A Proposed Plasma Wakefield Acceleration Experiment Using CLARA Beam

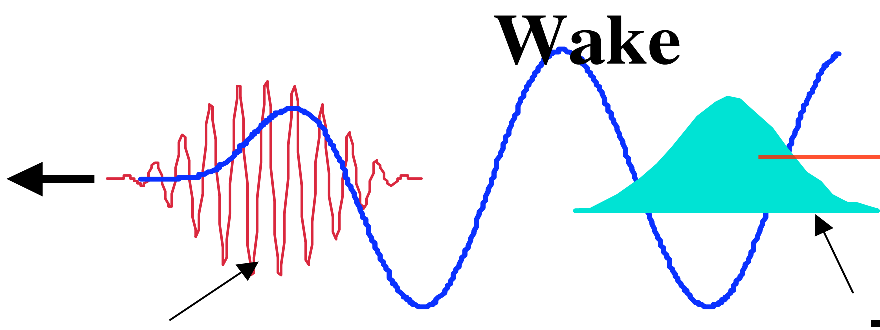
G. Xia[1], J. Clarke[2], D. Angal-Kalinin[2], J. Smith[3], E. Cormier-Michel[4], J. Jones[2], P. Williams[2], H. Kieran[1]

[1] Cockcroft Institute
[2] Daresbury Laboratory
[3] Tech-X UK
[4.] Tech-X US

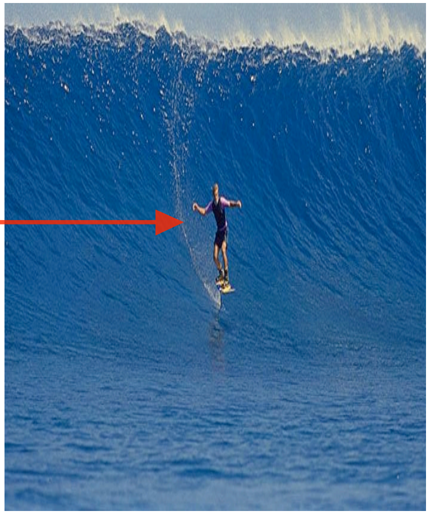
Outline

- Motivation
- CLARA facility
- Plasma acceleration at CLARA
- Other research topics at CLARA
- Summary

Why plasma?



- **Laser or beam**
- **Trailing beam**



$$c\tau \sim \lambda_p$$

The key is the super high accelerating gradient!

$$E_{Acc} \approx \sqrt{n_p[cm^{-3}]}V/cm$$

e.g. n_p=10^{18} cm^{-3}, the accelerating field will be 100 GeV/m!
10^3 orders of magnitude higher than the fields in conventional accelerators !

CLARA

- **C**ompact **L**inear **A**ccelerator for **R**esearch and **A**pplications
- ***A world class FEL test facility that can try out many of these new ideas so they can be implemented directly in a future light source facility***
- ***In parallel we will also be able test "Advanced Accelerator Technologies"***
- *The relatively small investment required for CLARA could pay for itself in the money we will save in the capital cost of a future light source*
- **More importantly, it will also make any national future light source a world beater !**

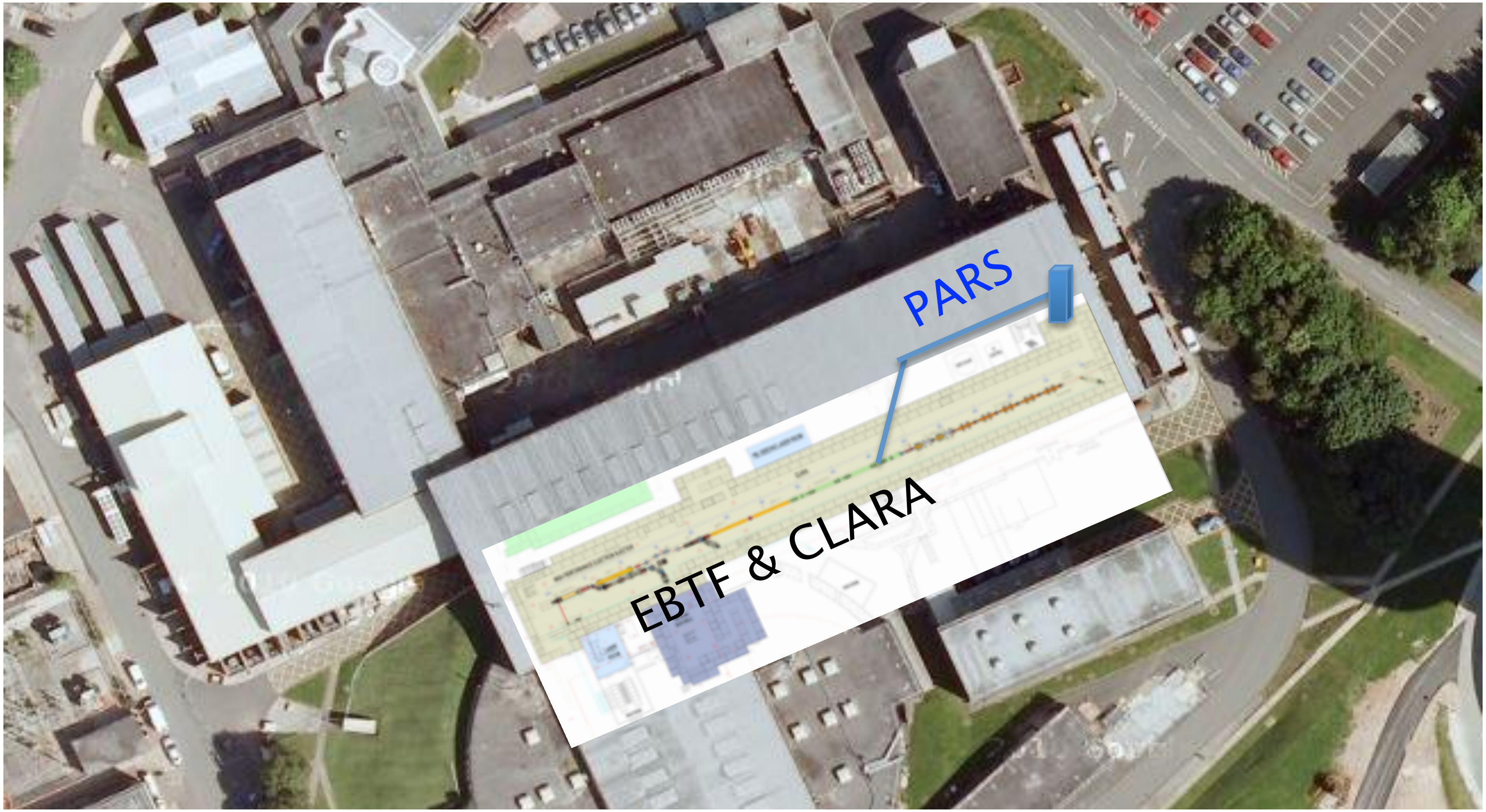
(J. Clarke)

Why PARS at CLARA?

- **Why it makes sense**
  - Free space available close to CLARA beam line
  - Unique beam properties (low emittance, high charge, relativistic)
  - Diverse beam operation modes (testing of scaling laws of PWFA)
  - Well developed beam diagnostic equipment for VELA and CLARA (deflecting cavities, longitudinal bunch length measurement, etc.)

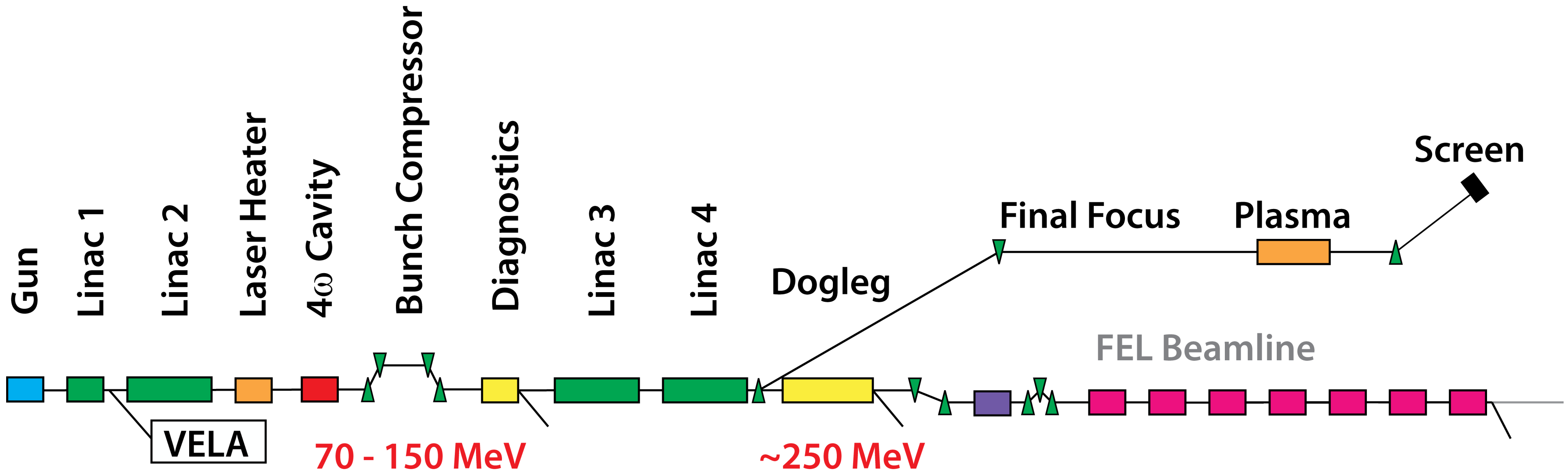
- **Possible contributions to advanced accelerator community**
  - Two bunch experiment for energy doubling of CLARA beam
  - High transformer ratio (laser shaping of the bunch density profile, hard-edge bunch for an efficient wakefield excitation)
  - Plasma undulator, plasma focusing effect, etc.
  - Hybrid wakefield acceleration
  - The self-modulation effect for a long beam (same gamma as SPS beam)

Plasma acceleration research station

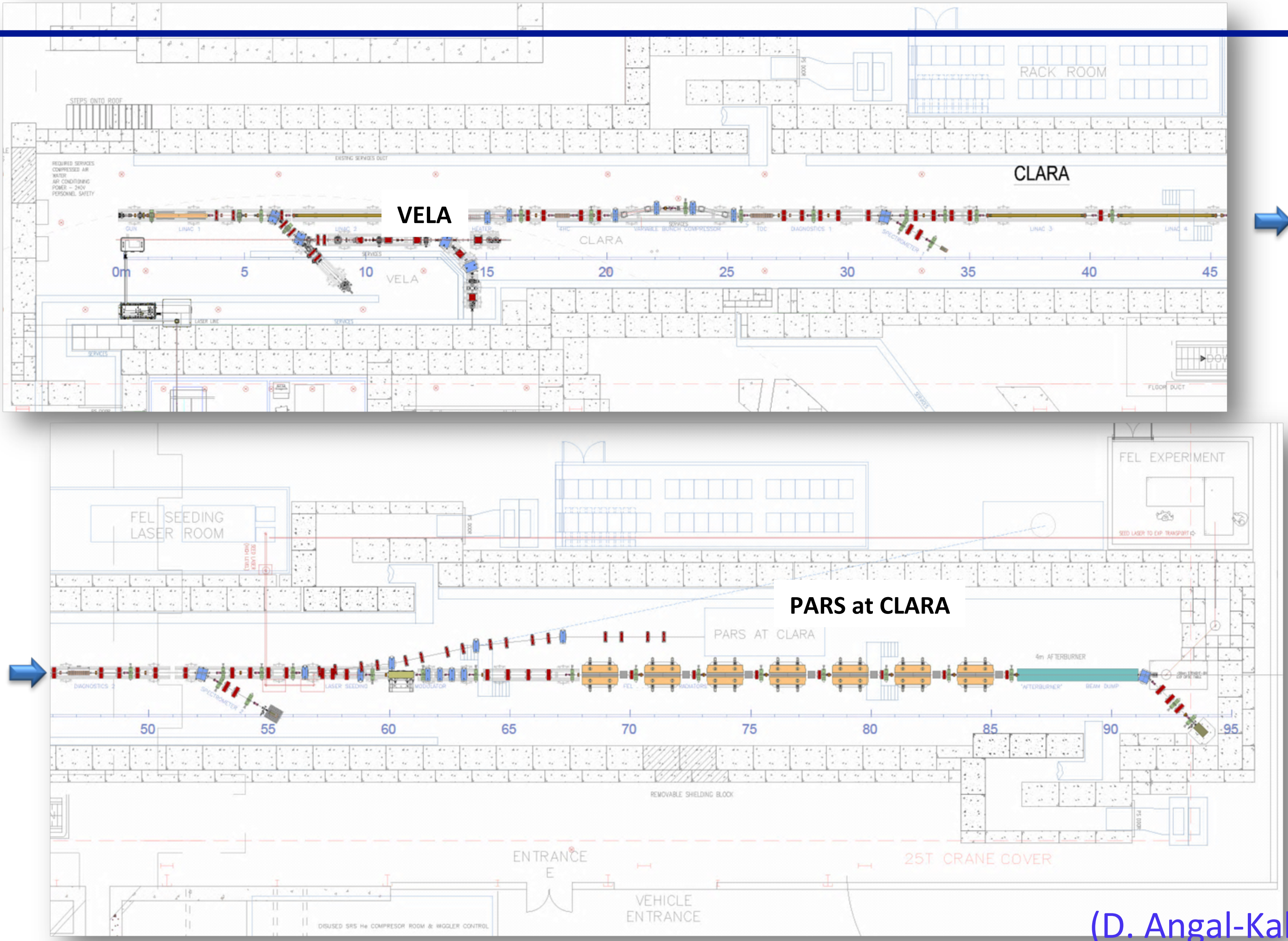


PARS beam line at CLARA

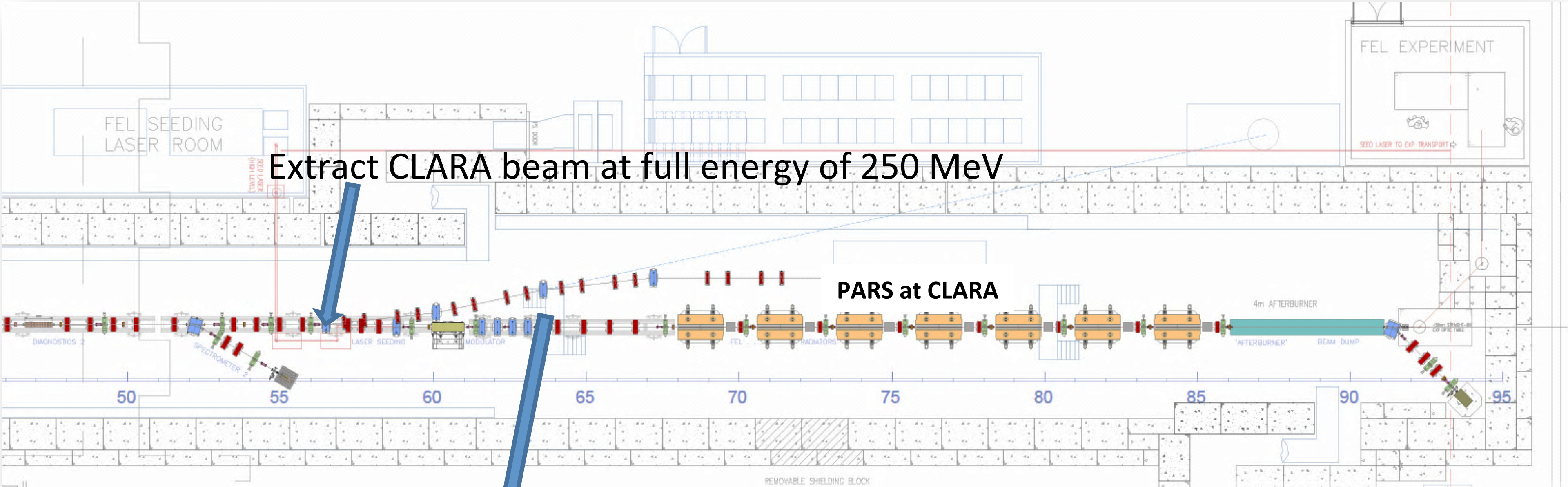
Another chicane may be needed to compress the electron bunch
Additional beam diagnostics (OTR, CTR, EOS, ICT…) are needed.

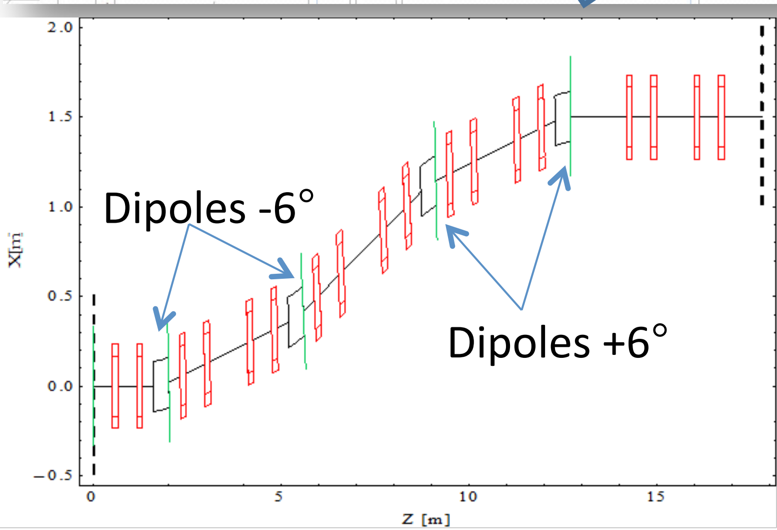


PARS beam line design



(D. Angal-Kalinin)





- The proposed dogleg beam line design using "–I " transform between the dipoles using two FODO doublets keeps the transverse beam emittance blow up due to coherent synchrotron radiation within acceptable limits for 250 pC at 250 fsec bunch length and for 20 pC at 30 fsec.
- The possibility of using the additional take off line at lower angle (~6°) from the 30° dipole for high energy diagnostics spectrometer or a seeding dogleg dipole is being investigated.
- The proposed beamline is contained within the CLARA shielding area with a transverse centre-to-centre offset of ~1.5m.

Plasma Accelerator Research Station at CLARA

- Compared to electron driven plasma wakefield experiments at ATF@BNL, FACET@SLAC, beam energy at CLARA is intermediate, easy to handle and less radiation.
- Many interesting topics will be investigated:
    - Two bunch experiment (crafting two bunches via laser or mask collimator, one for driving plasma wakefield, the other for sampling the wakefield); for demonstrating energy doubling of CLARA beam.
    - Beam shaping study for high transformer ratio (beam density profile shaping by shaping the laser pulse), e.g. multi-bunches or hard-edge beam can be an ideal driver beam;
    - Self-modulation of a long electron bunch—provide inputs to CERN proton-driven PWFA experiment (AWAKE);
    - As the electron injector for a laser-driven wakefield acceleration (combined with LWFA research).

CLARA parameters (v 2.0)

Operating Mode	Long Pulse	Short Pulse	Ultra Short Pulse	Multibunch	High Rep Rate
Motivation	Flat top for seeded FEL experiments	SASE FEL	Single Spike SASE FEL	Oscillator FEL (RAFEL)	Technology demonstration & commercial applications
Max Beam Energy (MeV)	250	250	250	250	100
Max Macropule Rep Rate (Hz)	100	100	100	100	400
Bunch Charge (pC)	250	250	20 to 100	250	250
Number of Bunches per macropulse	1	1	1	20	1
Bunch Spacing (ns)	N/A	N/A	N/A	~100	N/A
RF Pulse Width (μs)	2	2	2	3	2
Peak Current at FEL Entrance (A)	400/125	400	1500	400	N/A
Nominal Bunch Length (fs)	250/800 (flat region)	250 (rms)	<30fs	250 (rms)	
Normalised Projected Emittance (mm.mrad)	<1	<1	<1	<1	<1
Normalised slice emittance (mm.mrad)	< 0.5 over flat region (20fs slices)	< 0.5 (20fs slices)			
Rms slice Energy Spread (keV)	<25 over flat region	<100	150	<100	

J. Clarke

Plasma parameters

- The drive bunch length should satisfy

$$\sigma_z / \lambda_{pe} \cong \frac{1}{\sqrt{2\pi}} \qquad \lambda_{pe} = c / f_{pe} \qquad f_{pe} = \omega_{pe} / 2\pi$$

$$\omega_{pe} = \left(n_{pe} e^2 / \varepsilon_0 m_e \right)^{1/2} \qquad E_0 = \frac{m\omega_{pe} c}{e} \approx 0.96 n_{pe}^{1/2} [\mathrm{V/cm}]$$

$$n_{pe} = \begin{cases} 1.4 \times 10^{15}\,\mathrm{cm}^{-3} \\ 5.6 \times 10^{16}\,\mathrm{cm}^{-3} \end{cases}$$

for uncompressed bunch--- Scenarios 1

for compressed bunch --- Scenarios 2

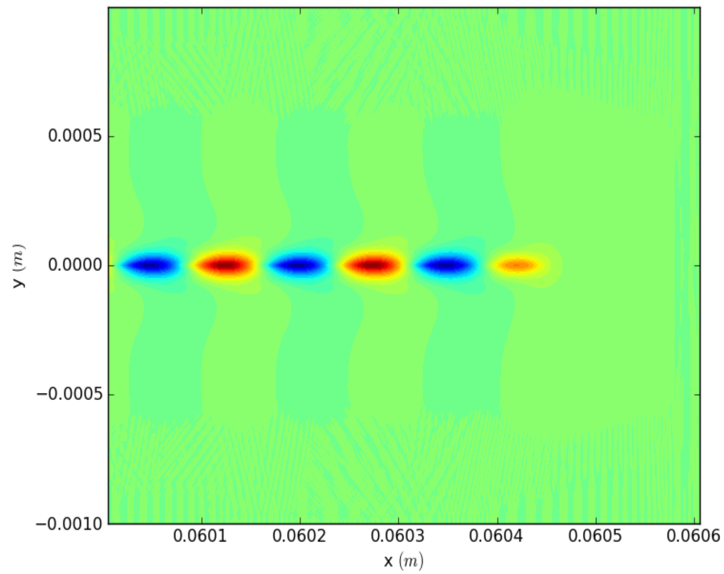
$$E_{wb} = \begin{cases} 3.7\ \mathrm{GeV/m} \\ 23.6\ \mathrm{GeV/m} \end{cases}$$

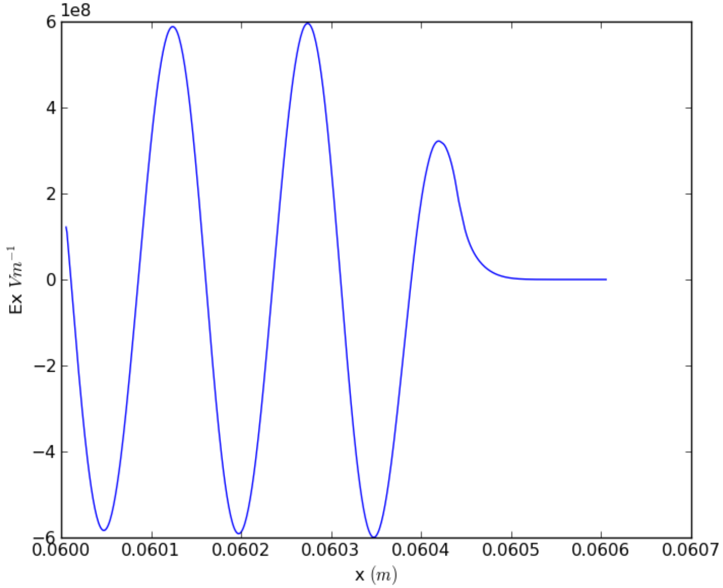
for uncompressed bunch--- Scenarios 1

for compressed bunch --- Scenarios 2

VORPAL simulation

Beam energy (MeV)	250
Bunch length (μm)	30
Beam size (x, y) (μm)	100
Bunch charge (pC)	250
Electrons per bunch	1.56×10^9
Plasma density (cm^{-3})	5×10^{16}
Plasma length (cm)	50





(J. Smith)

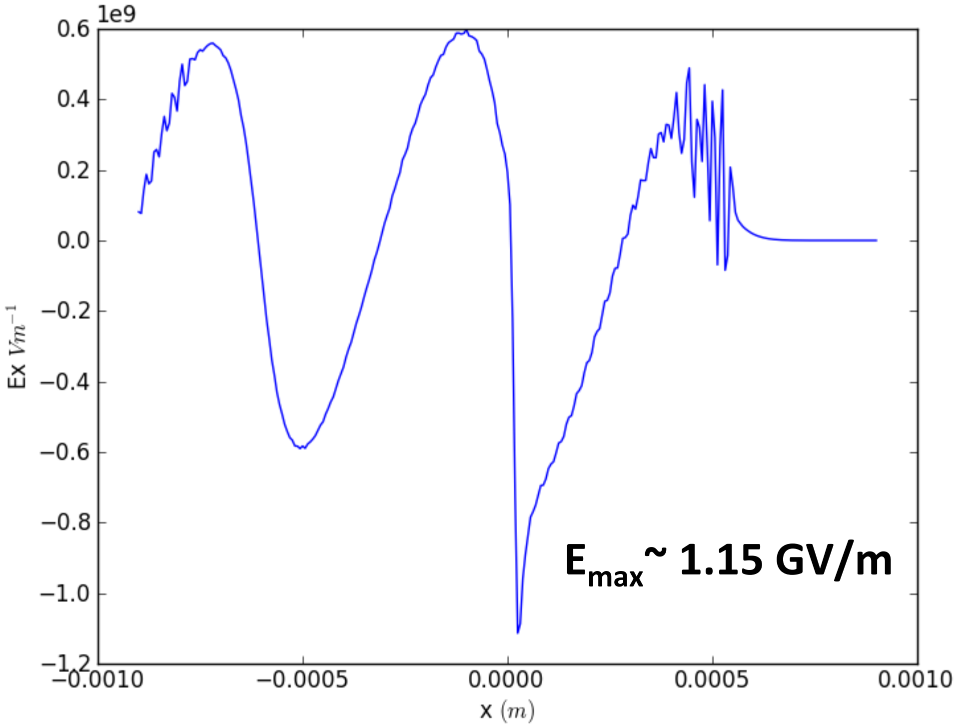
VORPAL simulation

Electron beam parameters	
Beam energy	250 MeV
Bunch length	75 µm
Beam size (x, y)	20 µm
Bunch charge	250 pC
Bunch intensity	1.56×10^{9}
Energy spread	0.1-1%
Normalized emittance	1 mm.mrad
Plasma parameters	
Plasma density	3×10^{15} cm^3
Plasma length	50 cm

$$n_b = N / \left[(2\pi)^{3/2}\sigma_r^2\sigma_z\right]$$

$$E_{acc}[\mathrm{MV/m}] = 244\frac{N_b}{2\times10^{10}}\left(\frac{600\mu\mathrm{m}}{\sigma_z}\right)^2$$

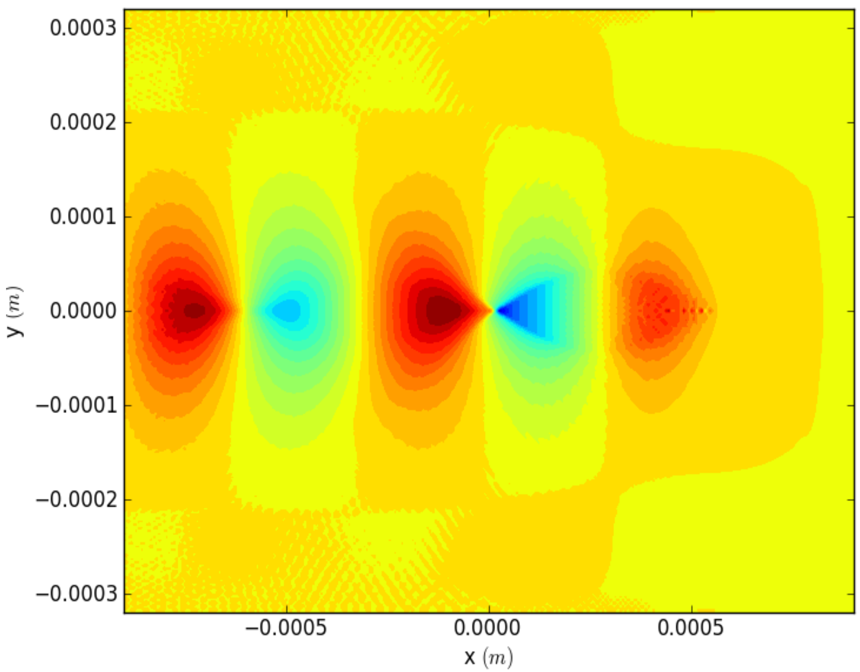
E_{acc_theory} = 1.2 GV/m !



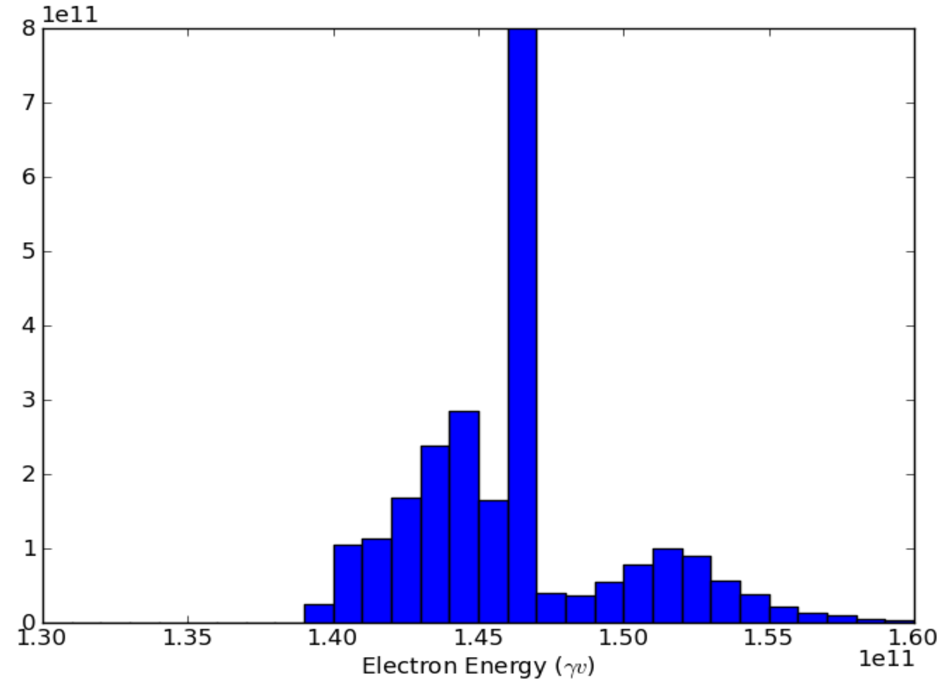
(J. Smith)

VORPAL simulation

Acceleration/deceleration structures



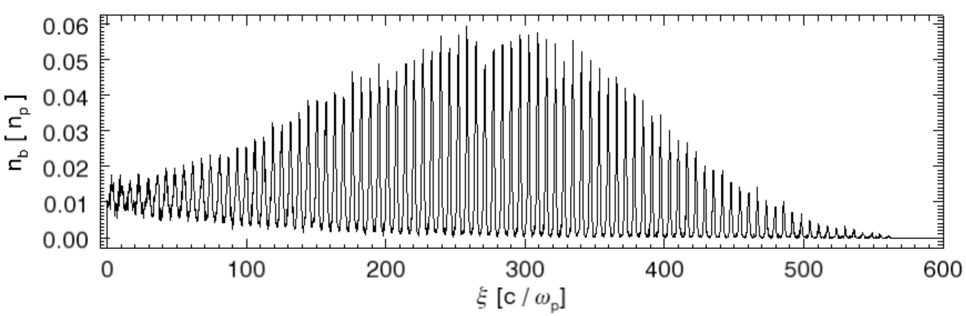
Energy distribution

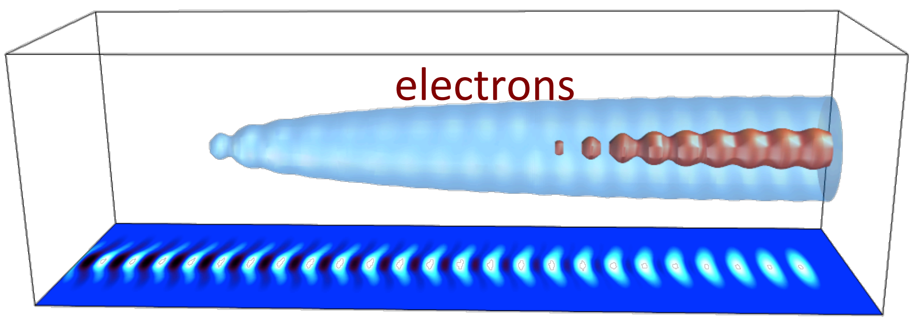


(J. Smith)

Self-modulation

- Long bunch gets modulation in the wakefield excited by itself (bunch head).
- Many ultra-short bunch slices (scale of a plasma wavelength) are produced and then excite the wakefield and add up coherently to a high amplitude (AWAKE experiment at CERN).
- CLARA beam has a similar gamma factor (gamma ~ 500) as SPS beam, many plasma-beam dynamics could be similar and could be tested here at PARS.





Other research topics at PARS

1. Plasma wiggler study, the plasma can be used as undulator to produce high brightness beam of keV to MeV photons via betatron radiation.

VOLUME 88, NUMBER 13 PHYSICAL REVIEW LETTERS 1 APRIL 2002

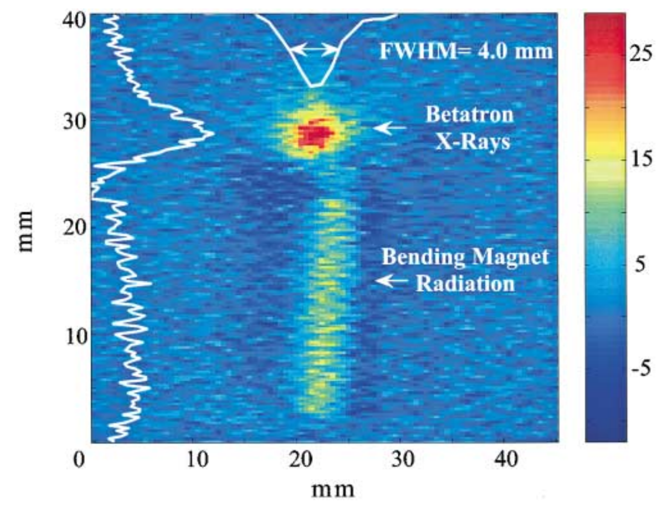
X-Ray Emission from Betatron Motion in a Plasma Wiggler

Shuoqin Wang,[1] C. E. Clayton,[1] B. E. Blue,[1] E. S. Dodd,[1] K. A. Marsh,[1] W. B. Mori,[1] C. Joshi,[1] S. Lee,[2] P. Muggli,[2] T. Katsouleas,[2] F. J. Decker,[3] M. J. Hogan,[3] R. H. Iverson,[3] P. Raimondi,[3] D. Walz,[3] R. Siemann,[3] and R. Assmann[4]

[1]*University of California, Los Angeles, California 90095*
[2]*University of Southern California, Los Angeles, California 90089*
[3]*Stanford Linear Accelerator Center, Stanford, California 94309*
[4]*CERN, Switzerland*

(Received 8 October 2001; published 19 March 2002)

The successful utilization of an ion channel in a plasma to wiggle a 28.5-GeV electron beam to obtain broadband x-ray radiation is reported. The ion channel is induced by the electron bunch as it propagates through an underdense 1.4-meter-long lithium plasma. The quadratic density dependence of the spontaneously emitted betatron x-ray radiation and the divergence angle of $\sim(1-3) \times 10^{-4}$ radian of the forward-emitted x-rays as a consequence of betatron motion in the ion channel are in good agreement with theory. The absolute photon yield and the peak spectral brightness at 14.2-keV photon energy are estimated.



Other research topics at PARS

4. Some advanced beam dynamics issues can be investigated in this test bed as well, e.g.

- Coherent synchrotron radiation-CSR (THz radiation), microbunching instability and its countermeasures, etc. ----crucial to FEL operation
- Beam manipulation and emittance exchange (deflecting cavities + dipole magnets)----for novel FEL modes like EEHG
- Beam diagnostics R&D for ultra-short electron beam (Electro-optical sampling, Smith-Purcell radiation etc.)

Summary

- The Plasma Accelerator Research Station (PARS) at CLARA will provide an ideal platform to investigate the key issues in plasma-based accelerators.
- It is expected that a high accelerating gradient can be achieved with the relativistic CLARA beam.
- For the two-bunch experiment, a trailing bunch can gain energy from the wakefield and preserve its low emittance and low energy spread and get energy doubled.
- Many other issues on the advanced beam dynamics, beam diagnostics, hybrid wakefield accelerators etc. can be investigated at PARS as well.

Thanks !

A genuine PARS project

Work packages:

- Electron Beam Delivery

  (design, operation and optimization of electron beam to the PARS; dogleg, final focus, e^- beam dump, laser beam dump)

- Plasma Source

  (produce a 10-50 cm long plasma source with diameter of ~1 mm, density of 10^{15}-10^{16} cm^{-3}, laser facility for photoionization of Lithium gas, plasma diagnostics, density and temperature)

- Beam Diagnostics

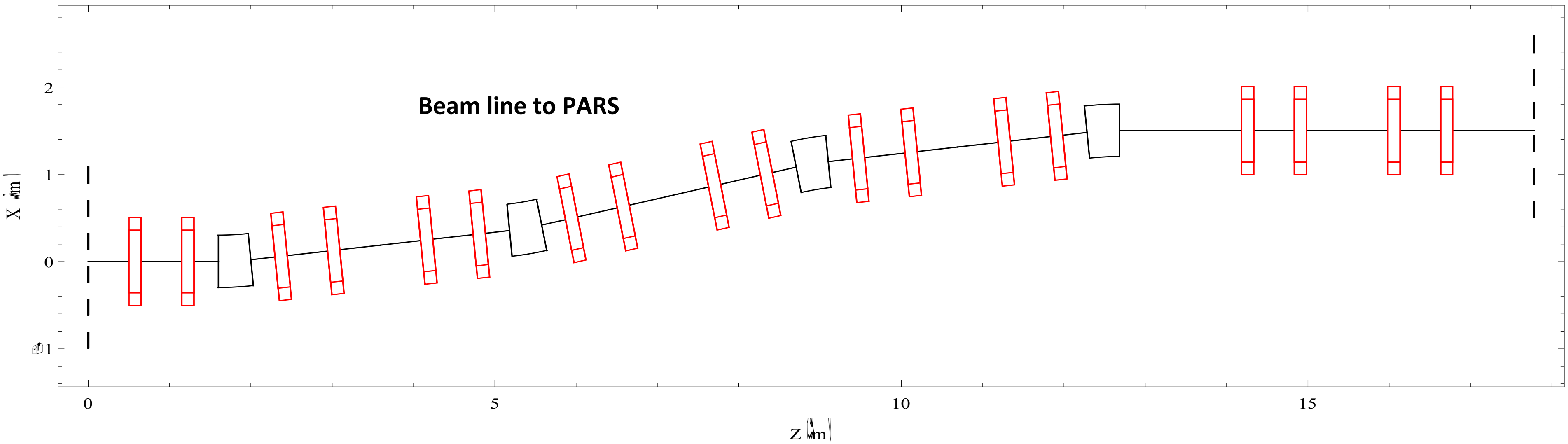
  (measurement of beam specifications before and after plasma, emittance, energy, beam size, bunch length, charge, etc. energy spectrometer, CTR, OTR, CCD, ICT, EOS, etc.)

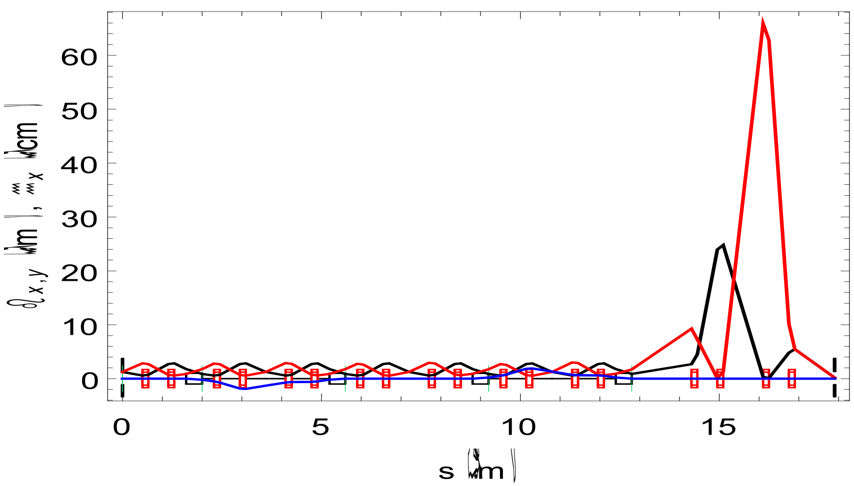
- Simulations

  (electron beam simulation, PIC simulation of interactions between plasma and beam, code benchmarking, benchmarking the simulation results against the experimental data, optimize beam and plasma parameters for next round of experiments etc.)

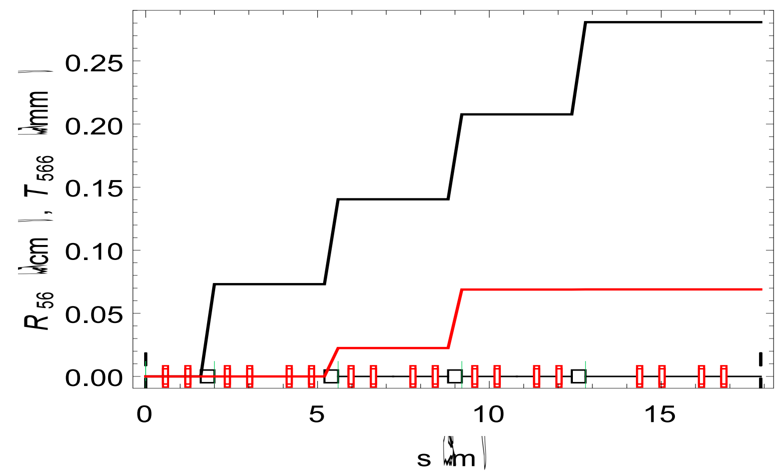
Two-bunch experiment

Drive bunch	
Beam energy	250 MeV
Bunch length	30 μm
Beam size (x, y)	50 μm
Bunch charge	250 pC
Bunch intensity	1.56×10^{9}
Energy spread	1%
Normalized emittance	1 mm.mrad
Witness bunch	
Beam energy	250 MeV
Bunch length	10 μm
Beam size (x, y)	50 μm
Bunch charge	50 pC
Bunch intensity	3.1×10^{8}
Energy spread	0.5%
Plasma parameters	
Distance between drive and witness beam	140 μm
Plasma density	5×10^{16} cm^{3}
Plasma length	50 cm





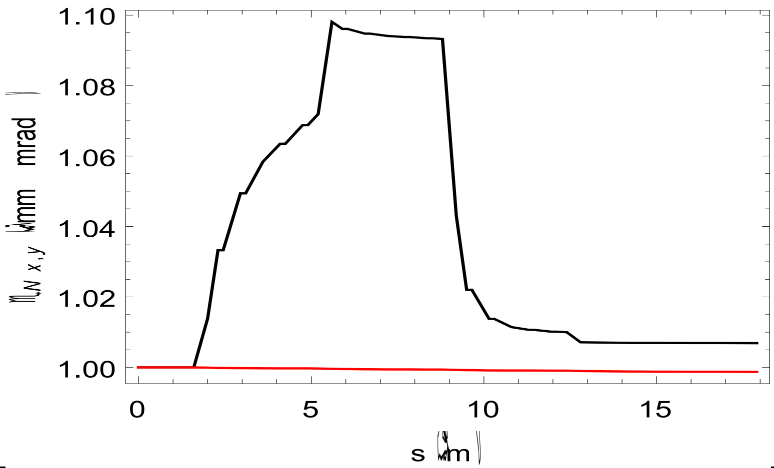
Twiss functions and η_x



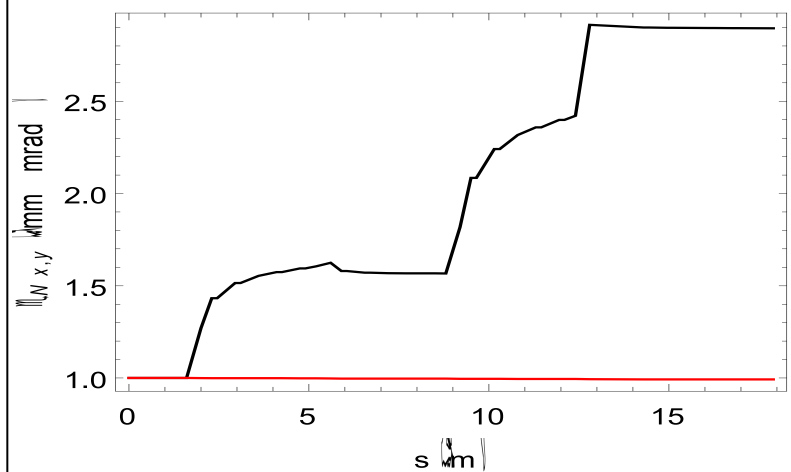
R_{56} and T_{566}

Tracking of Gaussian bunch through PARS beam line
Starting normalised emittance = 1mm.mrad

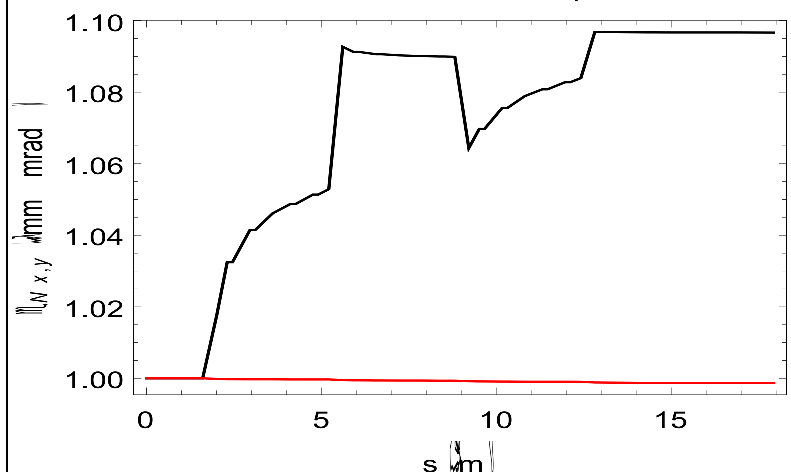
σ_s=75e-06, Q=250pC, σ_{dp}=0.001



σ_s=9e-06, Q=100pC, σ_{dp}=0.001



σ_s=9e-06, Q=20pC, σ_{dp}=0.001



- For bunch length 9µ and bunch charge 100pC, the normalised emittance increases from 1 mm.mrad to 2.7 mm.mrad
- For the same bunch length, the emittance growth is marginal for bunch charge of 20pC.
- Achieving transverse beam size (σ) of ~25µ at PARS location is possible with Gaussian beam in all the three cases shown here.