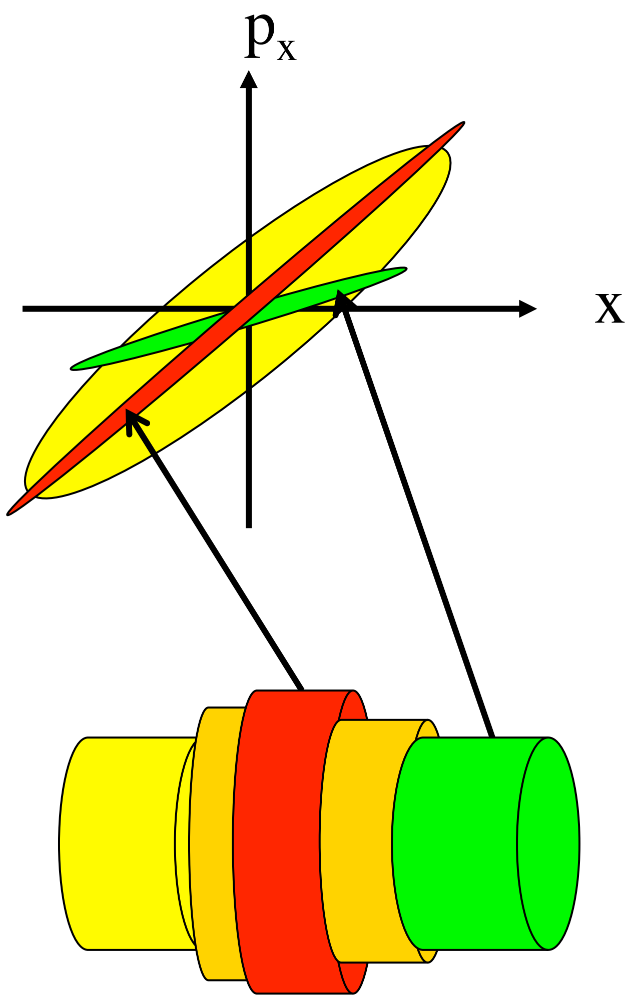
$$\frac{\delta\gamma}{\gamma} = 0$$

$$\sigma' = 0$$

$$\varepsilon_{rms} = \sqrt{\sigma_x^2 \sigma_{x'}^2 - \sigma_{xx'}{}^2} = \sqrt{\left(\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2\right)} \approx \left| sin\left(\sqrt{2} k_s z\right) \right|$$

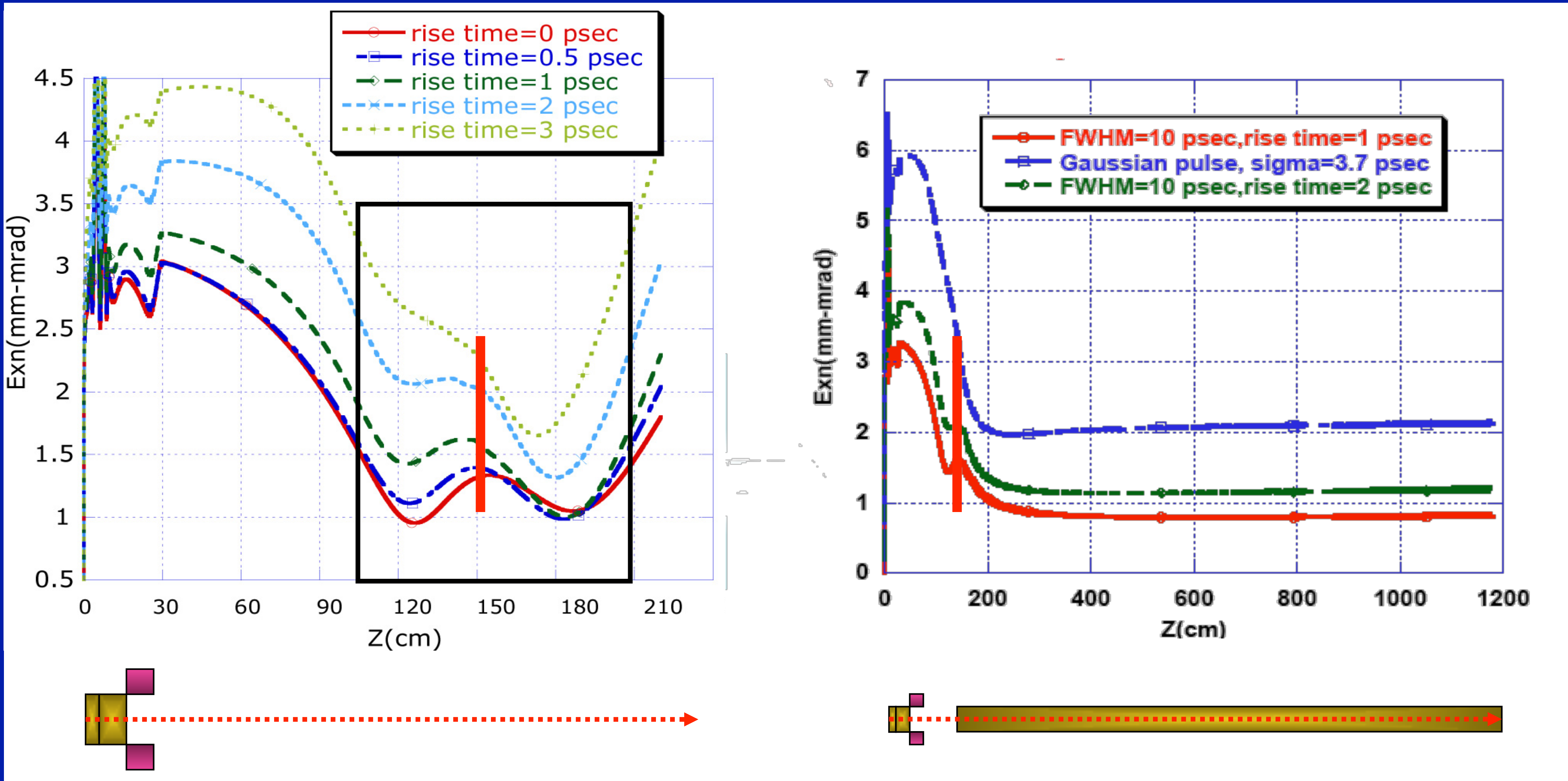
Emittance Oscillations are driven by space charge differential defocusing in core and tails of the beam

Projected Phase Space



Slice Phase Spaces

Emittance evolution for different pulse shapes



Optimum injection in to the linac with:

$$\sigma' = 0$$

$$\gamma' = \frac{eE_{acc}}{mc^2} = \frac{2}{\sigma}\sqrt{\frac{I}{2\gamma I_A}}$$

PRL 99, 234801 (2007) PHYSICAL REVIEW LETTERS week ending 7 DECEMBER 2007

Direct Measurement of the Double Emittance Minimum in the Beam Dynamics of the Sparc High-Brightness Photoinjector

M. Ferrario,[1] D. Alesini,[1] A. Bacci,[3] M. Bellaveglia,[1] R. Boni,[1] M. Boscolo,[1] M. Castellano,[1] L. Catani,[2] E. Chiadroni,[1] S. Cialdi,[3] A. Cianchi,[2] A. Clozza,[1] L. Cultrera,[1] G. Di Pirro,[1] A. Drago,[1] A. Esposito,[1] L. Ficcadenti,[5] D. Filippetto,[1] V. Fusco,[1] A. Gallo,[1] G. Gatti,[1] A. Ghigo,[1] L. Giannessi,[4] C. Ligi,[1] M. Mattioli,[7] M. Migliorati,[5] A. Mostacci,[5] P. Musumeci,[6] E. Pace,[1] L. Palumbo,[5] L. Pellegrino,[1] M. Petrarca,[7] M. Quattromini,[4] R. Ricci,[1] C. Ronsivalle,[4] J. Rosenzweig,[6] A. R. Rossi,[3] C. Sanelli,[1] L. Serafini,[3] M. Serio,[1] F. Sgamma,[1] B. Spataro,[1] F. Tazzioli,[1] S. Tomassini,[1] C. Vaccarezza,[1] M. Vescovi,[1] and C. Vicario[1]

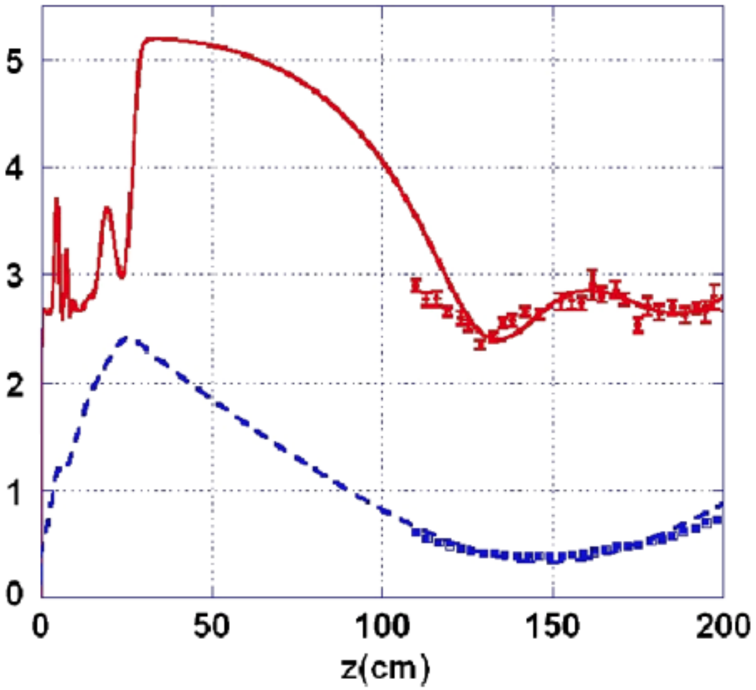
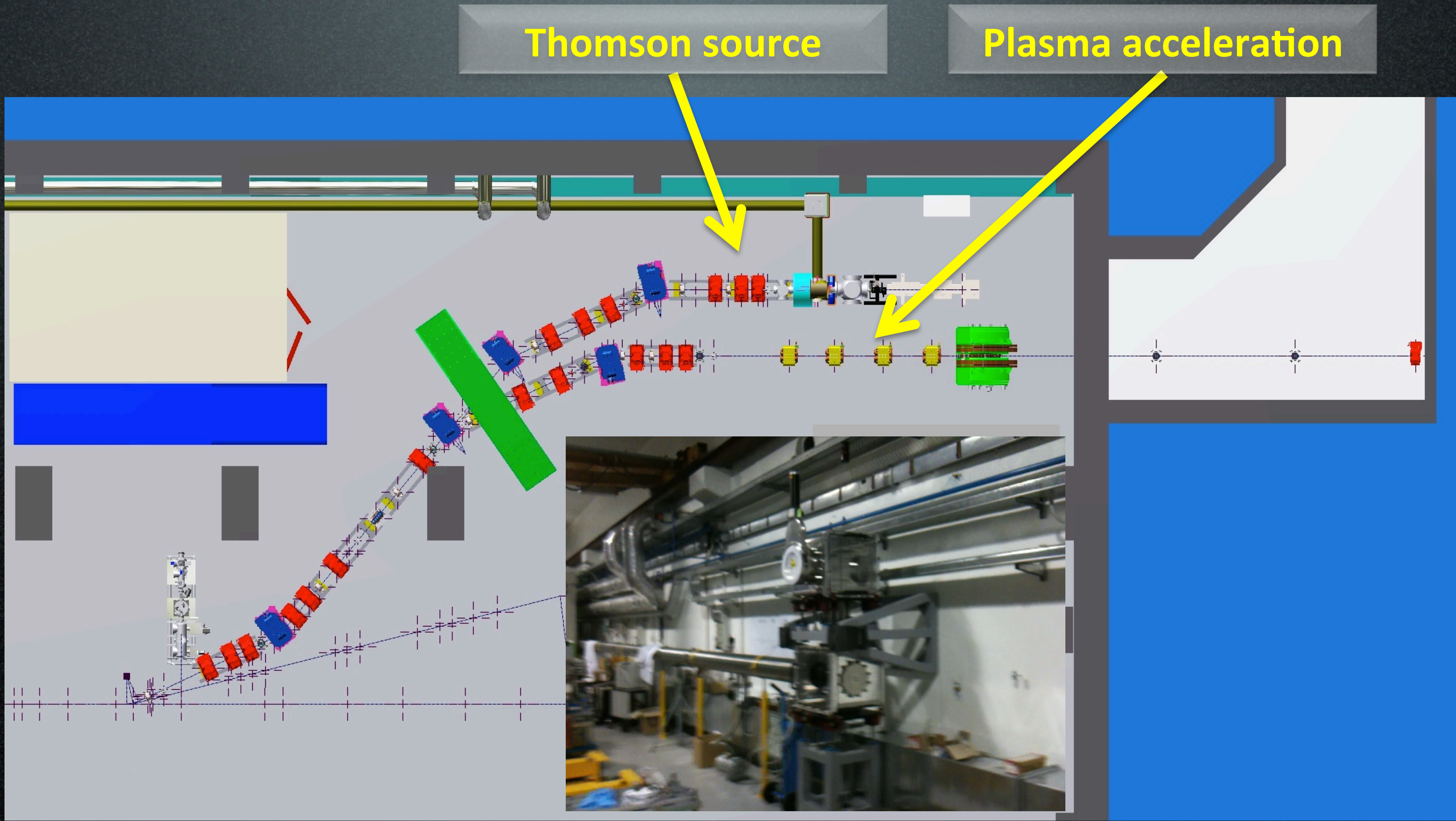


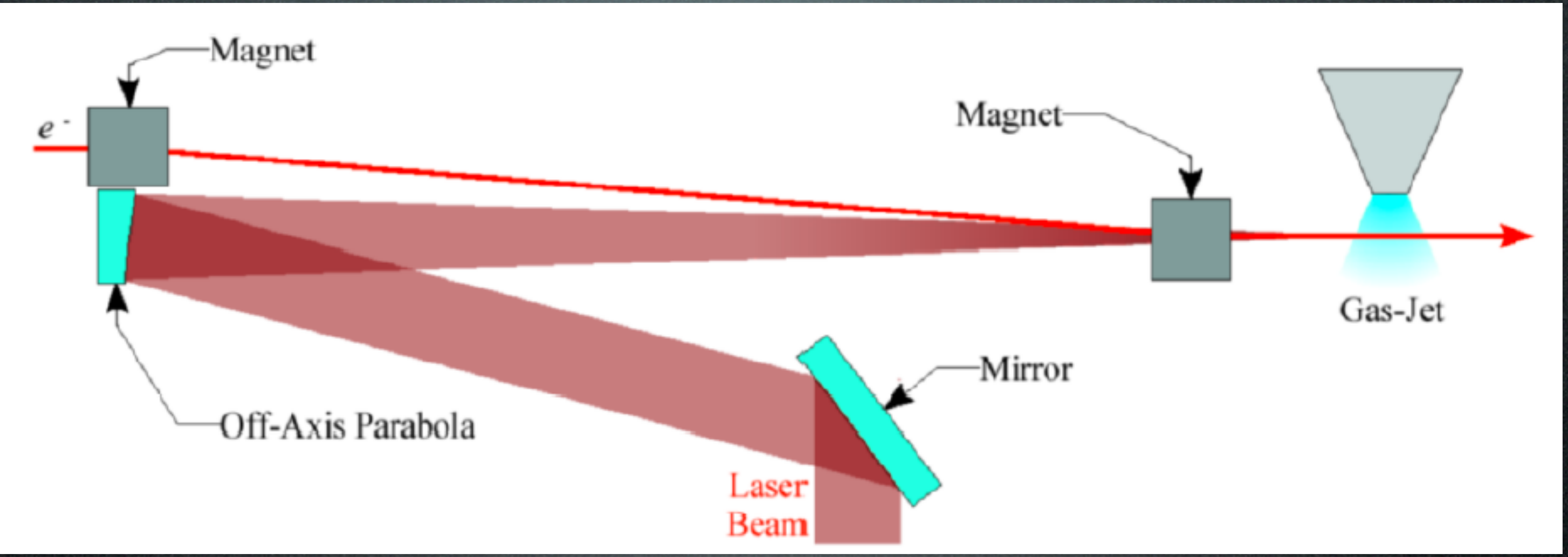
FIG. 6 (color online). rms envelope and rms norm. emittance evolution from the cathode up to the beam line end as computed by PARMELA, compared to measurements taken in the emittance-meter range.

Particle Wake Field Acc.

New installations



EXIN (EXternal INjection)



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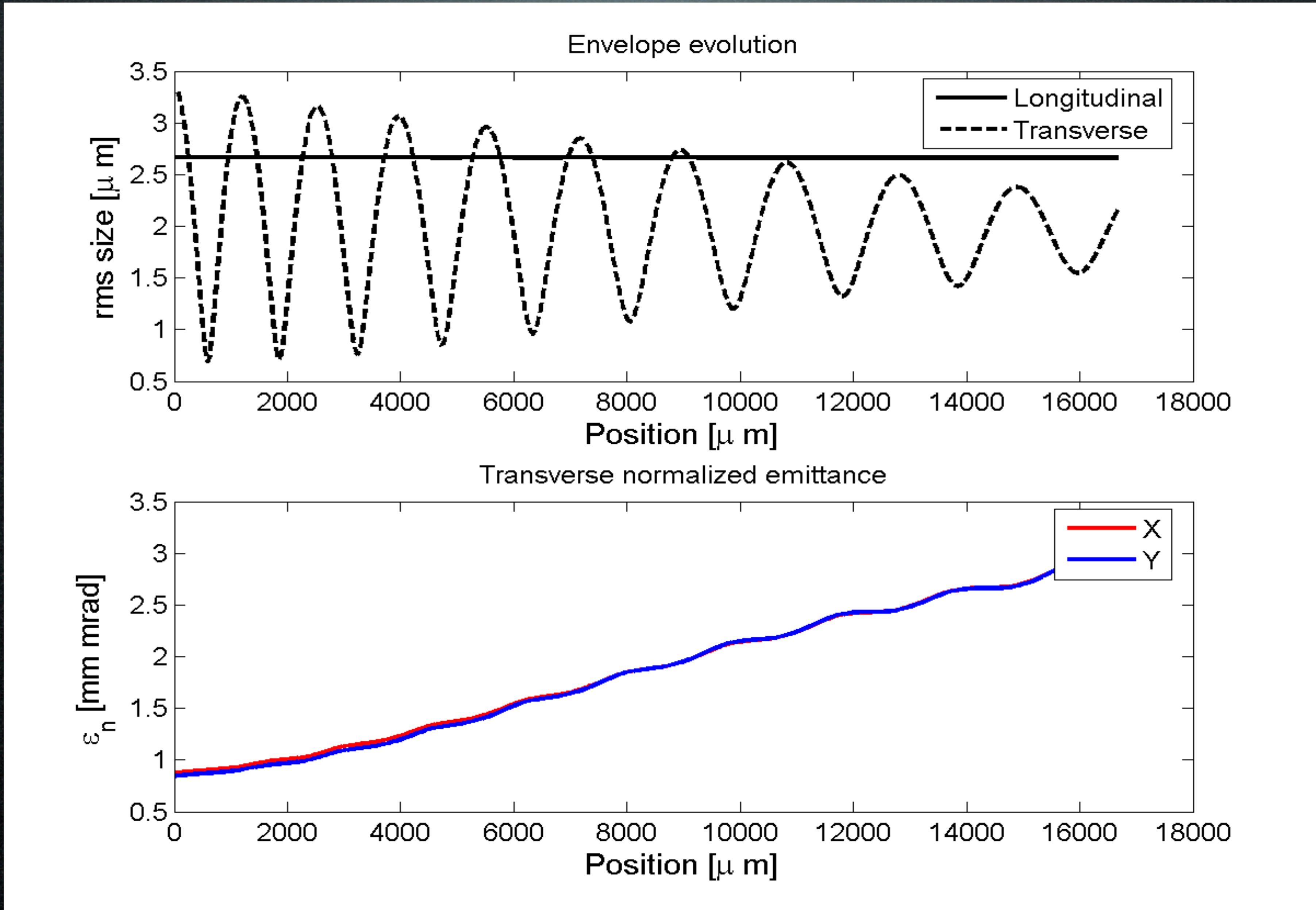
Courtesy L. Serafini



Courtesy P. Tomassini

When $\eta = \frac{4\gamma k_p^2}{3\gamma'^2} >> 1$ $\rho = \frac{k_{sc}^0 \sigma_x^2}{\gamma_o \varepsilon_n^2} << 1$

$$\gamma'' = 0$$
$$\gamma' \neq 0$$

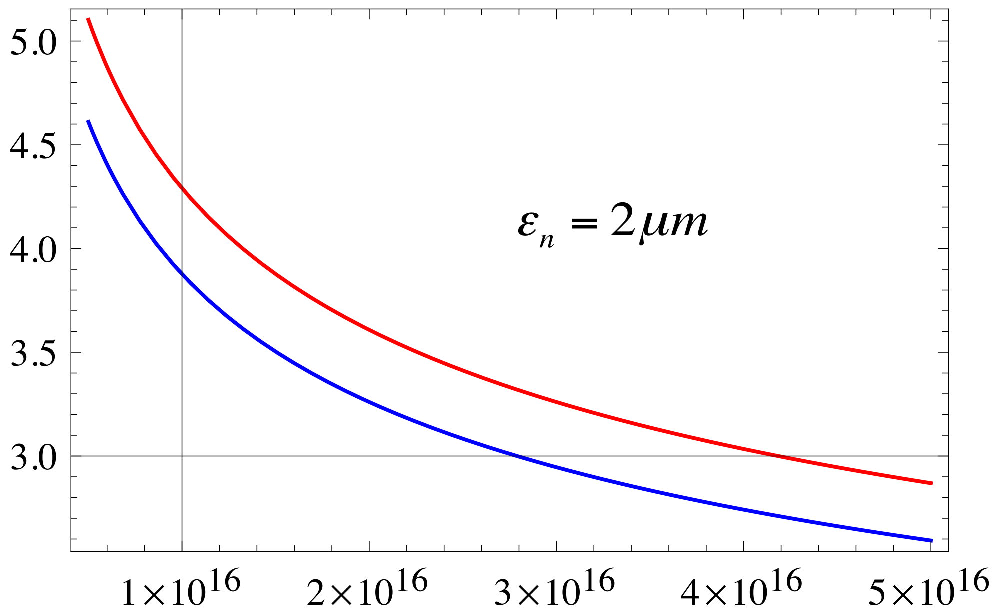
$$\sigma_x'' + \frac{k_p^2}{3\gamma}\sigma_x = \frac{\varepsilon_n^2}{\gamma^2 \sigma_x^3}$$

Looking for an equilibrium solution of the form: $\sigma_\varepsilon = \gamma^n \sigma_o$

We get the matching condition with acceleration:

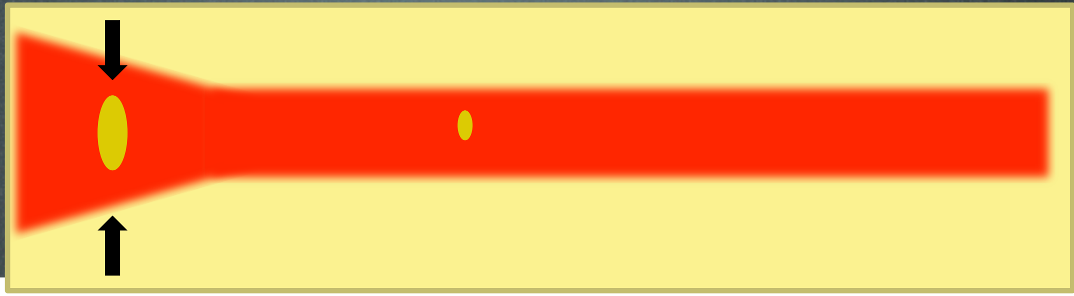
$$\sigma_\varepsilon = \sqrt[4]{\frac{3}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_p}}$$

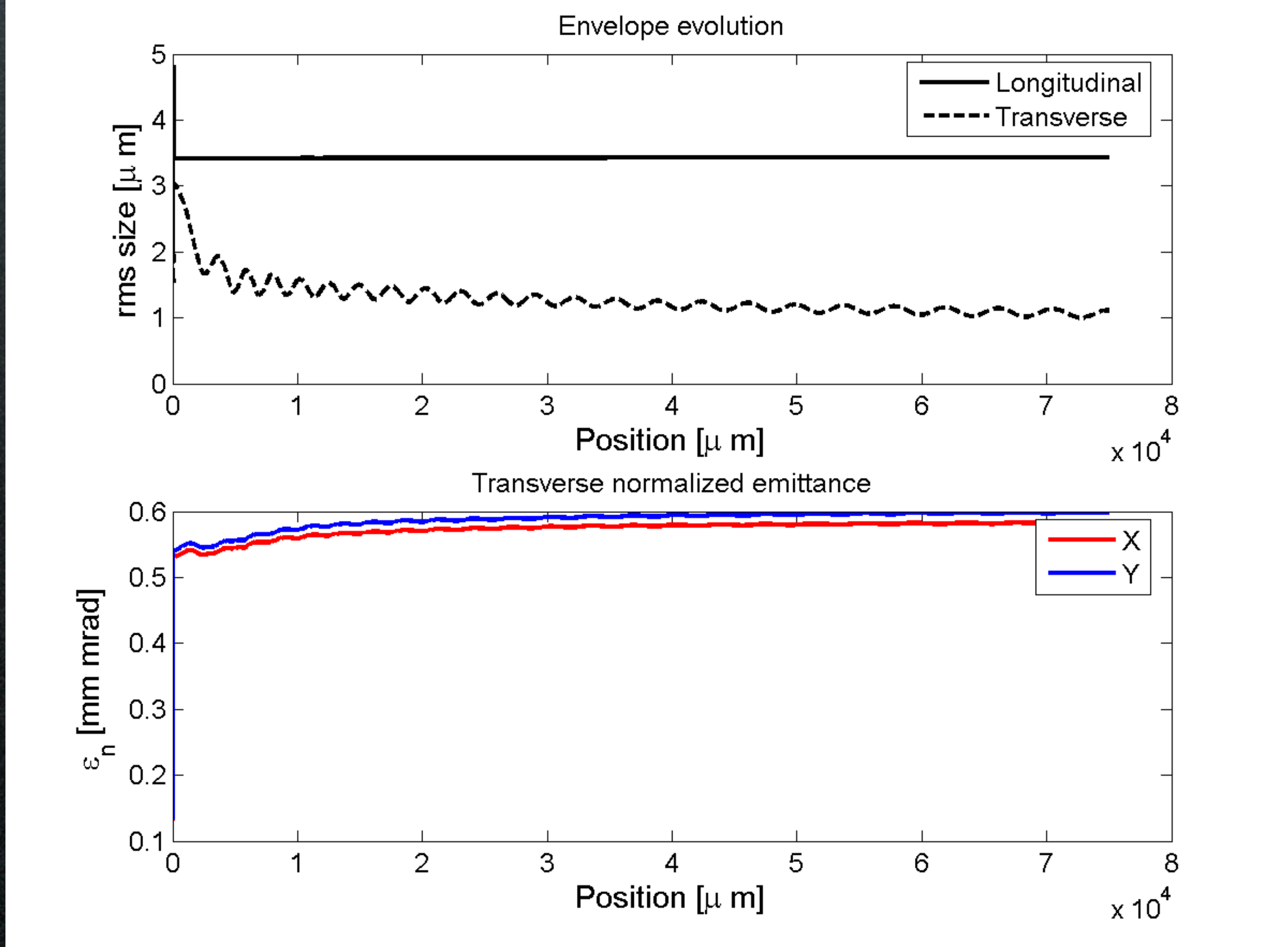
sigma_r [um]



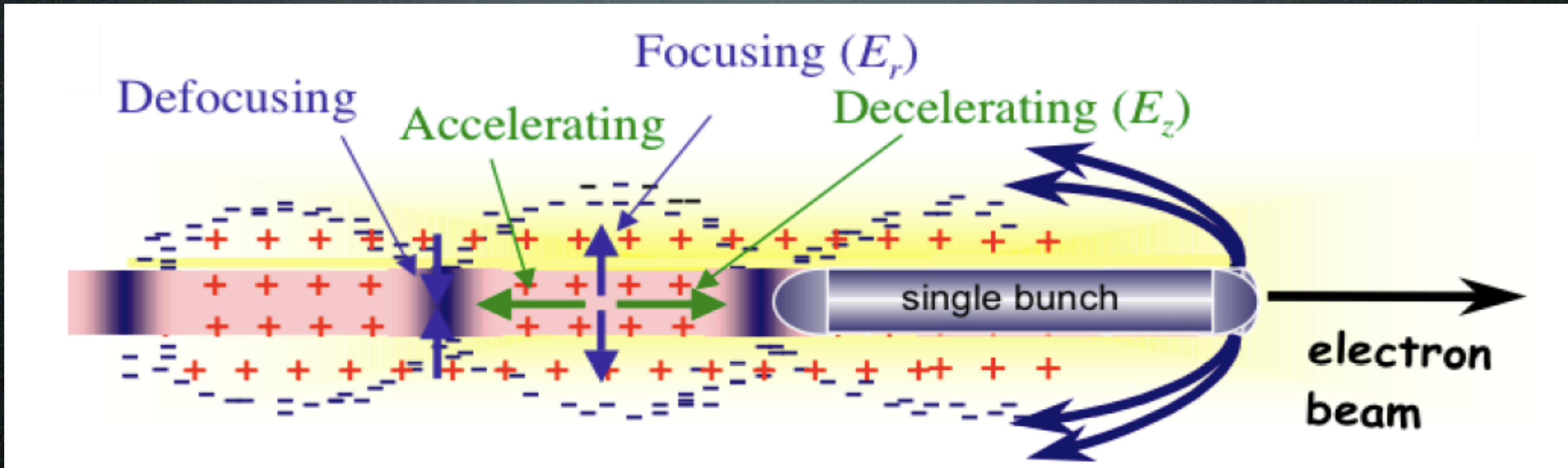
n [cm−3]

$$\sigma_{\varepsilon} = \sqrt[4]{\frac{3}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_p}}$$



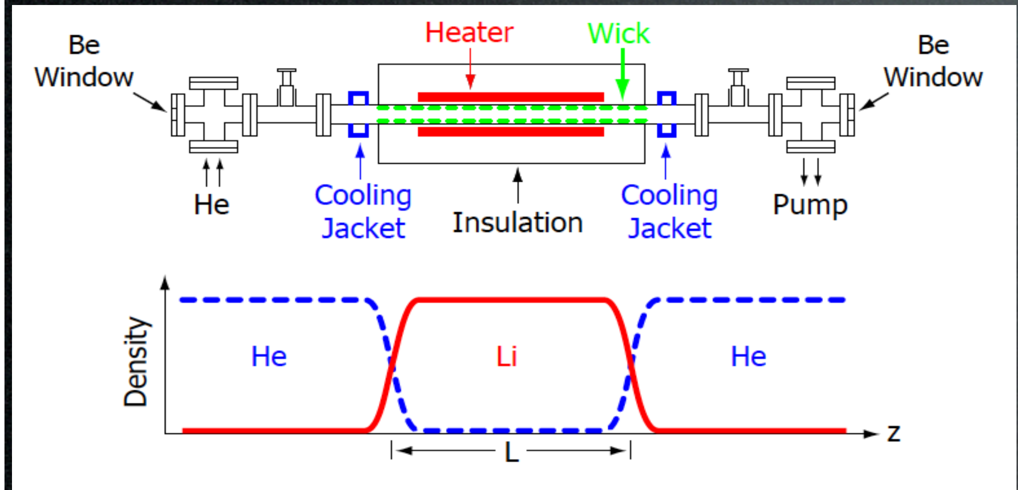


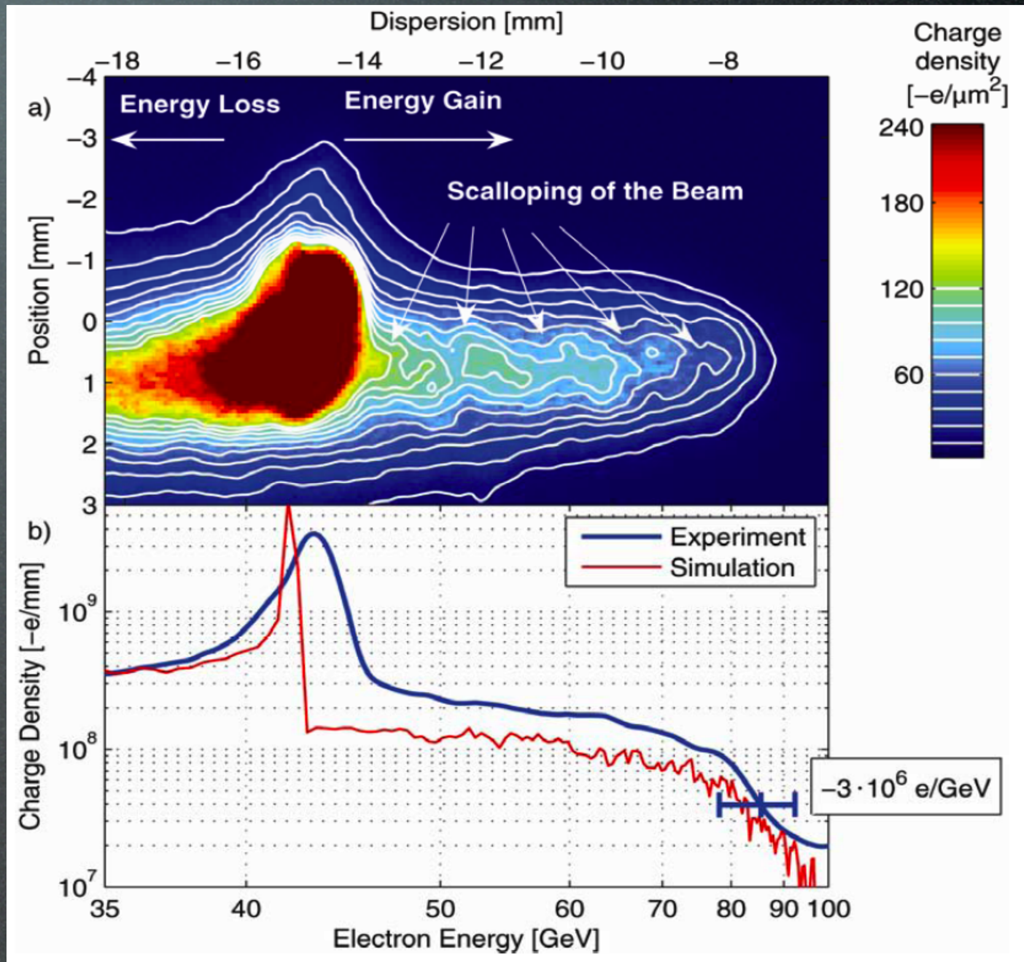
Using a high charge driving bunch to accelerate a low charge witness bunch



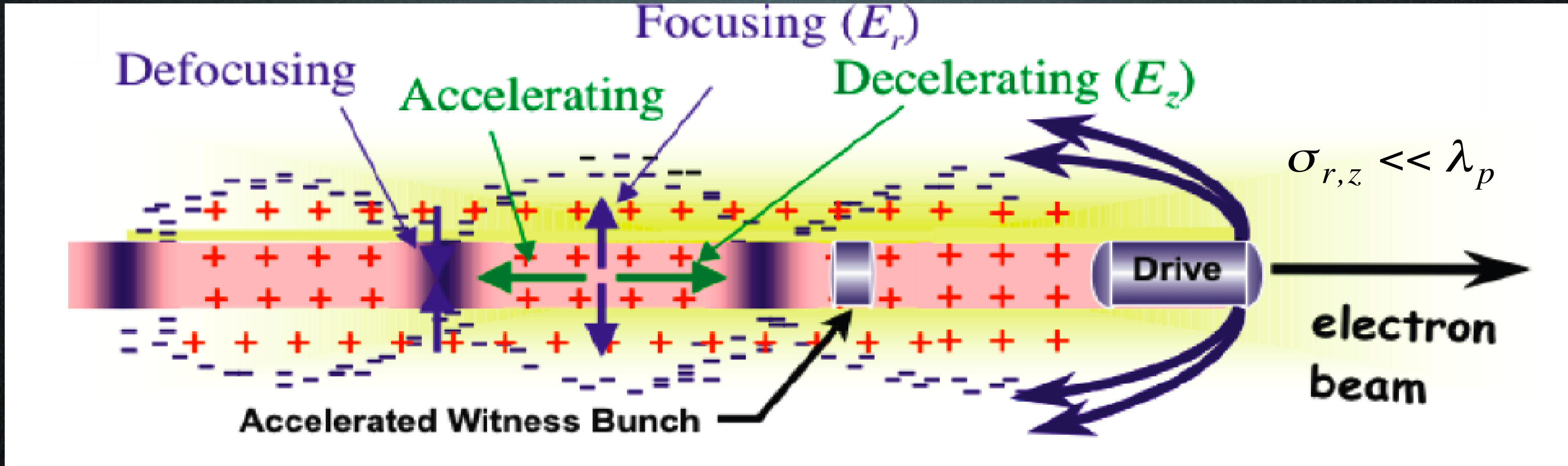
Ultra high gradient (40 GV/m) experiment at SLAC

Parameter/symbol/unit	Long bunch
Beam	e^- and e^+
Energy E_0 (GeV)	28.5
Beam relativistic factor γ_0	55,773
Bunch length σ_z (μm)	730
Bunch radius $\sigma_{x,y}$ (μm)	30, 30
Bunch population N_b	$1.8 \times 10^{10} e^-$, $1.2 \times 10^{10} e^+$
Beam density n_b (cm^{-3})	1.8×10^{15}, 1.2×10^{15}
Normalized emittance[a] $\epsilon_{Nx,y}$ (m-rad)	$50, 5 \times 10^{-6}$
Lithium plasma	Photo-ionized
Density range n_e (cm^{-3})	10^{12}–5×10^{14}
Length L_p (cm)	140





Plasma Wake Field Acceleration with external injection



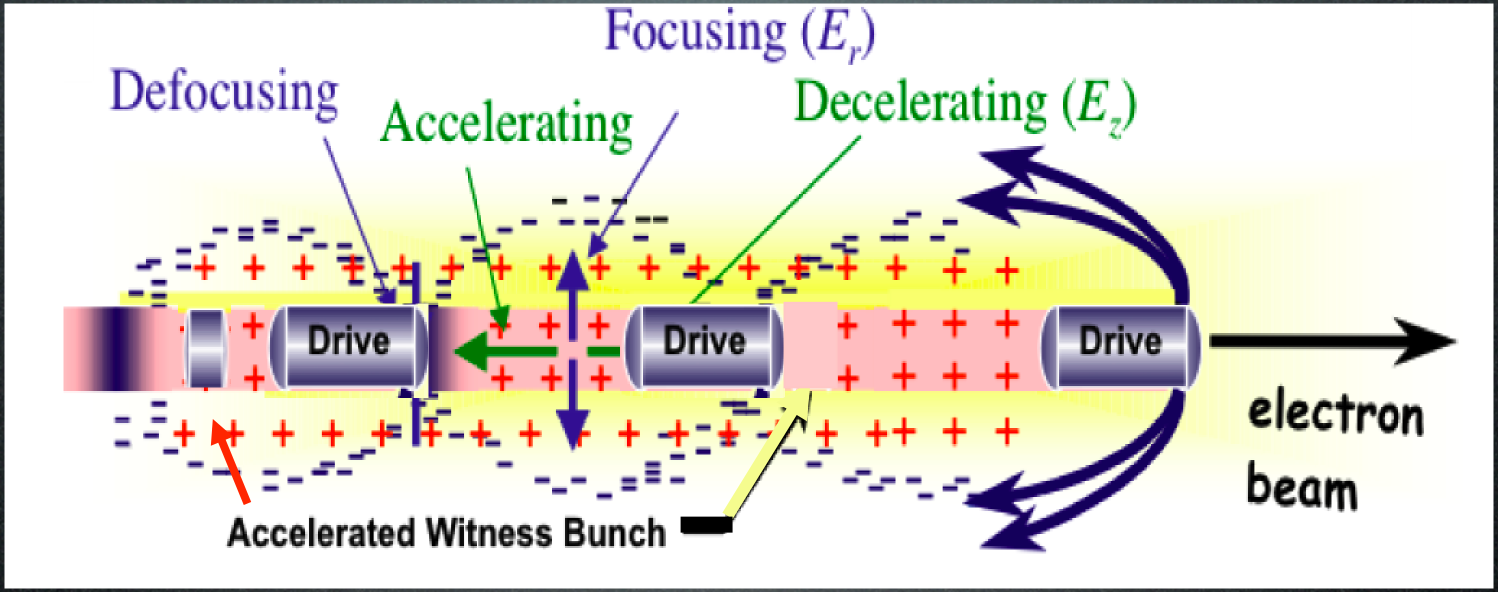
Accelearting field

$$E_{acc}[MV/m] = 27.5 \frac{Q[pC]}{(\sigma_z[\mu m])^2}$$

Plasma frequency

$$\omega_p^2 = \frac{n\, e^2}{\epsilon_0\, m}$$

Resonant plasma excitation by a Train of Bunches



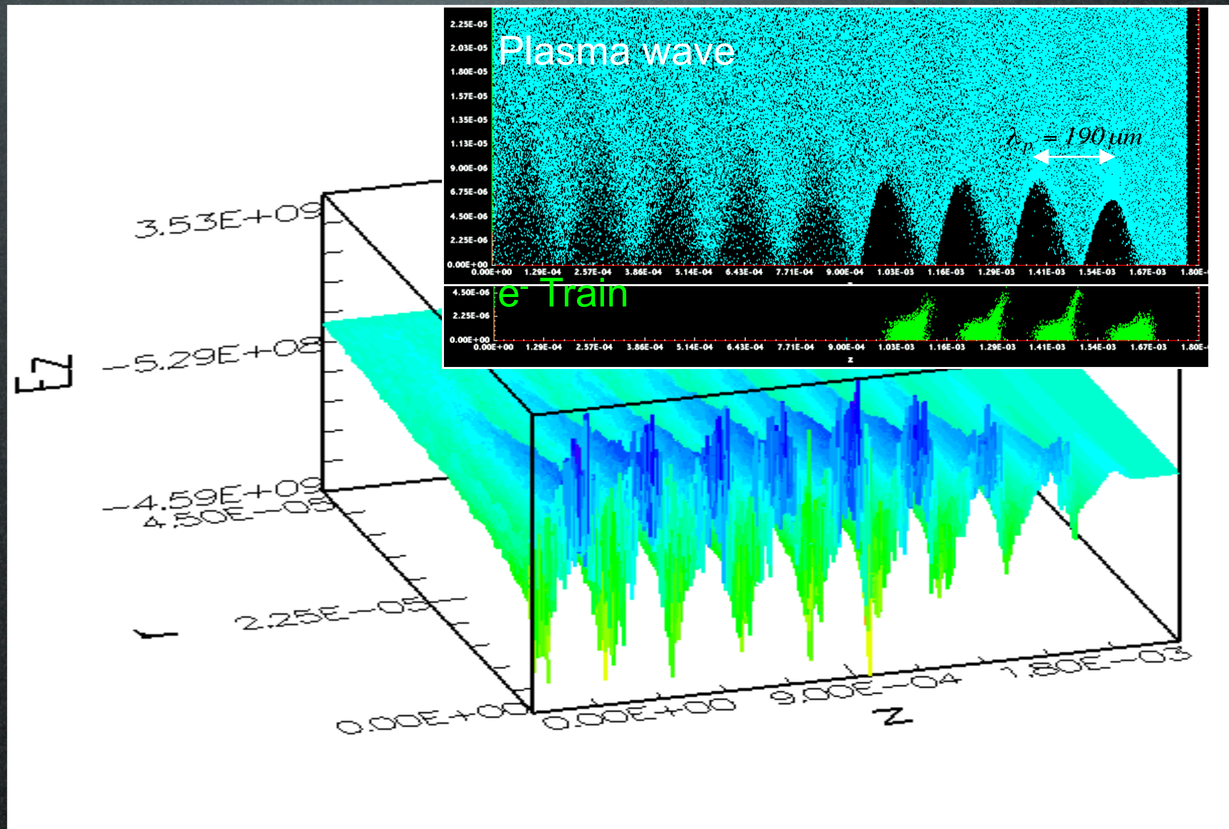
- **Weak blowout regime** with resonant amplification of plasma wave by a train of high Brightness electron bunches produced by **Laser Comb** technique?
- **Ramped bunch train configuration** to enhance tranformer ratio?
- **High quality bunch** preservation during acceleration and transport?

Weak Blowout Regime: operation in the quasi-nonlinear regime, where one uses beam with relatively low charge and longitudinal and transverse beam size smaller than a plasma wavelength

$$\sigma_z, \sigma_r << \lambda_p$$

In this case, the beam density may exceed that of the plasma, producing blowout, but due to the small total charge, producing a disturbance that behaves in many ways as linear, having frequency essentially that of linear plasma oscillations.

N_b=4
Q=16 pC
N_e=10^8
n_e=3 10^{22} m^{-3}
λ_p=190 μm
==> 3 GV/m



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
13, 052803 (2010)

Simple method for generating adjustable trains of picosecond electron bunches

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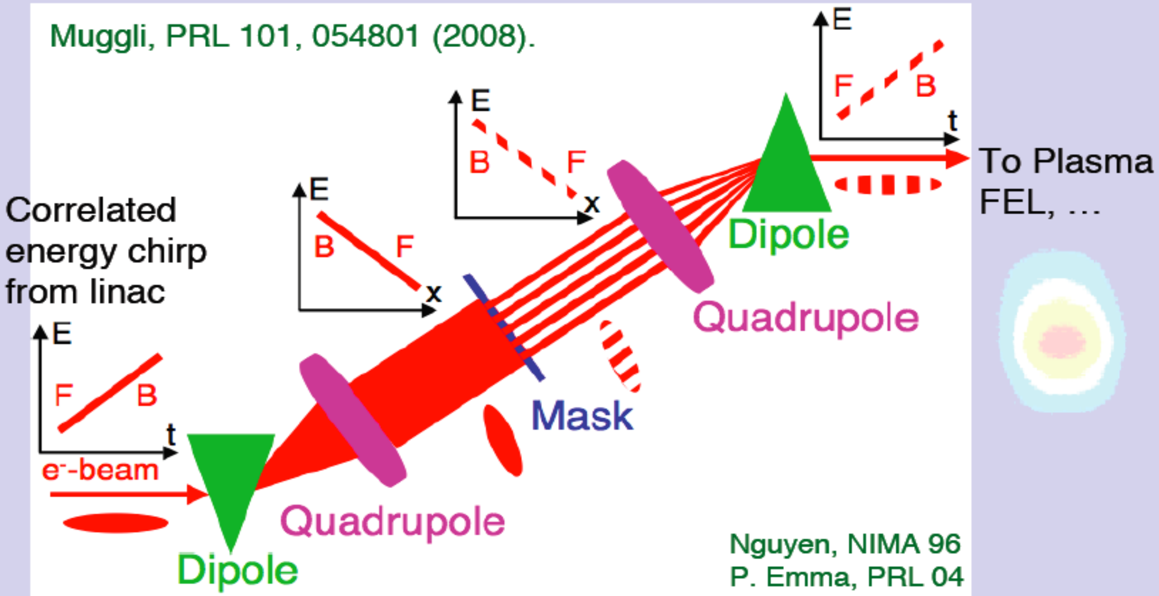
Brookhaven National Laboratory, Upton, Long Island, New York 11973, USA

W. D. Kimura

USC

MULTIBUNCH GENERATION

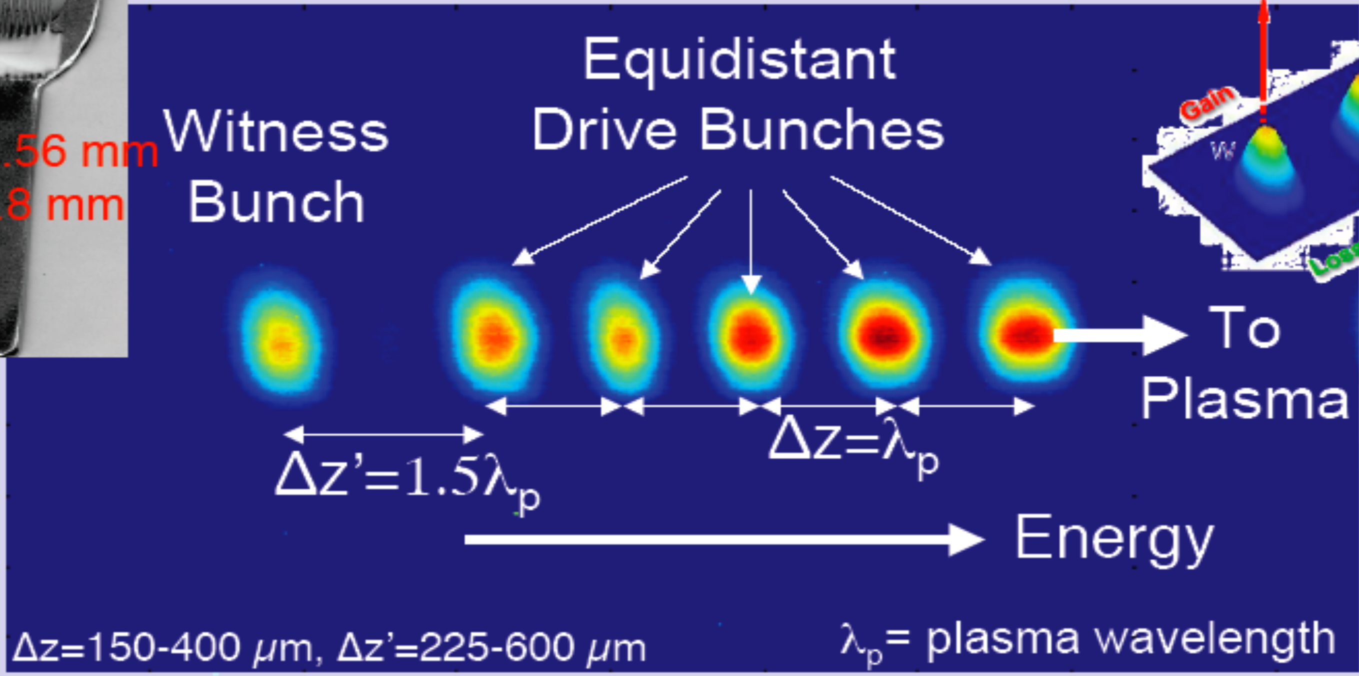
BROOKHAVEN NATIONAL LABORATORY

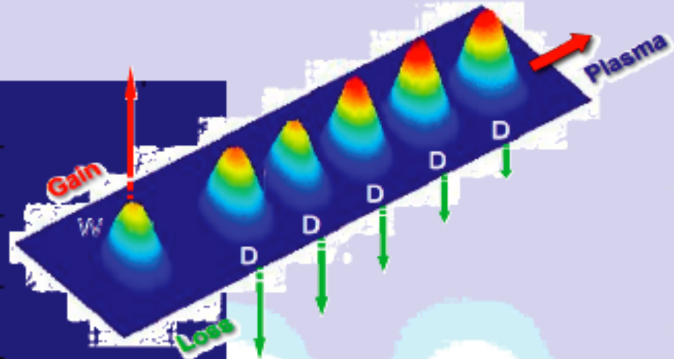


➡ Choose microbunches spacing and widths with mask and beam parameters: N, Δz, σ_z, Q

TRAIN FOR PWFA

Mask with non-equidistant "wires"
Measurement in energy plane





WARNING:
NOT simulations!
Experimental Data!

- Generate "ideal" train for resonant PWFA
- Select number of drive bunches (high energy slit): Choose 3D+1W
- Typical bunch separation: $\Delta z \approx 300\text{-}400\ \mu m$
- Expected plasma resonance: $\lambda_{pe}(n_e)=\Delta z$, $n_e \approx 1.2\text{-}0.7 \times 10^{16}\ cm^{-3}$

Laser Comb technique

Laser Comb: beam echo generation of a train bunches

M. Boscolo et al. / Nuclear Instruments and Methods in Physics Research A 593 (2008) 106–110 107

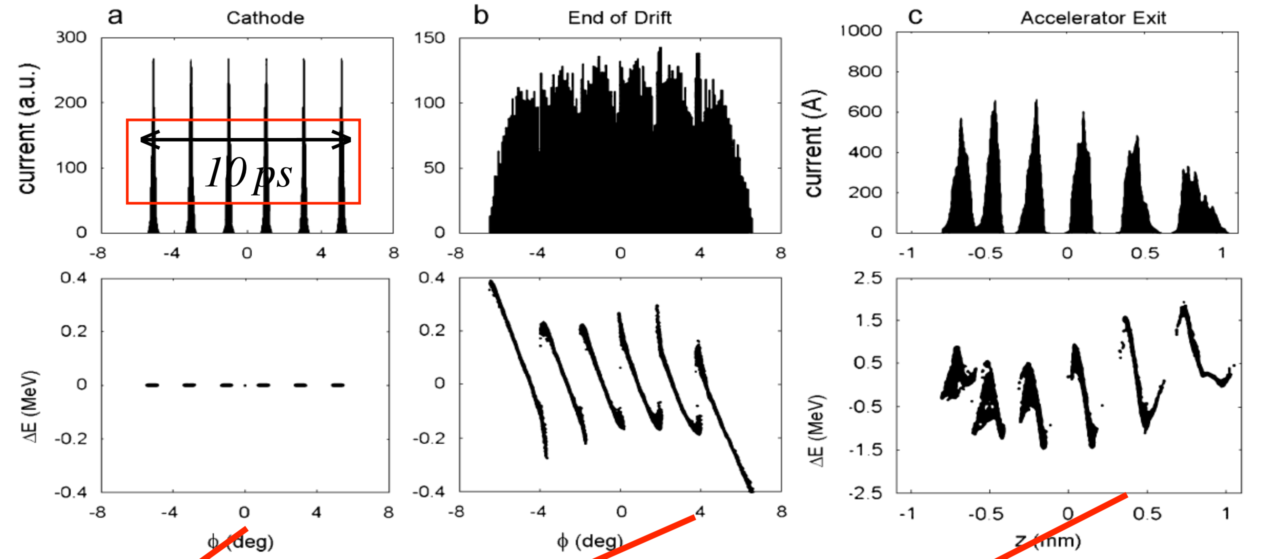
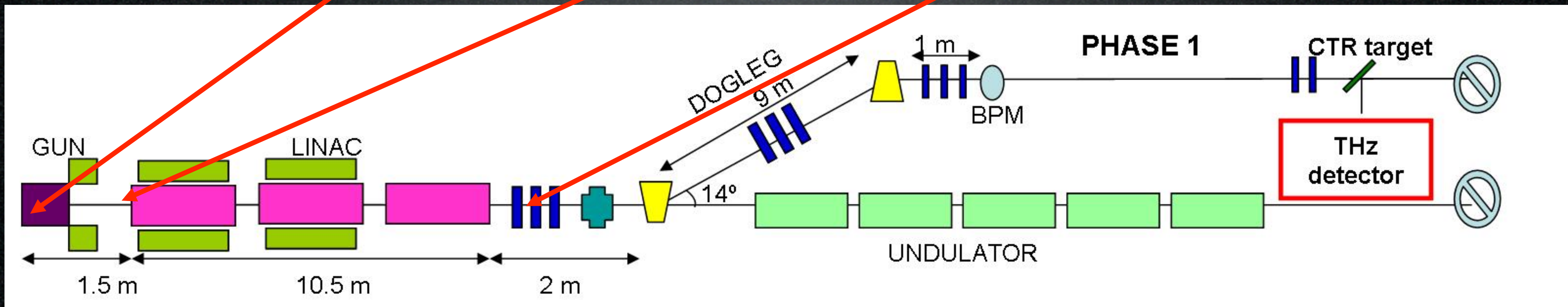
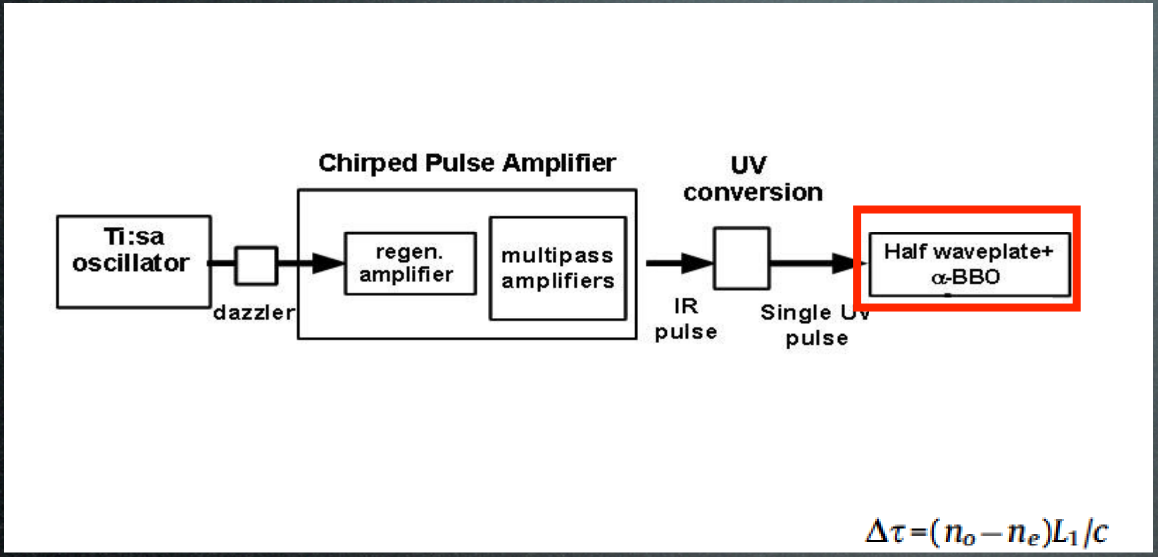


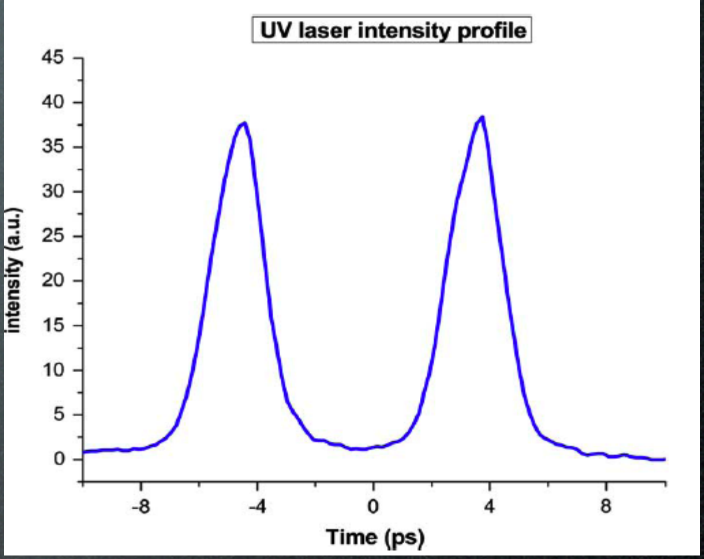
Fig. 1. Evolution of a six bunches electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation ΔE (MeV).



- P.O.Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
- M. Ferrario. M. Boscolo et al., Int. J. of Mod. Phys. B, 2006 (Taipei 05 Workshop)

A train of laser pulses at the cathode

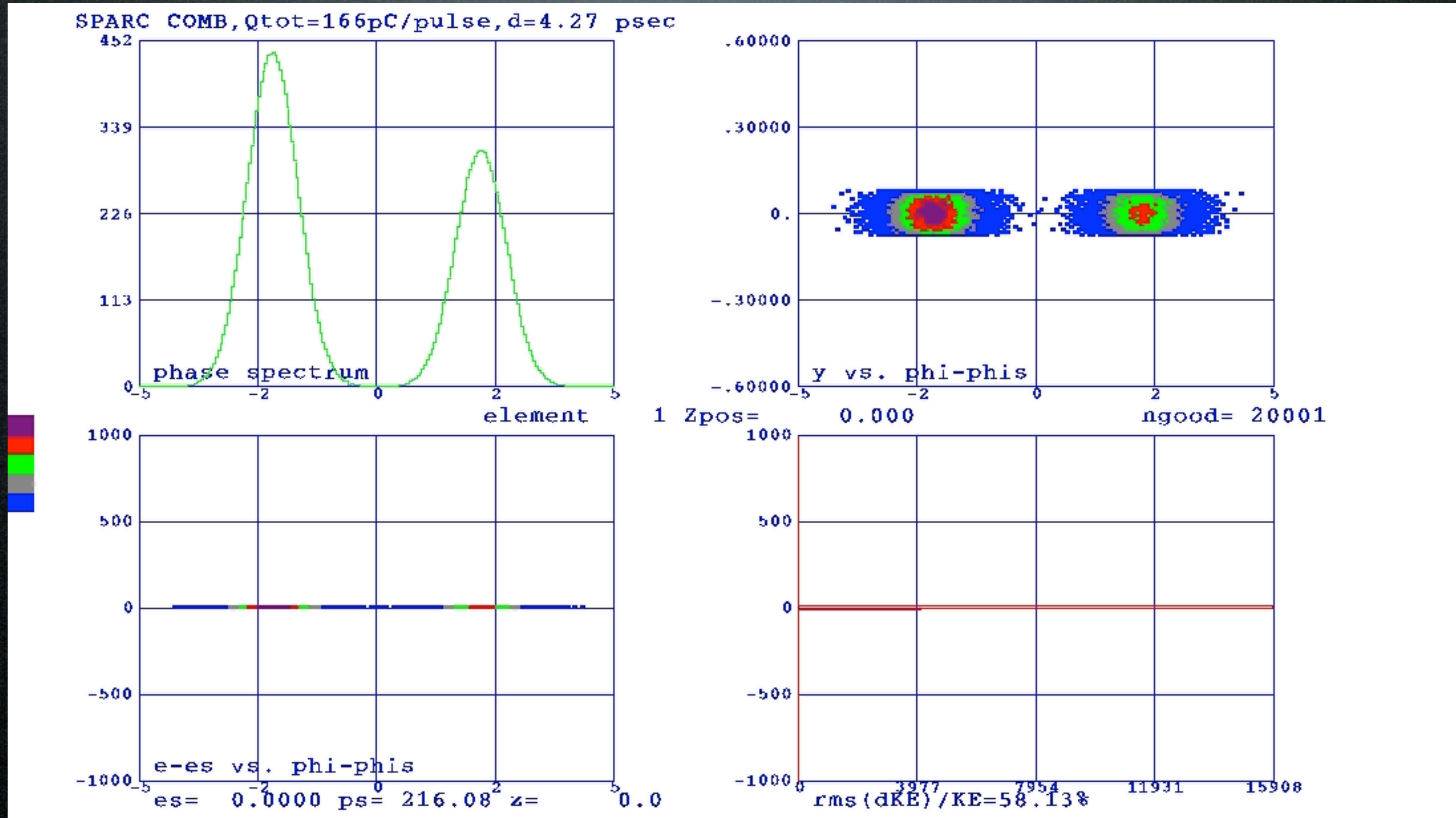




The technique used for this purpose relies on a birefringent crystal, where the input pulse is decomposed in two orthogonally polarized pulses with a time separation proportional to the crystal length.

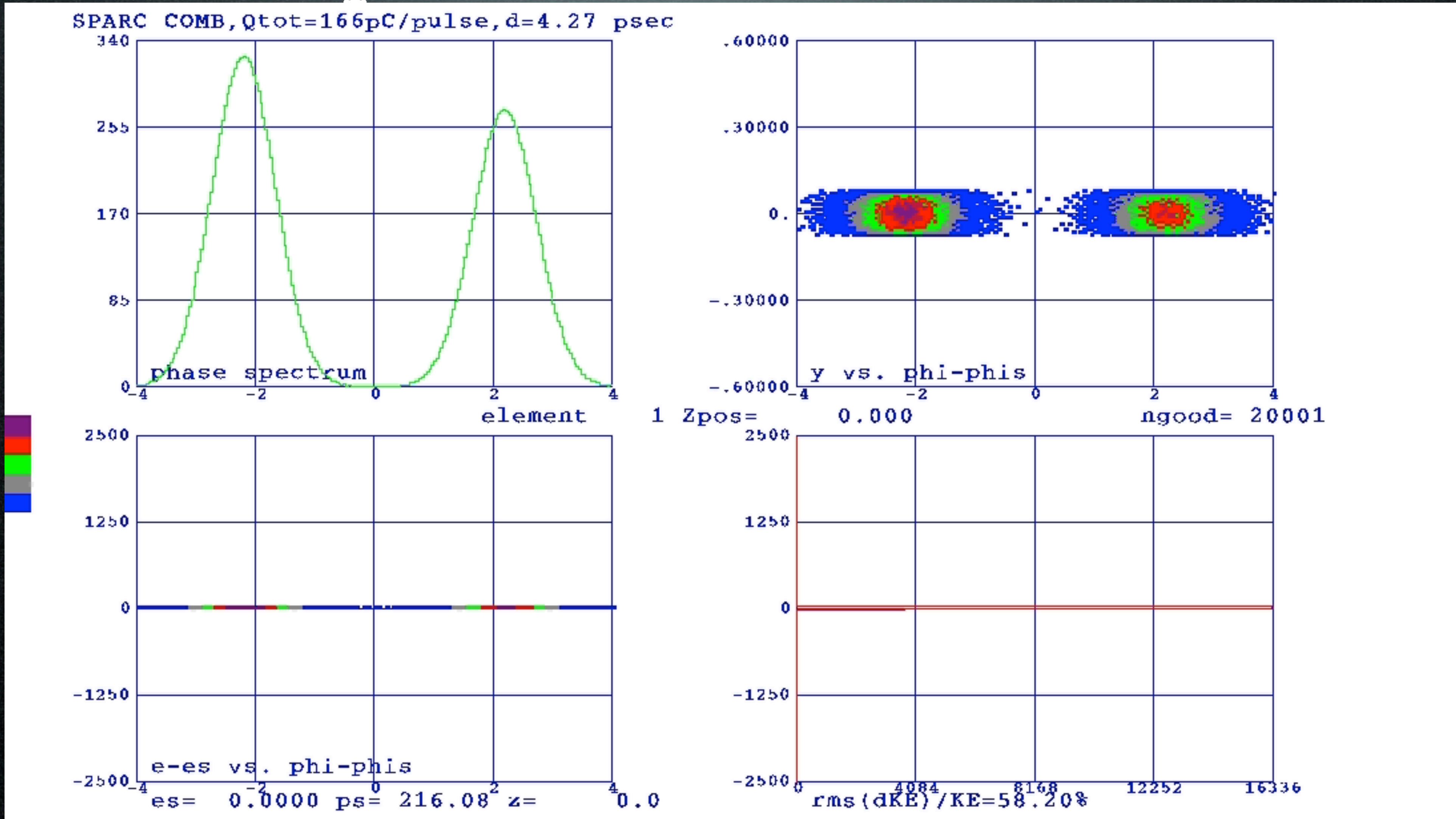
Different crystal thickness are available (10.353 mm in this case).
Using more than one crystals, one can generate bunch trains (e.g. 4 bunches).
The intensity along the pulse train can be modulated

On Crest

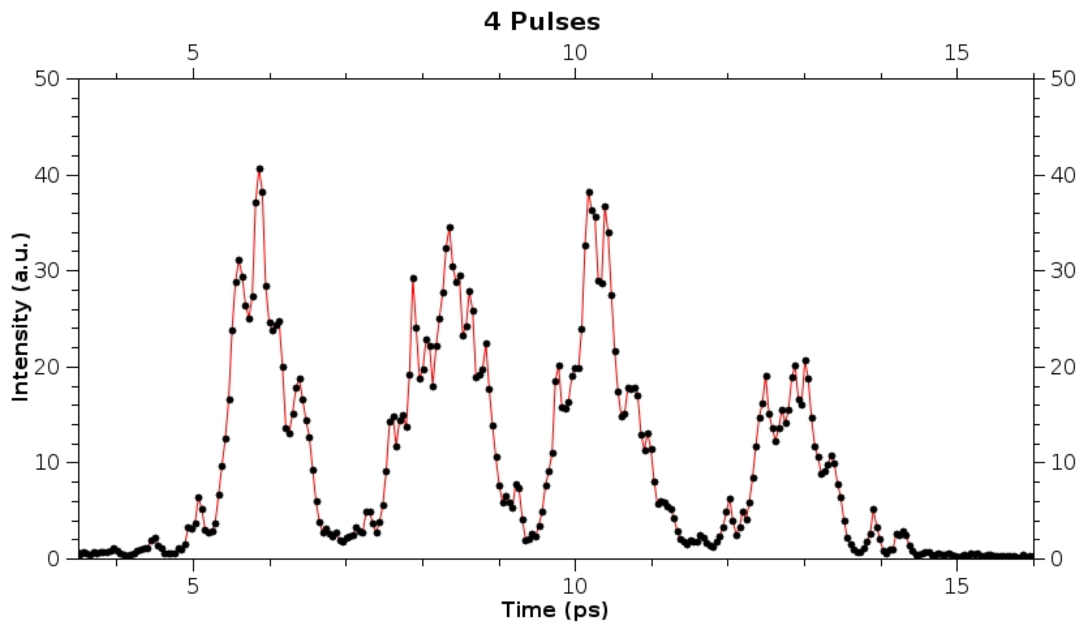


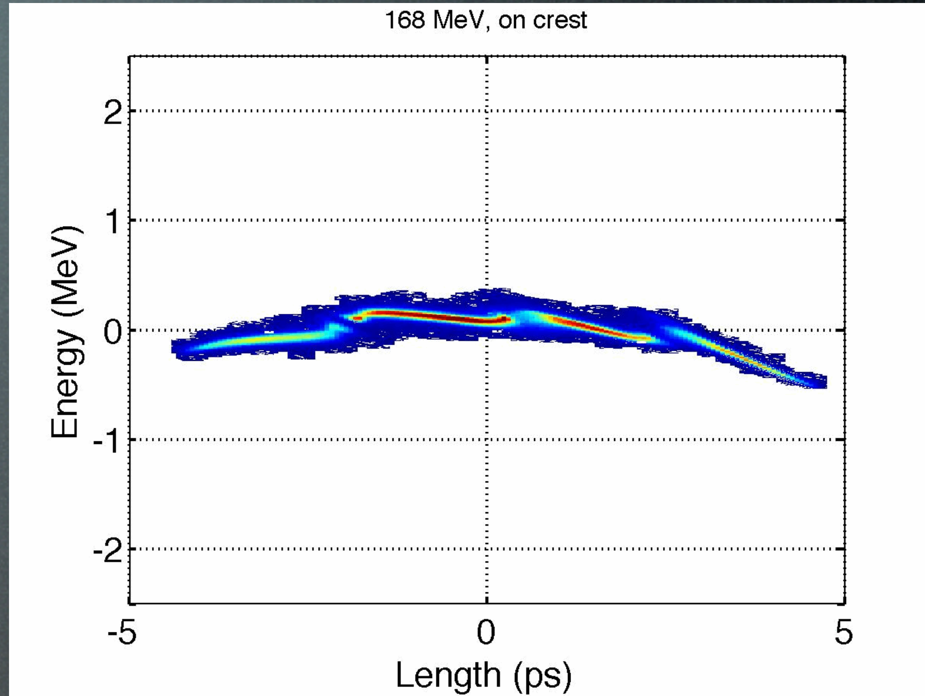
c. ronsivalle & a. mostacci

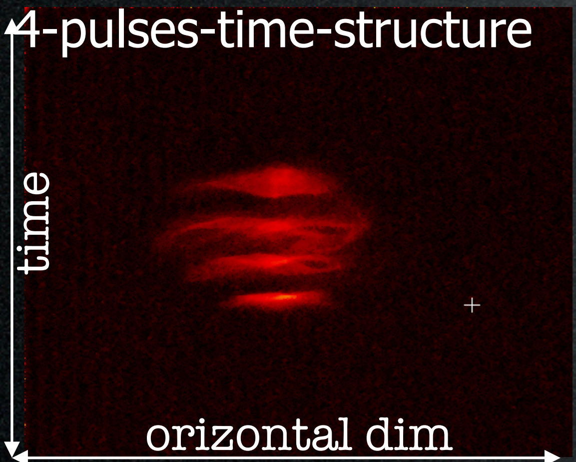
Overcompression

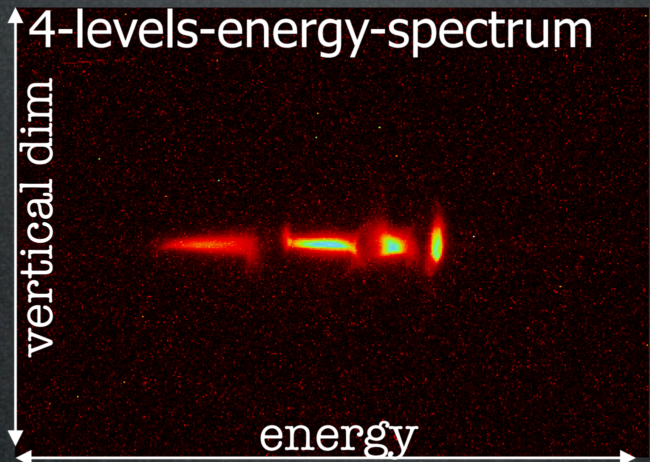


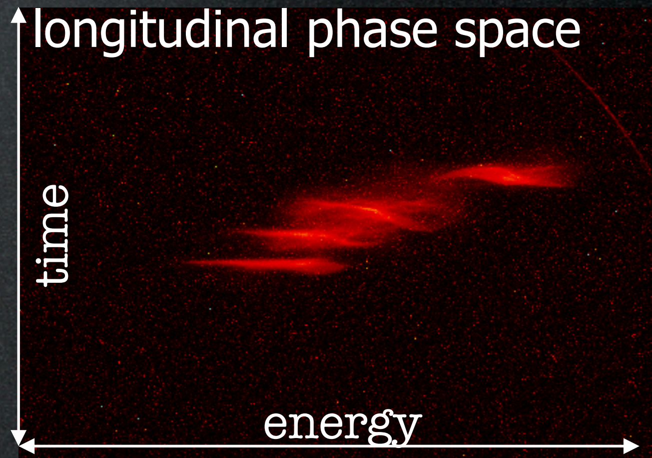
Laser COMB technique



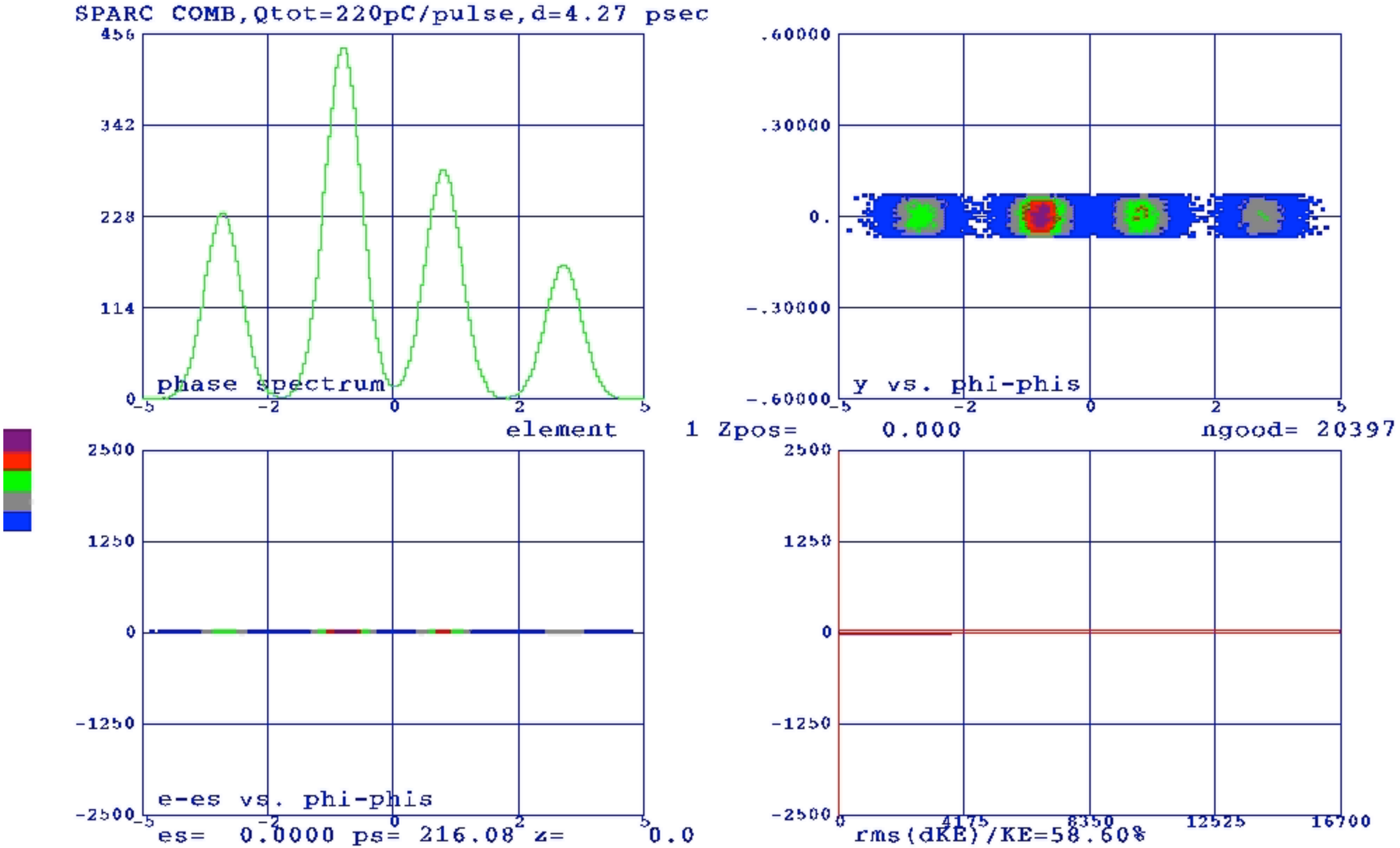








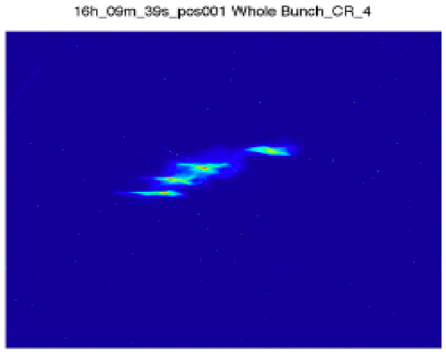
Overcompression

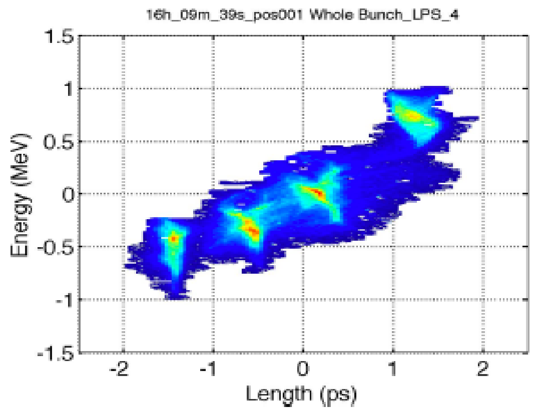


2011/06/03 - 200 pC - Overcompression

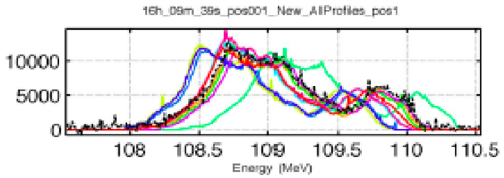
Total projected emittance: 5.68 μm (4.09 μm)

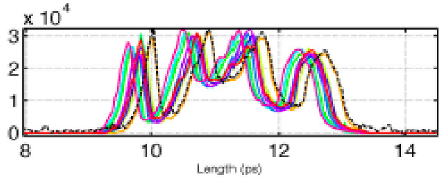
	Energy (MeV)	En. Spread(%)	Length (ps)	Charge(%)
I	108.555(0.045)	0.158(0.002)	0.141(0.002)	14.48(0.19)
II	108.756(0.050)	0.177(0.002)	0.202(0.004)	25.45(0.42)
III	108.998(0.051)	0.191(0.002)	0.278(0.005)	35.80(0.37)
IV	109.609(0.051)	0.235(0.003)	0.230(0.005)	25.95(0.41)
Whole	109.033(0.048)	0.393(0.003)	0.937(0.002)	100.00(0.93)

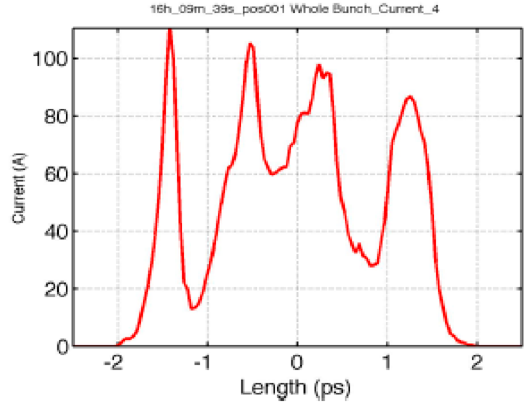




EnergySeparation I-II(MeV)	-0.2007 (0.07)
TimeSeparation I-II(ps)	-0.8326 (0.05)
EnergySeparation II-III(MeV)	-0.2425 (0.07)
TimeSeparation II-III(ps)	-0.8231 (0.05)
EnergySeparation III-IV(MeV)	-0.6104 (0.07)
TimeSeparation III-IV(ps)	-1.0587 (0.05)
FirstBunchCharge(%)	14.48
SecondBunchCharge(%)	25.45
ThirdBunchCharge(%)	35.80
FourthBunchCharge(%)	25.95
ConsistencyCheck(%)	101.68

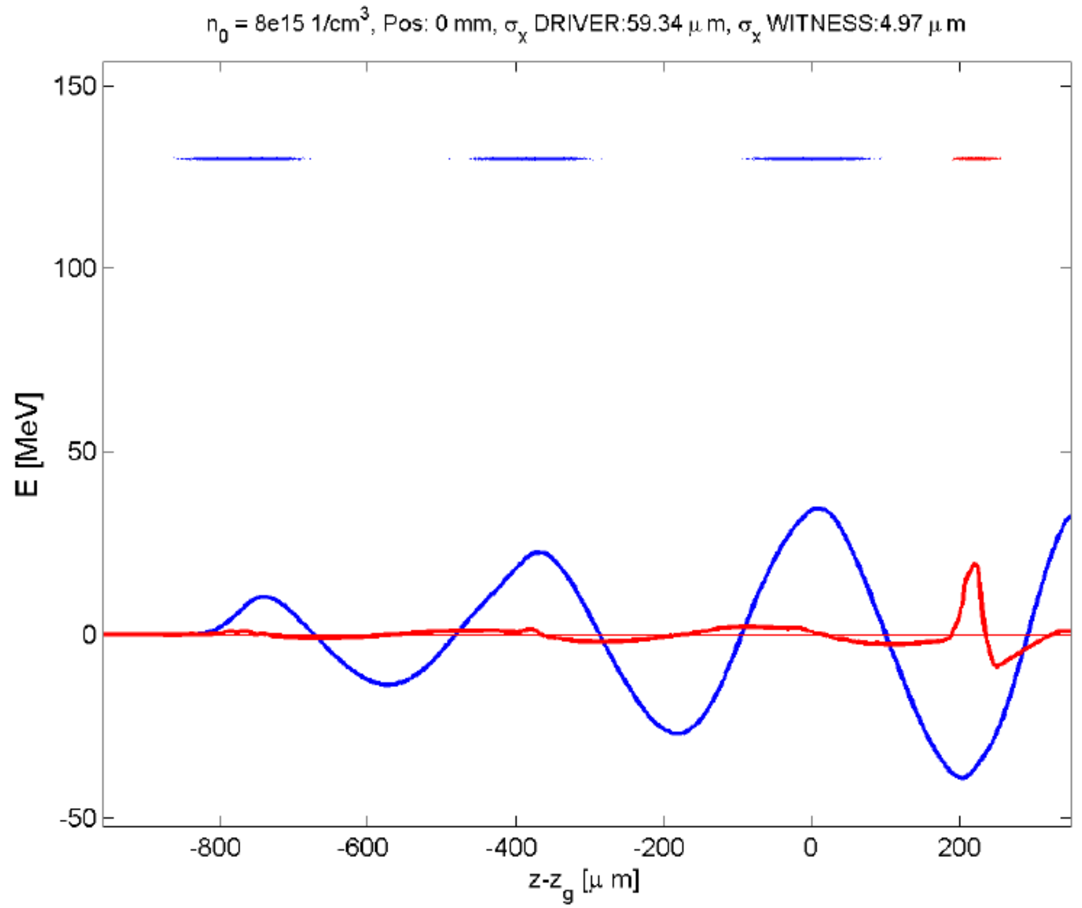


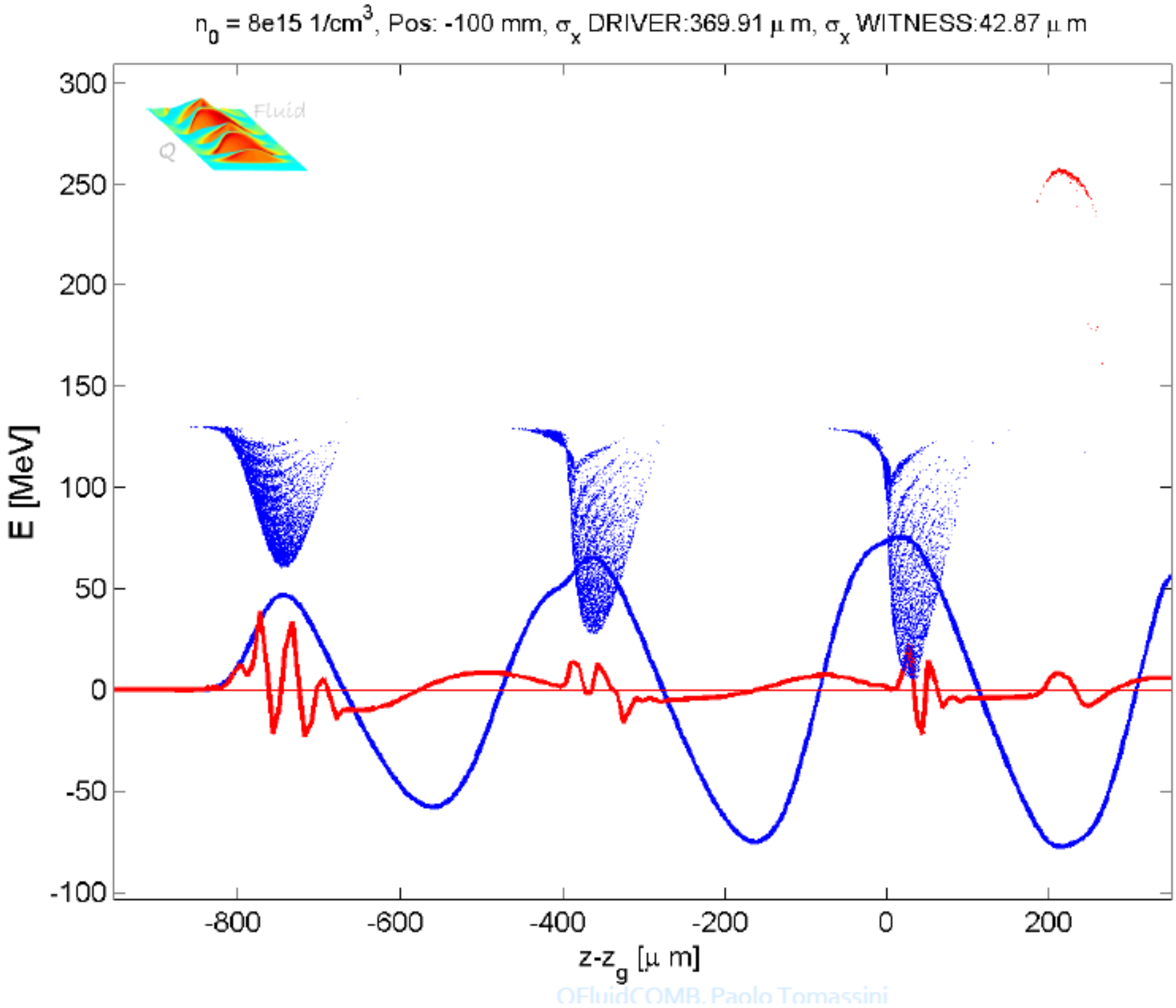




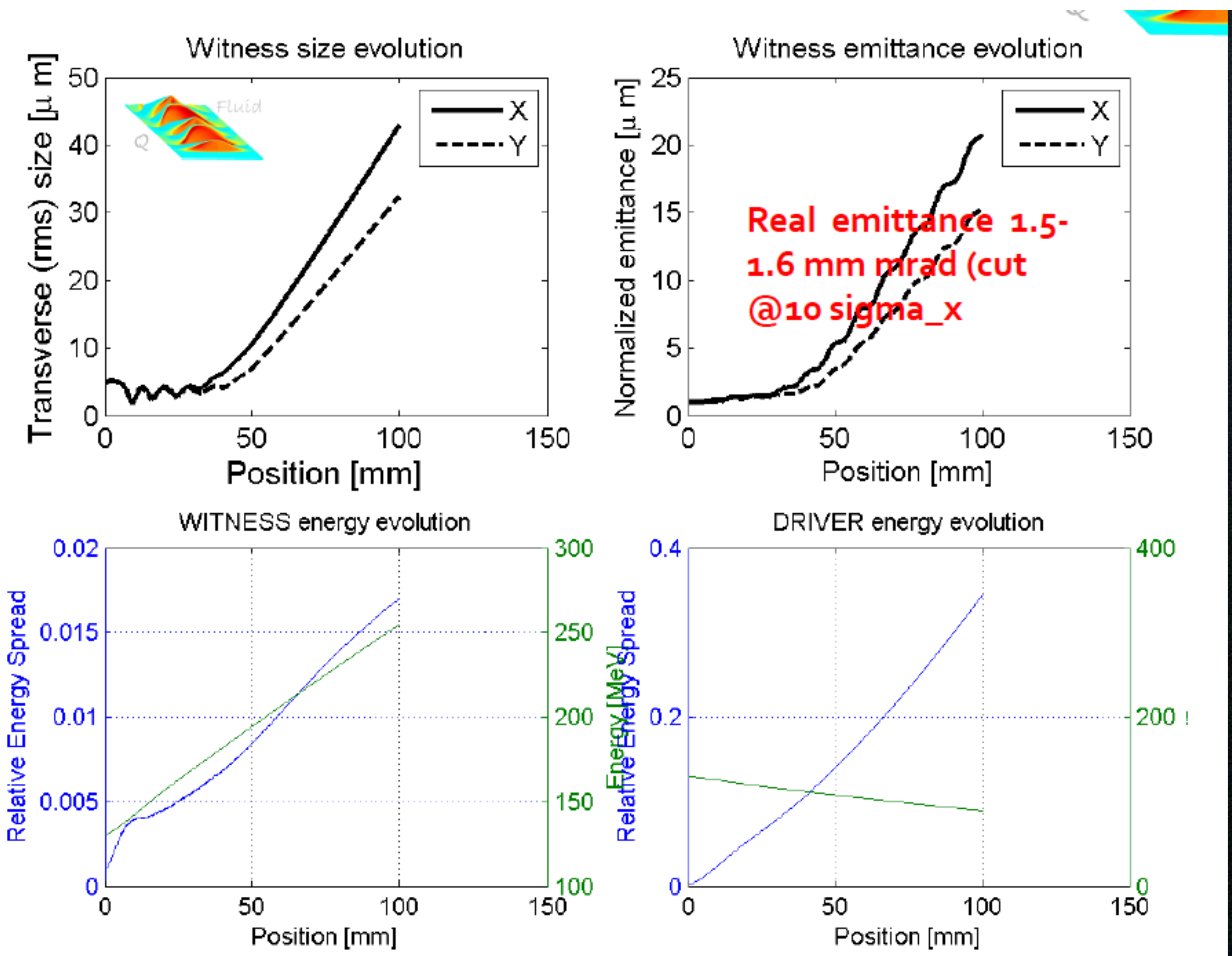
no=0.75e16 1/cm^3 Lambda_p=383 um,
Lacc=10cm Ez=1.2GV/m

	DRIVER (each, pC)	WITNESS
Charge (pC, each)	200	20
sigma_x (um)	**60**	**5**
Sigma_z (um)	25	10





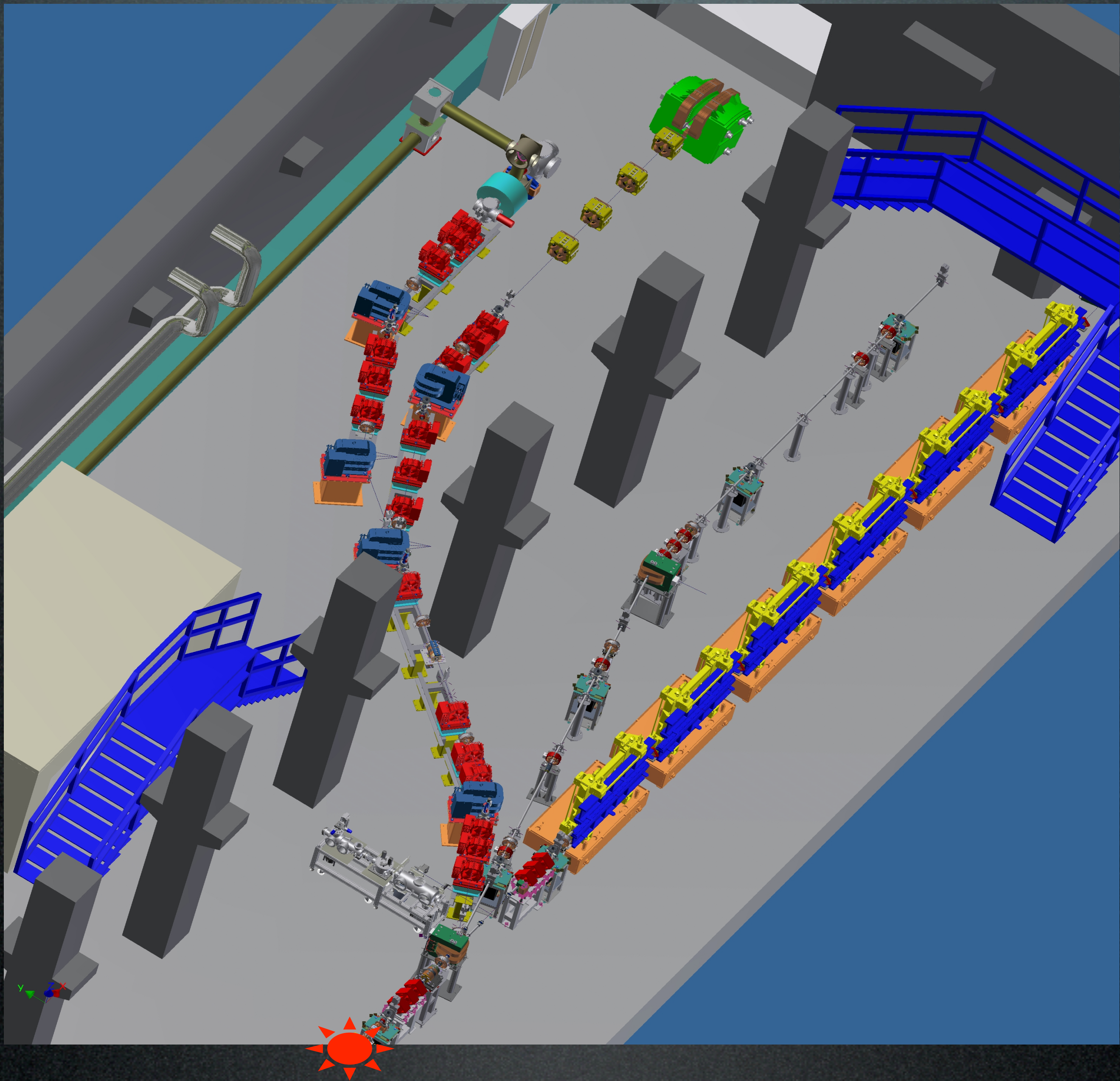
n_0 = 8e15 1/cm^3, Pos: -100 mm, σ_x DRIVER:369.91 μ m, σ_x WITNESS:42.87 μ m
Fluid
Q
E [MeV]
300
250
200
150
100
50
0
-50
-100
-800
-600
-400
-200
0
200
z-z_g [μ m]
QFluidCOMB, Paolo Tomassini



Witness size evolution
Transverse (rms) size [μ m]
Position [mm]
X
Y
Fluid
Q
Witness emittance evolution
Normalized emittance [μ m]
Position [mm]
X
Y
Real emittance 1.5-1.6 mm mrad (cut @10 sigma_x
WITNESS energy evolution
Relative Energy Spread
Position [mm]
DRIVER energy evolution
Relative Energy Spread
Energy [MeV]
Position [mm]

	DRIVER (each, pC)	WITNESS
energy (mean, MeV)	90	255
energy spread	35	0.9%
norm. emittance (um)	303	1.6
sigma_x (um)	370	3.5

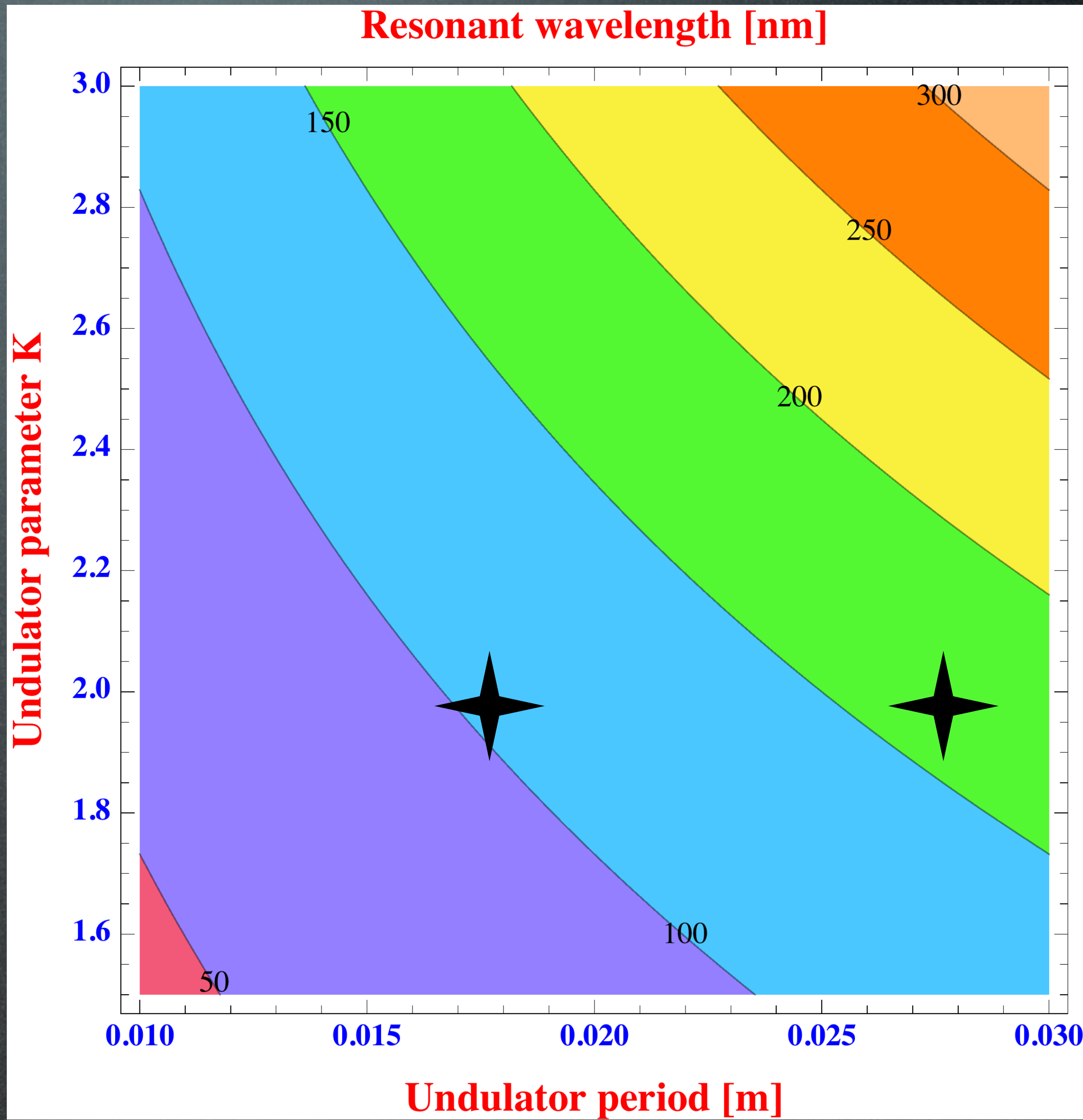
A FEL driven by Plasma Accelerator at SPARC_LAB?



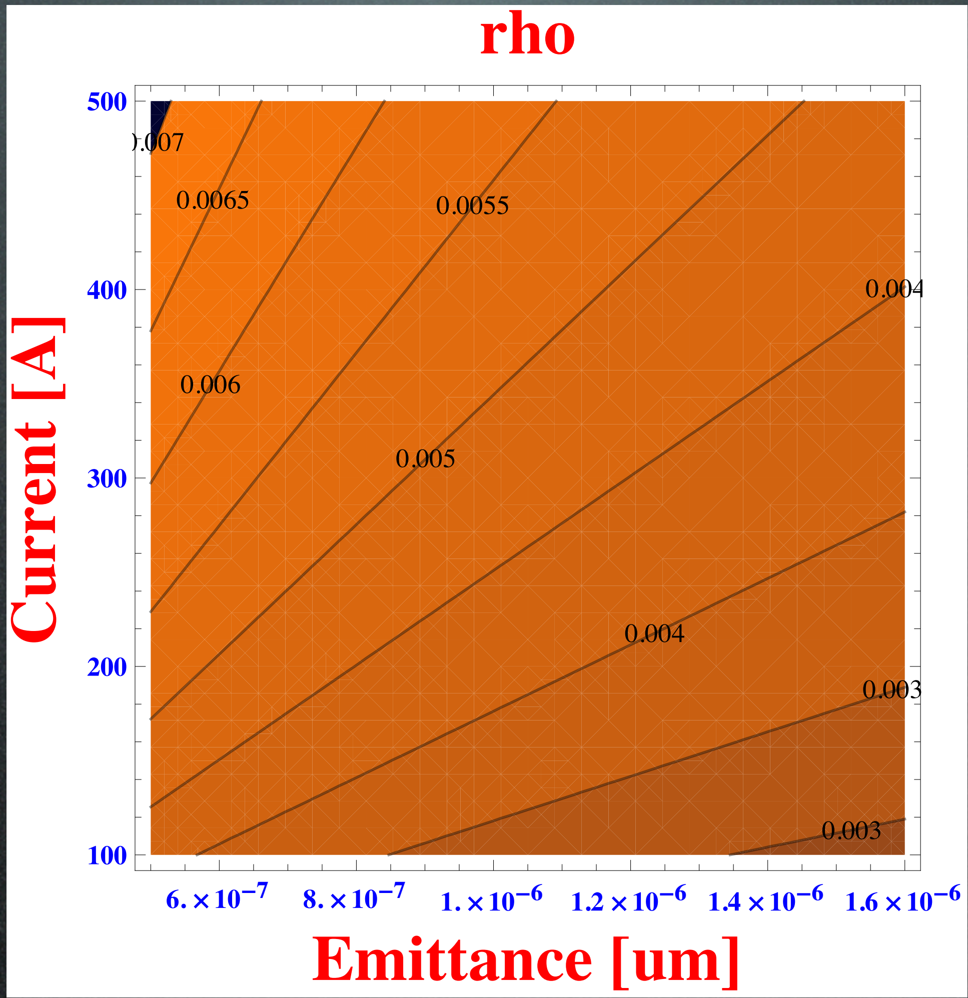
$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + a_u^2\right)$$

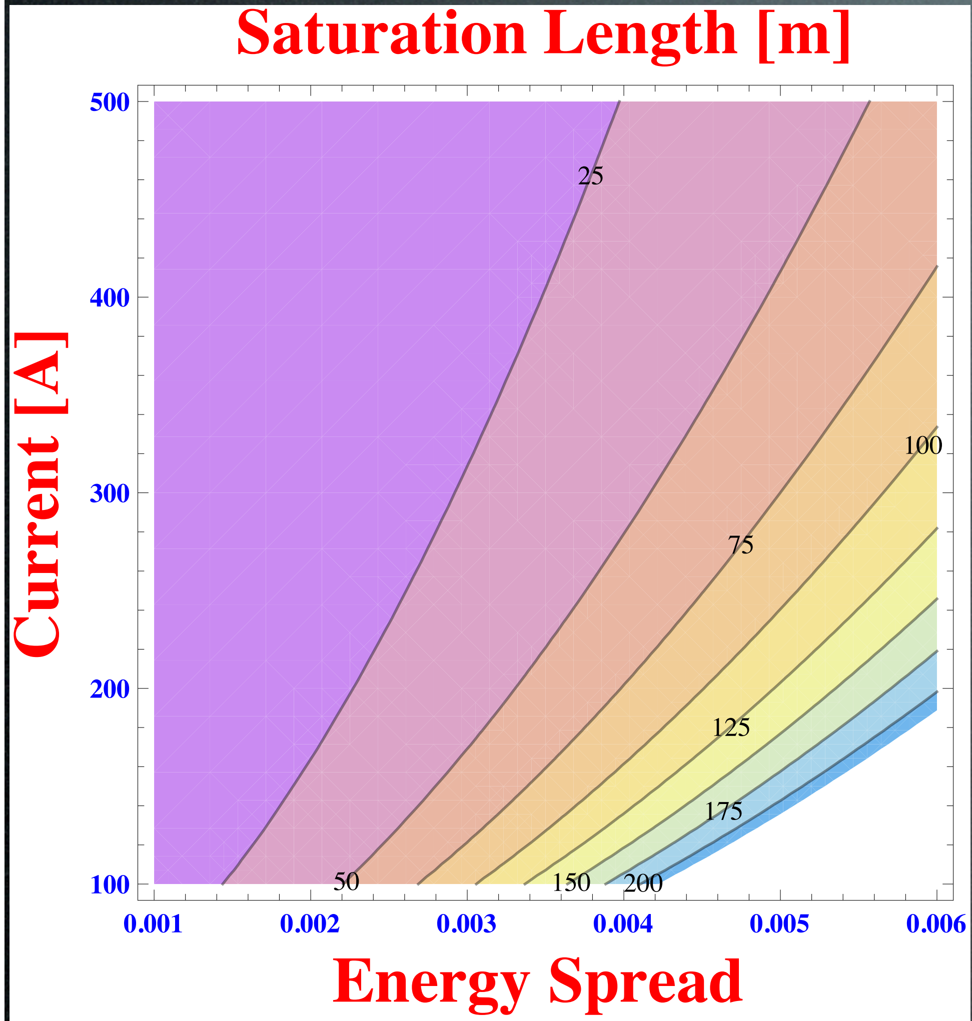
$$a_u = K/\sqrt{2}$$

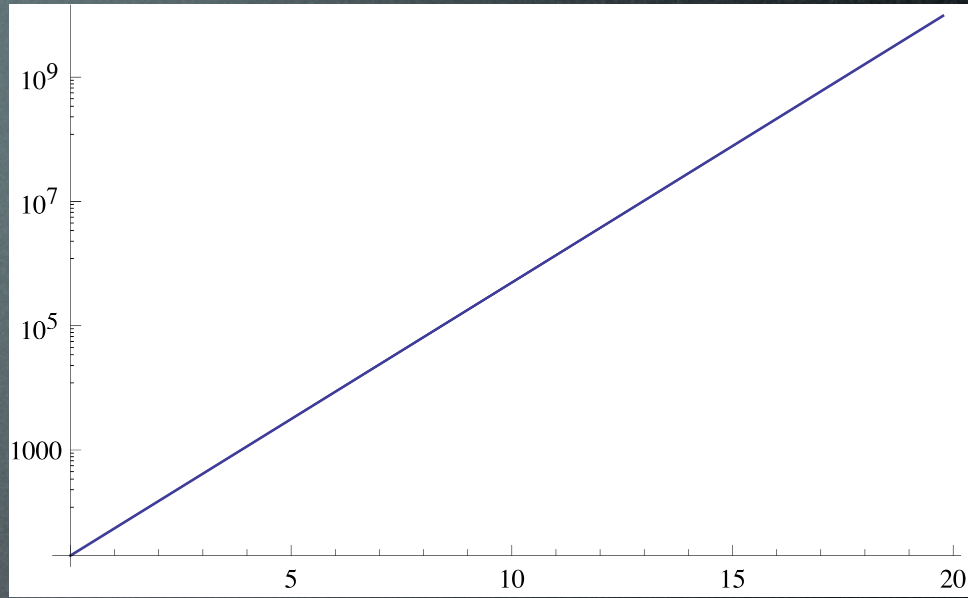
$$K = 0.934\lambda_u[cm]\hat{B}[T]$$

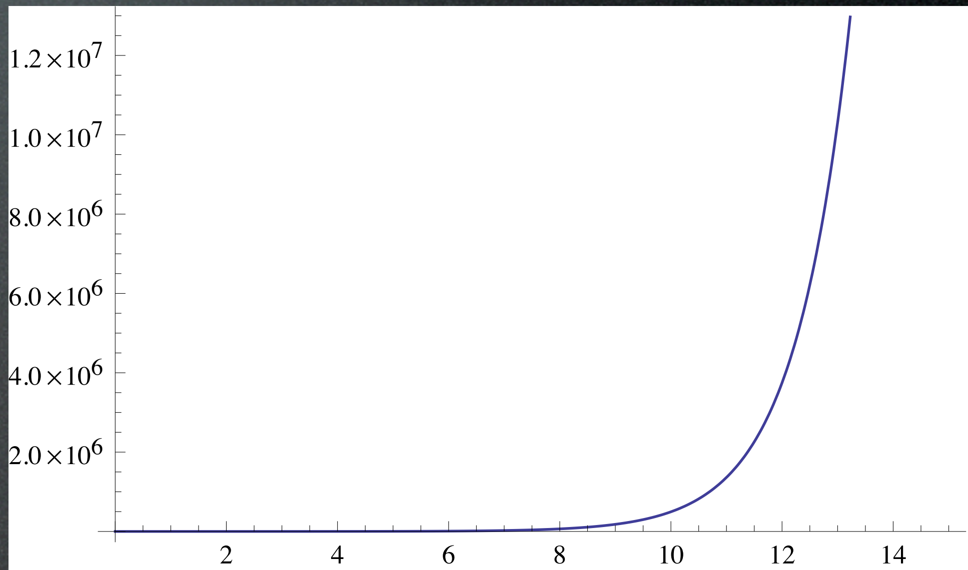


$$\lambda_w = 2.8cm$$
$$\lambda_w = 180nm$$
$$K = 2$$




Saturation Length [m]
Current [A]
Energy Spread
500
400
300
200
100
0.001
0.002
0.003
0.004
0.005
0.006
25
50
75
100
125
150
175
200


10^9
10^7
10^5
1000
5
10
15
20

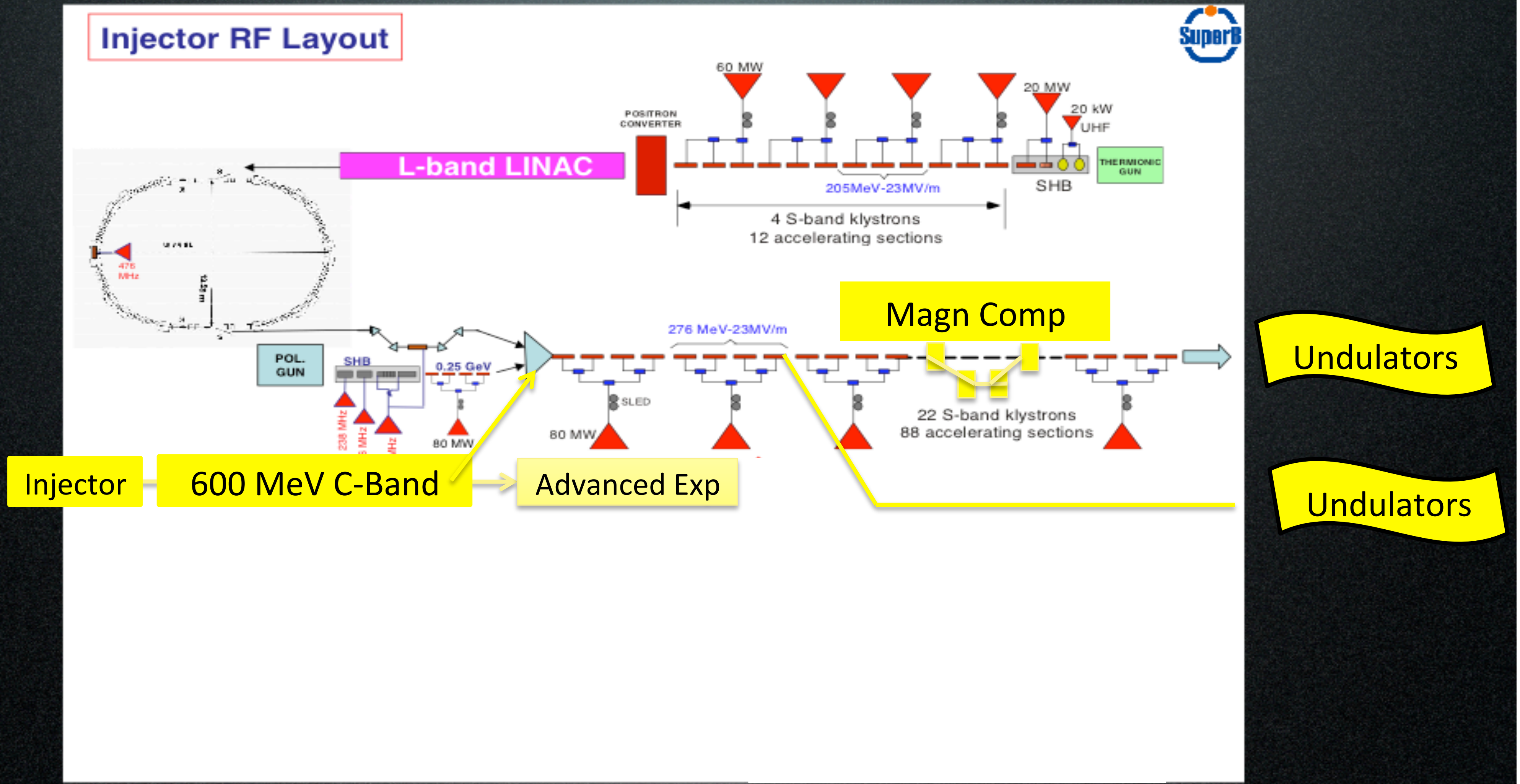

1.2×10^7
1.0×10^7
8.0×10^6
6.0×10^6
4.0×10^6
2.0×10^6
2
4
6
8
10
12
14

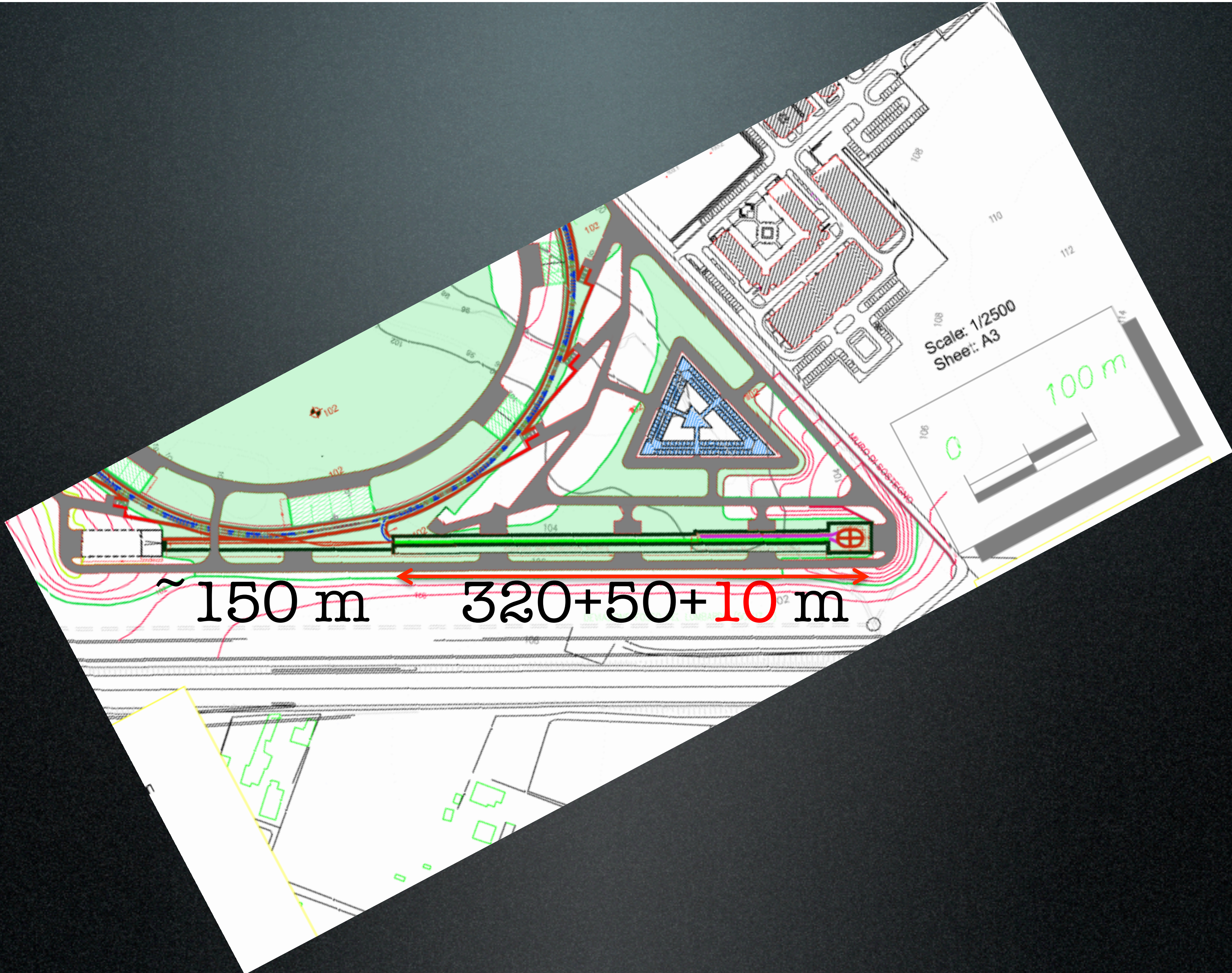
Parameter	Simulated value	Target value
Plasma gradient	1.2 GV/m	
Matched spot	5 μm	
Charge	20 pC	10 pC
rms Bunch length	10 μm (33 fs)	3 μm (10 fs)
Beam energy	255 MeV	
Norm. emittance	1.6 μm	
Energy spread	9×10^{-3}	4×10^{-3}
Peak current	240 A	400 A
K undulator	2	
λ_u	2.8 cm	
Radiation wavelength	180 nm	
ρ	3×10^{-3}	4.5×10^{-3}

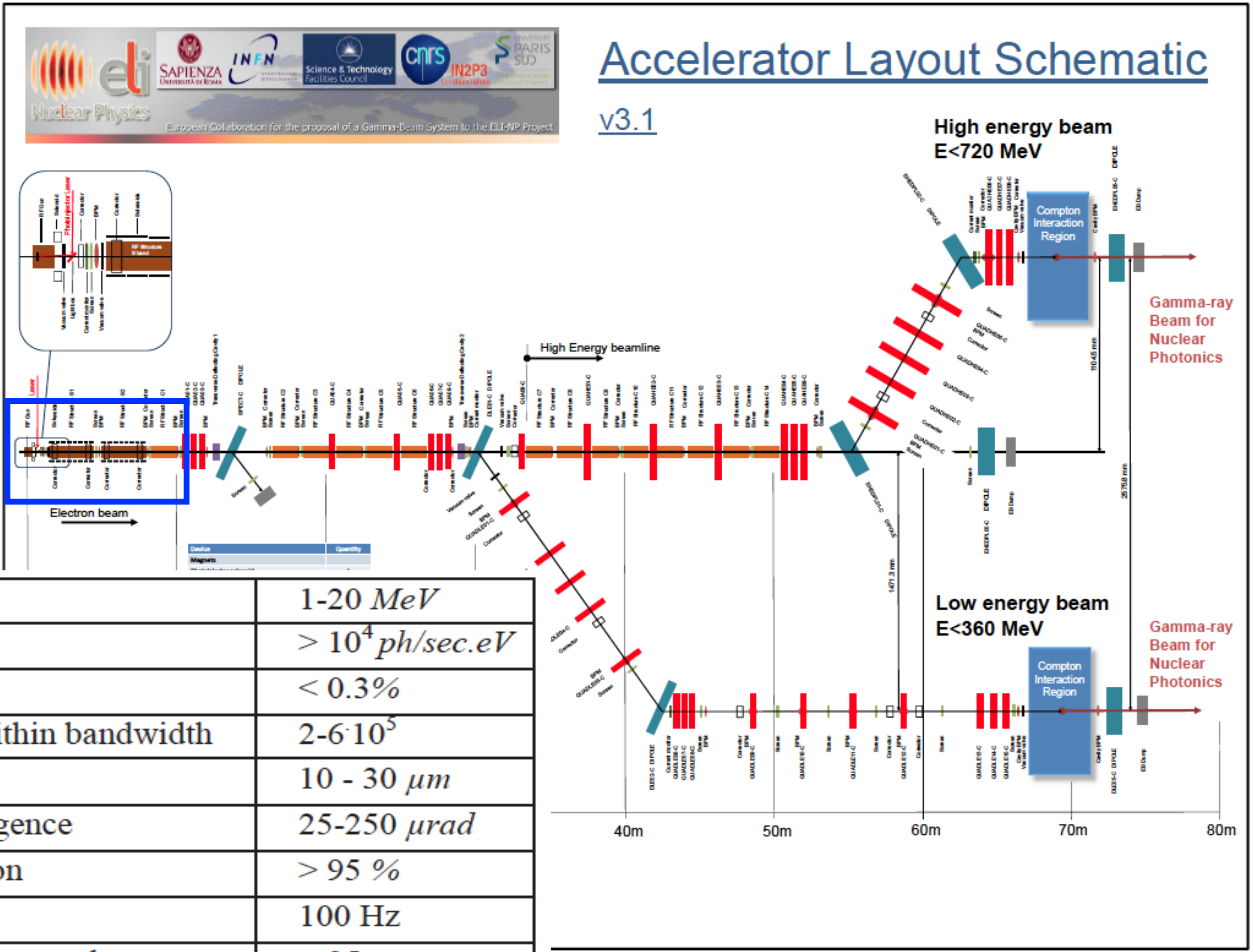
SPARC_LAB contribution to:

SuperB

A hard X-ray FEL with the SuperB linac



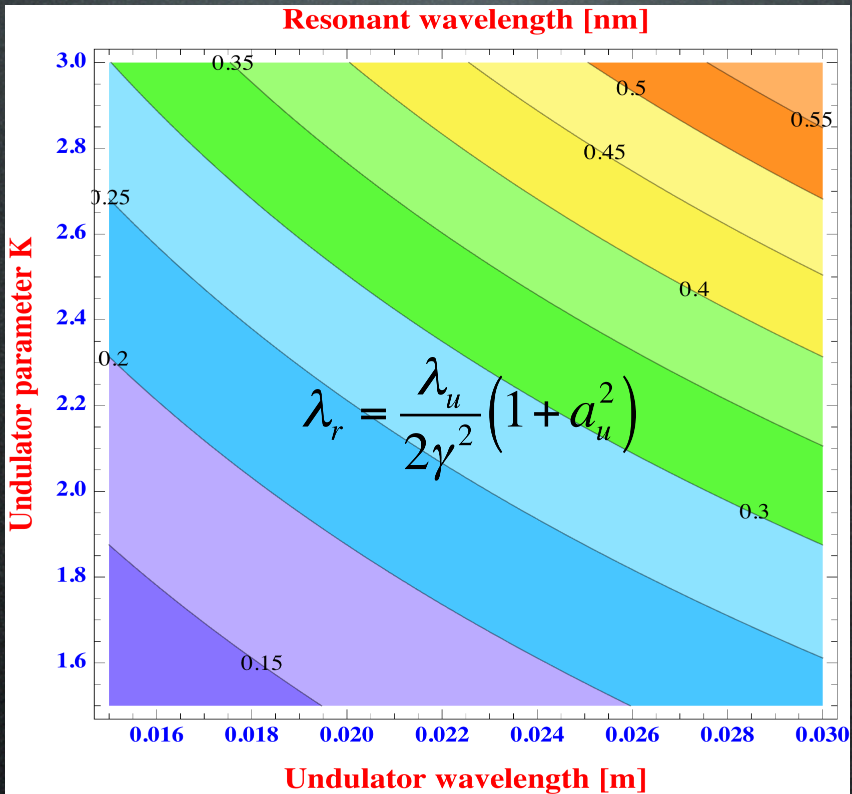

~150 m
320+50+10 m
Scale: 1/2500
Sheet: A3
0
100 m



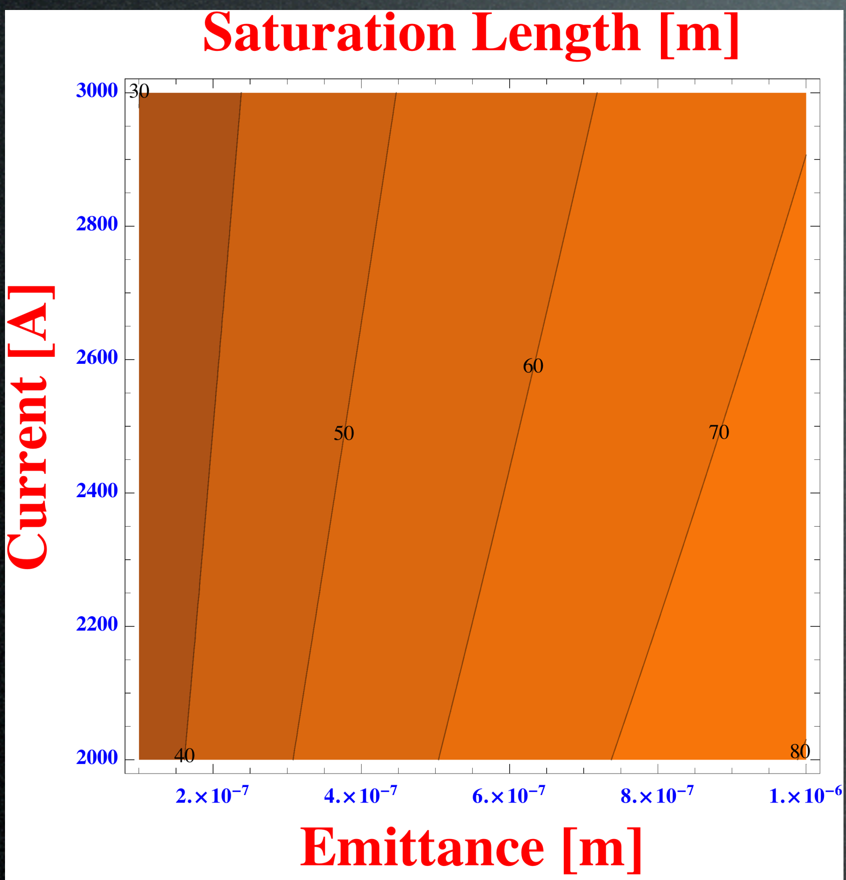
Photon energy	1-20 *MeV*
Spectral Density	> 10^4 *ph/sec.eV*
Bandwidth (rms)	< 0.3%
# photons/shot within bandwidth	$2\text{-}6 \cdot 10^5$
Source rms size	10 - 30 μm
Source rms divergence	25-250 μrad
Linear Polarization	> 95 %
Macro rep. rate	100 Hz
# of pulses per macropulse	< 25
Pulse-to-pulse separation	> 15 *nsec*

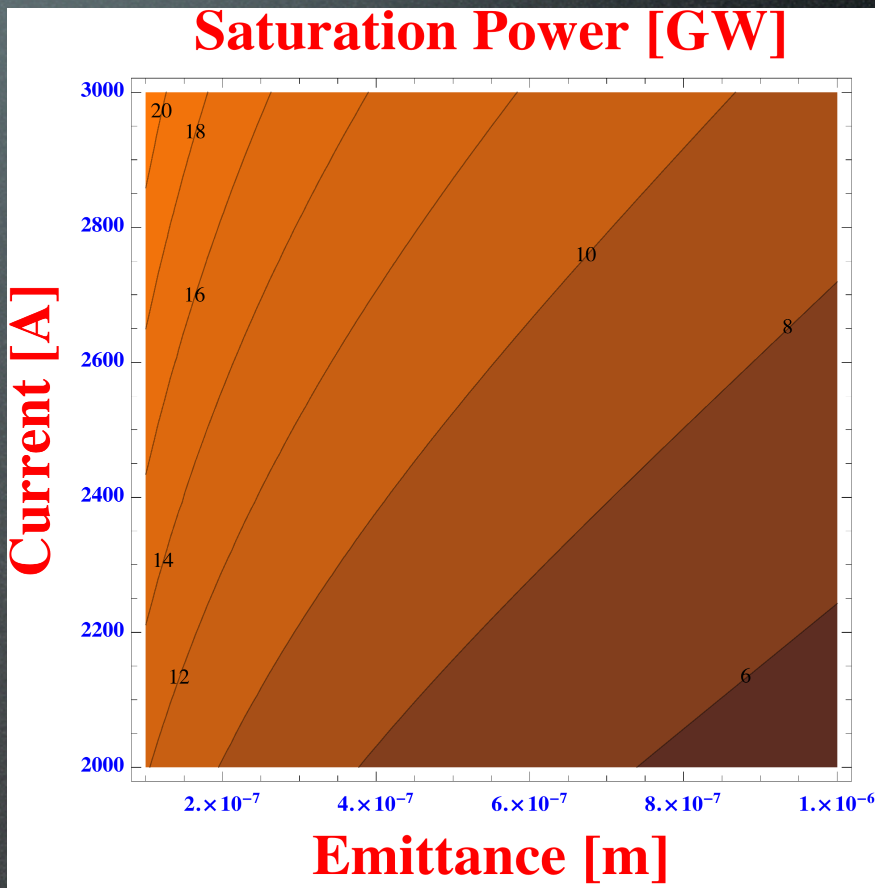
- The possibility to drive a SASE X-ray FEL using the 6 GeV electron linac foreseen by the SuperB project has been very recently considered.

- A preliminary design study, based on FEL scaling laws supported by HOMDYN and GENESIS simulations, shows that an FEL source in the range of 1-3 Angstrom can be implemented preserving the compatibility with the standard SuperB operation.



E_b	λ_r	K	λ_u	I_{FWHM}	$\varepsilon_{n,rms}$	σ_γ/γ
6 GeV	3 A	2	2.8 cm	>2 kA	<1.5 μm	$<5\times10^{-4}$





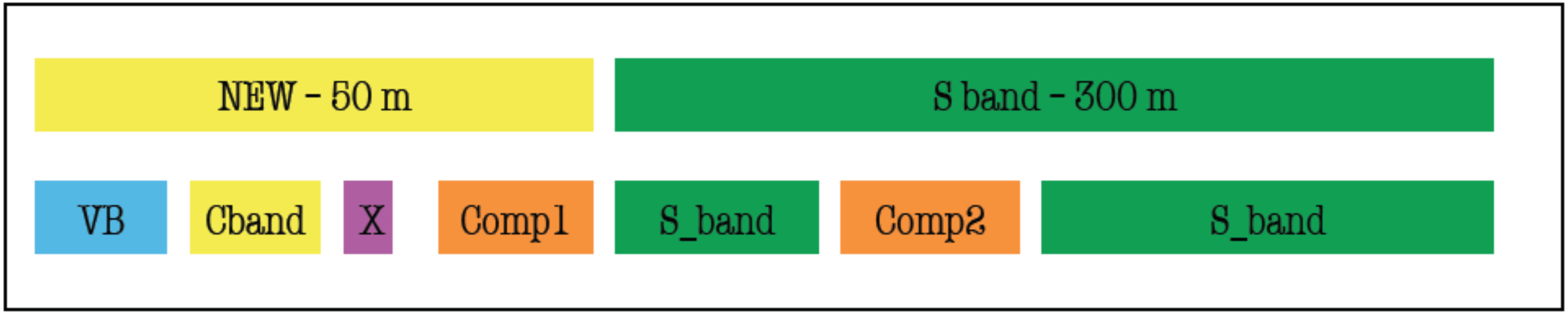
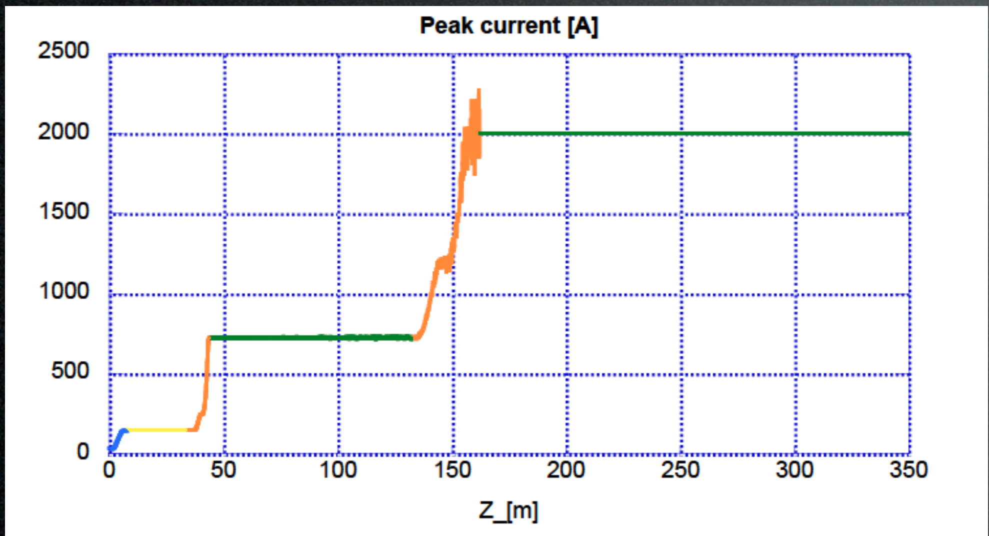
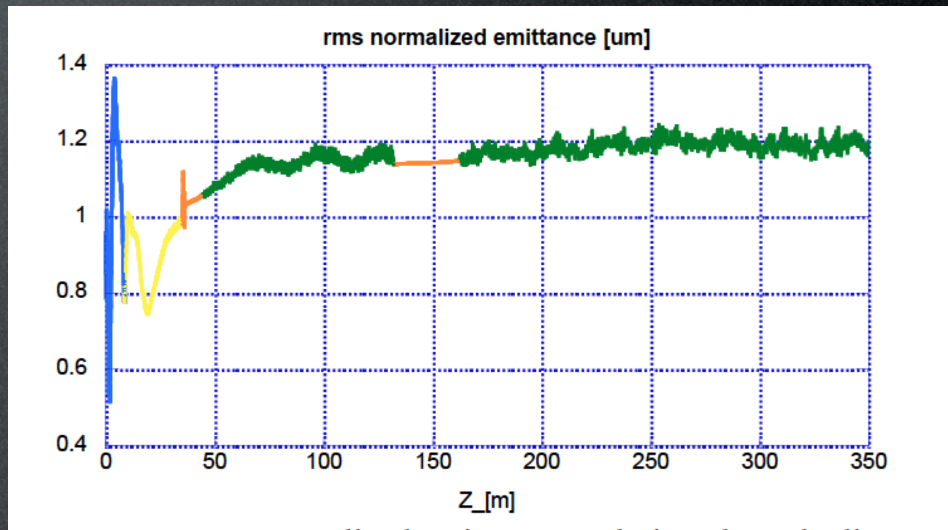


Figure 8 – Upper plot: shematic layout of the SuperB linac (green) and the new XFEL injection system (yellow). Lower plot: details of the foreseen modifications.



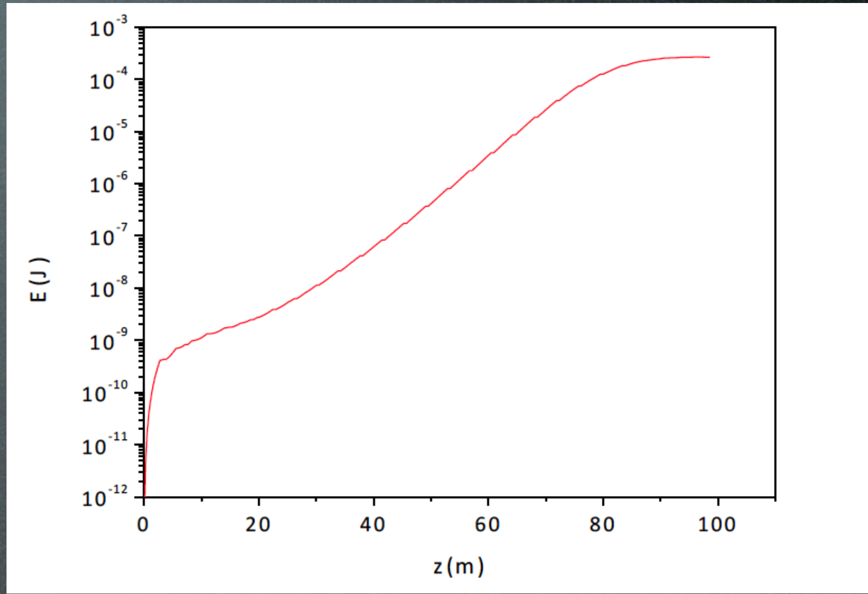


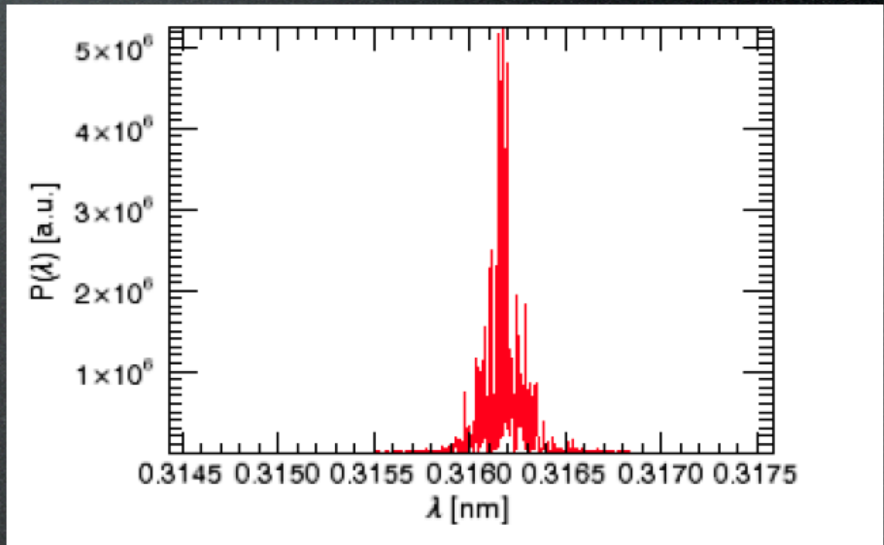
Preliminary GENESIS simulations

E_b	I_{slice}	$\varepsilon_{n,slice}$	σ_γ/γ
6 GeV	2.5 kA	0.6 μm	1×10^{-4}

	SPARC-like	Short period
Period λ_u (cm)	2.8	1.8
a_{w0} $(=K/\sqrt{2})$	1.51	1.2
Section length (m)	3.36	2.16
Gap length (m)	0.42	0.27
λ_r(Å)	3.16	1.525
σ_x(μm)	66	50
σ_y(μm)	40	35
β(m)	50	32

	SPARC-like	Short period
λ_r(Å)	3.16	1.525
L_s(m)	~90	~78
E_s(μJ)	270	114
bw(%)	0.04	0.023
L_g(m)	~4.8	~4.4





CONCLUSIONS

SPARC_LAB, a facility based on the unique combination of high brightness electron beams with high intensity ultra-short laser pulses, will be soon available for the entire scientific community, such to allow the investigation of all the different configurations of plasma accelerator and the development of a wide spectrum inter-disciplinary leading-edge research activity with advanced radiation sources.

In collaboration with University of Roma the first Accelerator Physics PhD course is now open. Submission of application until July 15.


Thank you