Report from VI Working Group 2

Beam dynamics and instrumentation

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Project FLASHForward ▸▸

Scope of VI Working Group 2

> Design, commissioning and operation of electron beamline at FLASHForward
> Diagnostics of driver and witness beams
> Beam dynamics simulations, optimisation of the driver beam

Collaborating institutes:

DESY

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C. Palmer
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M. Streeter
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JAI – John Adams Institute for Accelerator Science

R. Bartolini
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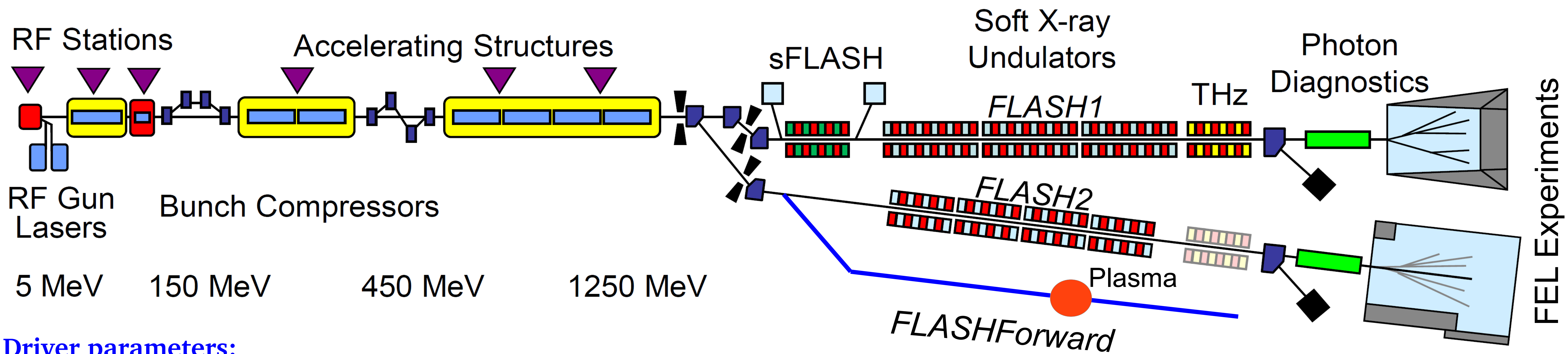
S. Mangles

INFN – Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati

R. Pompili
V. Shaposhnikov

FLASH and FLASHForward



Driver parameters:

Energy, GeV	ε_N, µm	$\beta_{x,y}$ (at plasma)	Bunch Length	Slice energy spread	Charge
0.5 – 1.2	2-5	20 mm	~50-500 fs	<0.1%	20 pC - 1 nC

> Requirements for the FLASHForward beam line:
- achromatic beam translation
- minimise coherent-synchrotron radiation (CSR) effects
- tight focus at the plasma entrance

"Pre-plasma"

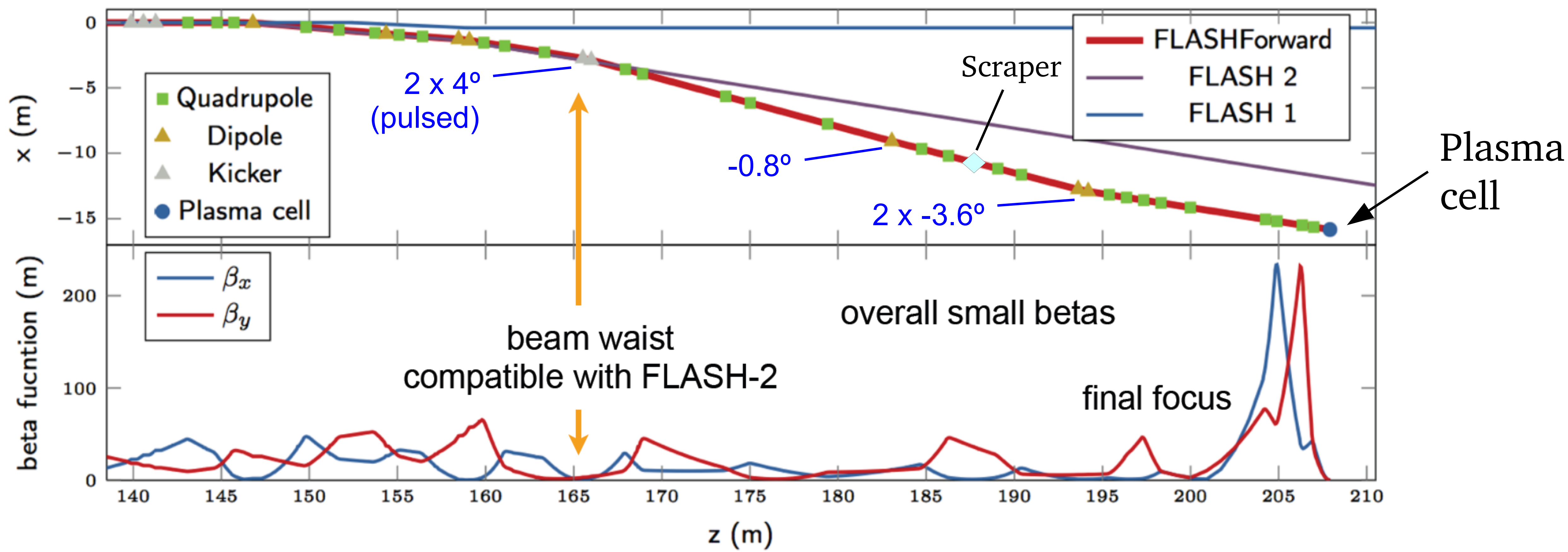
- capturing and diagnosis of the witness beam after plasma
- transport to the undulators (Phase II)

"Post-plasma"

FLASHForward beamline (pre-plasma)

Top-view

> Achromatic beam translation system (4m) with *variable longitudinal dispersion* (R_{56})



> small β-functions in the dipoles (minimises CSR effects)
> β-functions at the plasma entrance: ~25 mm

FLASHForward beamline (pre-plasma)

Magnet supports were installed during the FLASH shutdown of December 2015

Further installation work (magnets, power supplies, some of the vacuum parts) is foreseen for the summer and winter shutdowns of 2016

Standard diagnostics in procurement phase (MDI group of DESY)

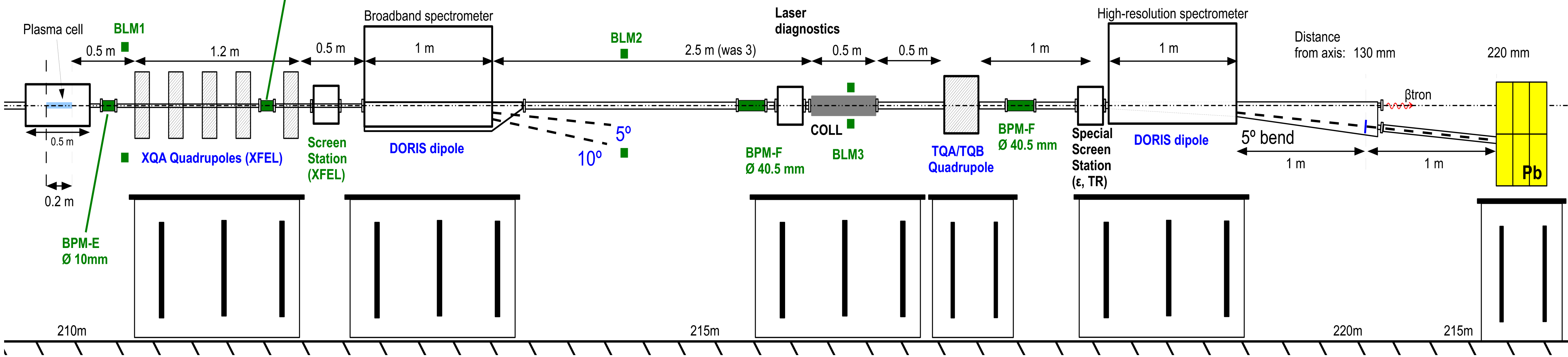
Expect to finish installation and start commissioning in July 2017

FLASHForward beamline (post-plasma)

Side-view

Witness parameters:

Energy, GeV	ε_N, µm	$\beta_{x,y}$ (at plasma)	Bunch Length	Slice energy spread	Charge
1.2 – 2.5 (5)	0.1 - 1	1-10 mm	~1 fs	1%	1-500 pC



> Witness capturing with a 100 T/m triplet (paired)

> Coarse and fine energy measurement

> Beam position/charge with cavity BPMs

> Emittance (single quadrupole scan planned; single-shot options are under study)

> Beam profile with scintillators

Design finalised, technical drawings in progress

Discussions are ongoing to incorporate a **transverse-deflecting cavity** for longitudinal phase space diagnostics ($\sigma_t \leq 10$ fs)

Beam quality preservation at FLASHForward

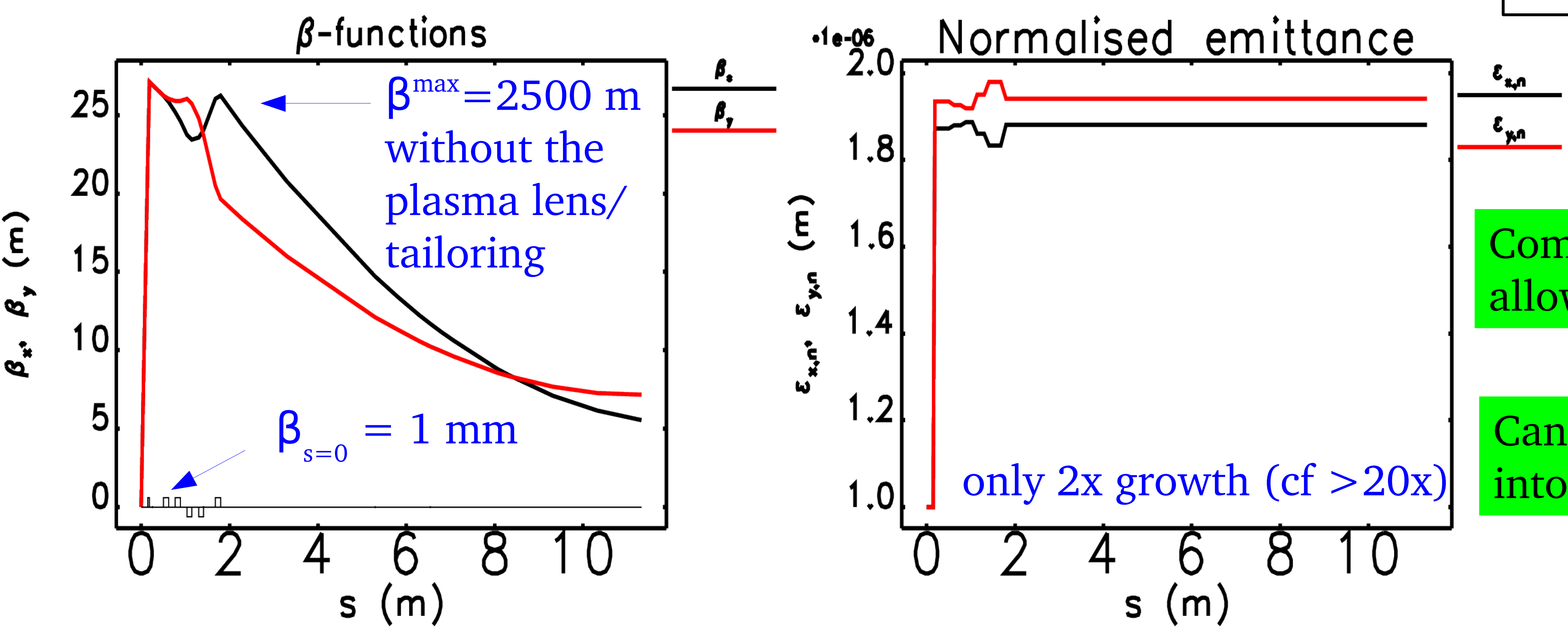
J. Tilborg et al., PRL **115**, 184802 (2015)

- Witness beams in plasmas have small beta-function ($\beta \sim 1$mm) and large energy spread ($\sigma_p \sim 1\%$)
  - → Significant emittance growth

Mitigation strategies at FLASHForward:

- Capturing close to the source with strongest available quadrupoles
- Tailored plasma-to-vacuum transitions (increasing β)
- Beam loading (decreasing σ_p)
- Plasma lens – ultrahigh gradients → see talk L. Schaper (WG3)

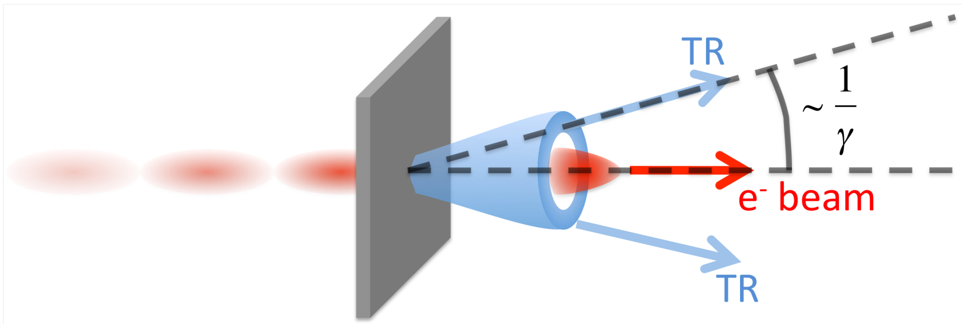
Assumed plasma lens parameters:
1600 T/m (R=250um, 500A)
$k=192\text{m}^{-2}$ for 2.5 GeV
L=33mm
Distance from source: 150mm



Combining with tailoring would allow emittance conservation!

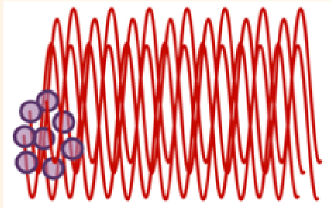
Can be also used for matching into plasma with β<1mm

Transition radiation (TR) as a longitudinal bunch diagnostic



INCOHERENT TR:

$$\omega \gg \frac{1}{\tau_{bunch}}$$



COHERENT TR:

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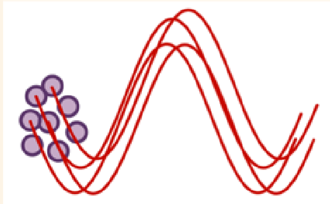
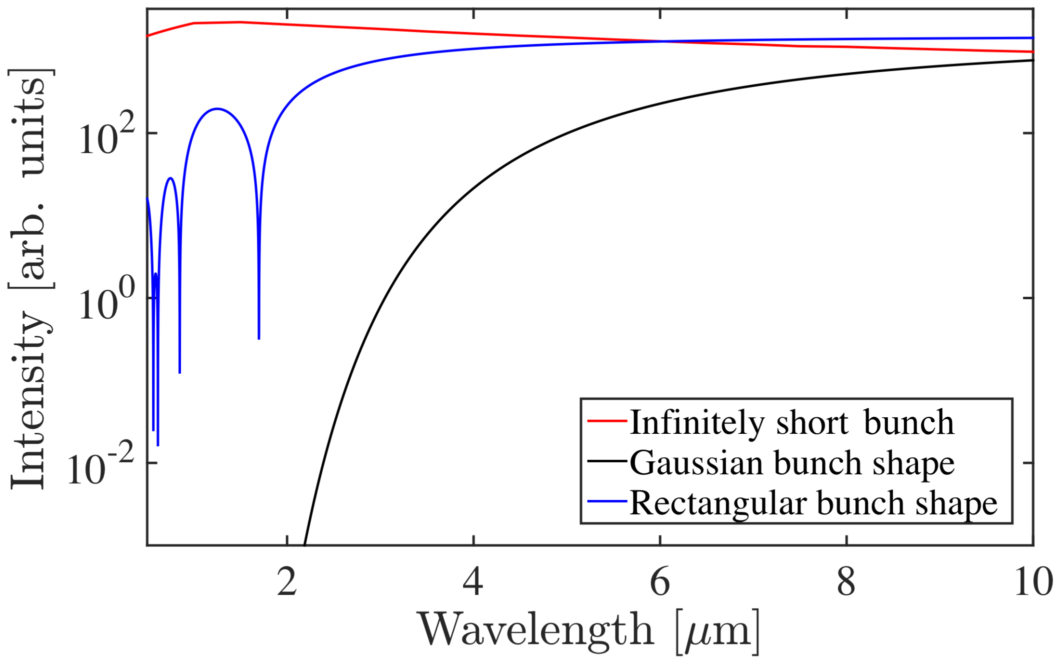
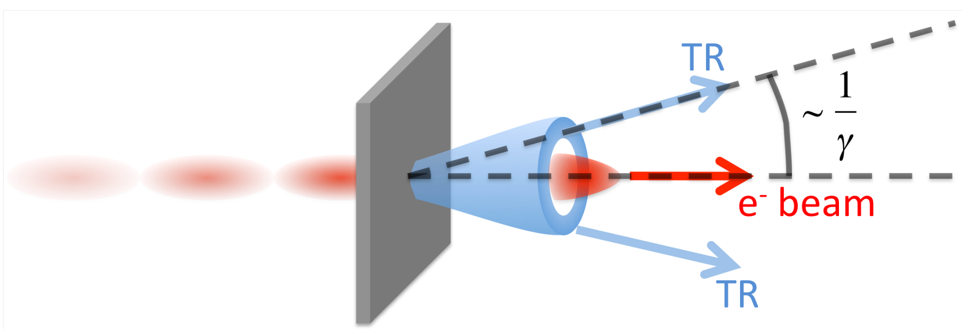




✚ Phase retrieval → Estimate of longitudinal charge distribution

Transition radiation (TR) as a longitudinal bunch diagnostic



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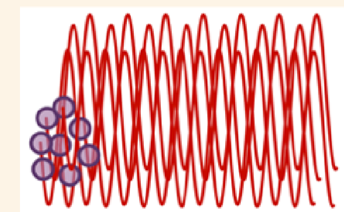

COHERENT TR:

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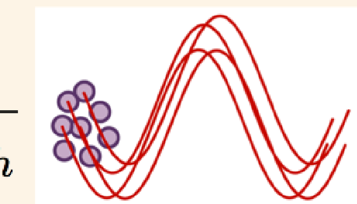
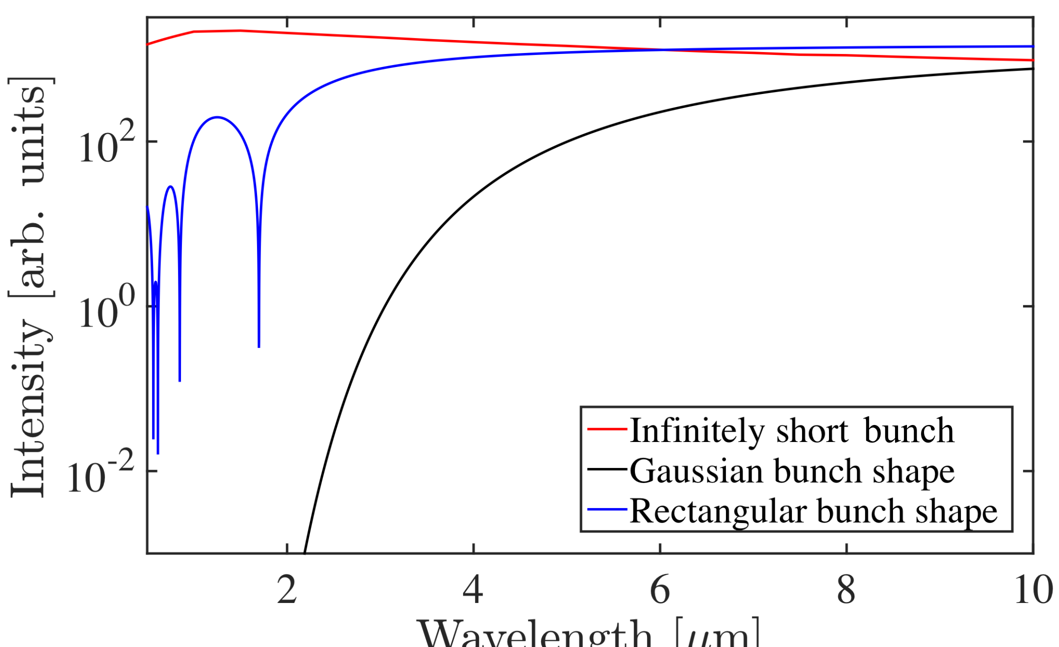




To use TR as diagnostics of fs PWFA electron bunches, it must:

> Have spectral sensitivity extending into the visible/UV.

> Measure the spectrum across a broad frequency range.

> Be capable of capturing this broad spectrum within a single shot.

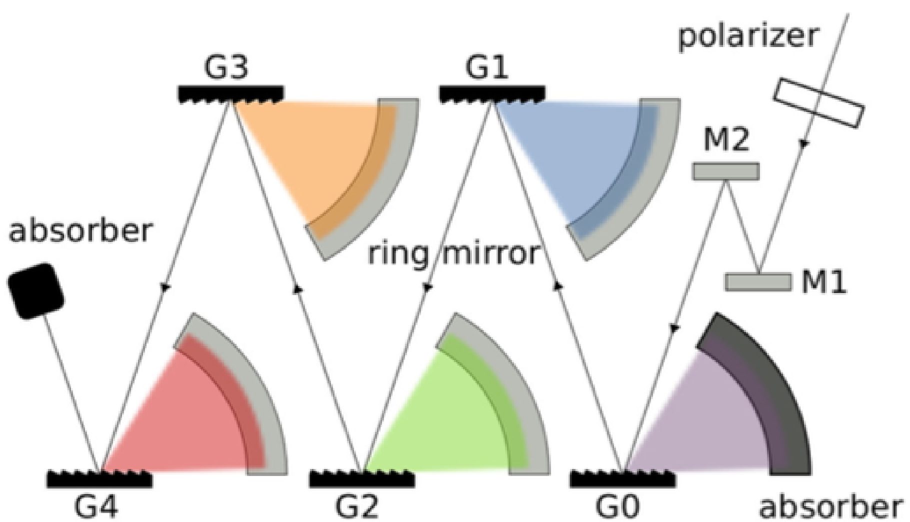
Currently available spectrometers

CRISP4:
MIR-FIR spectrometer

- Two possible configurations:

$$5 - 44\ \mu m$$
$$45 - 430\ \mu m$$

- Multi-stage grating spectrometer.
- Used as a standard tool at FLASH.



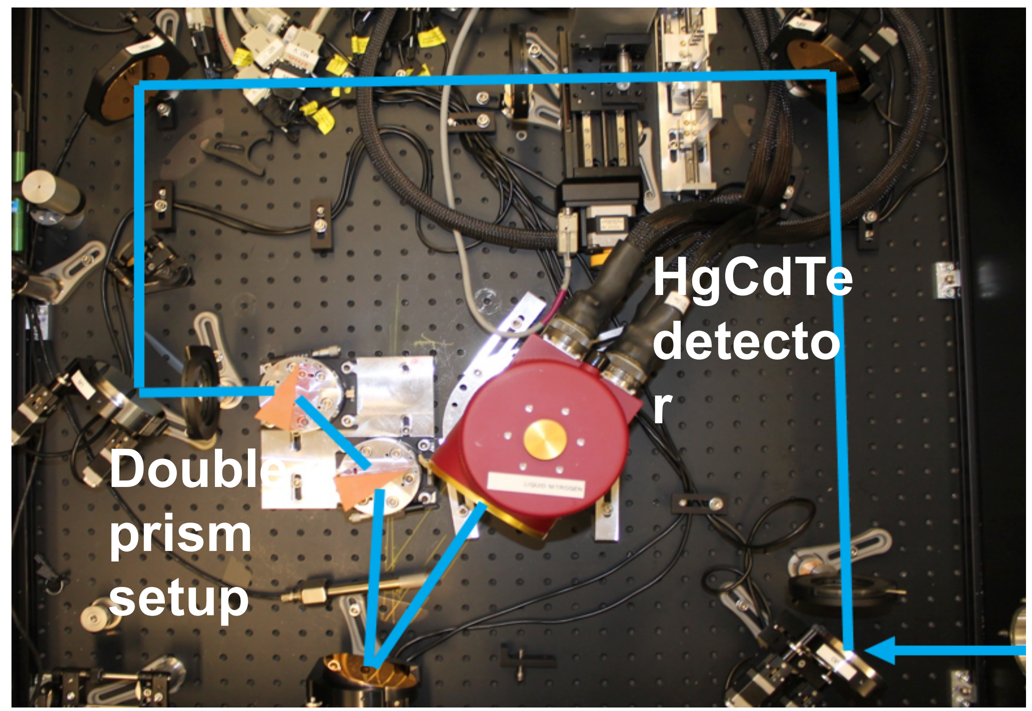
S. Wesch et al. NIM **A 665,** 40-47 (2011)

Double prism:
NIR-MIR spectrometer

- Sensitive to:

$$2 - 18\ \mu m$$

- Dispersion in two ZnSe prisms.
- High sensitivity HgCdTe detector.
- Recently calibrated during beam time in the Netherlands.



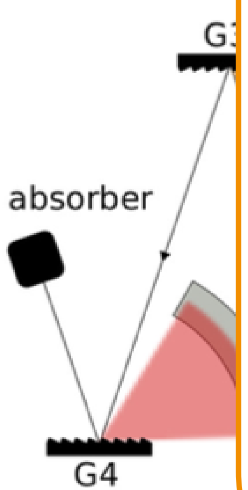
S. Wunderlich et al. Proc. IBIC2014

Currently available spectrometers

MIR

> Two p

> Multi-
> Used
FLASH.



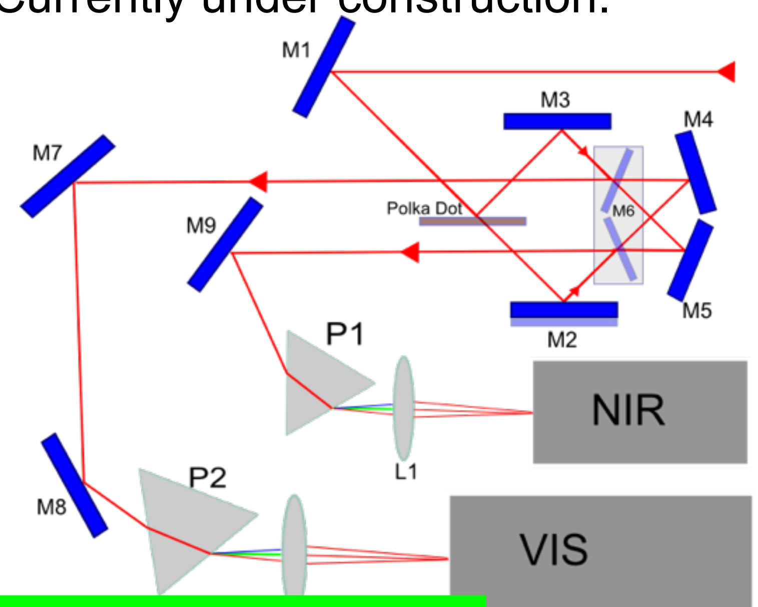
Wesch e

Two stage prism:
VIS-NIR spectrometer
0.3-2 μm

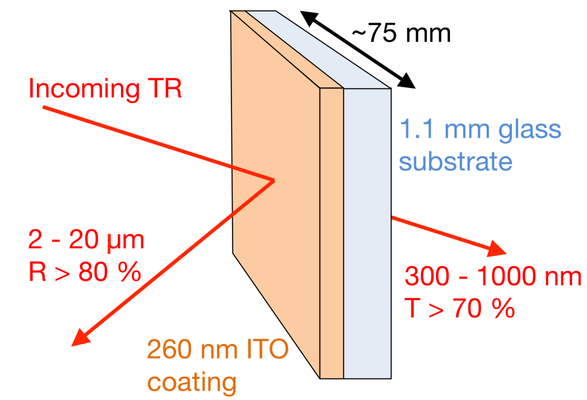
> Setup combining beamsplitters and two prisms.

> Flexible configuration to enable TR spectral measurements and beamsplitter calibration.

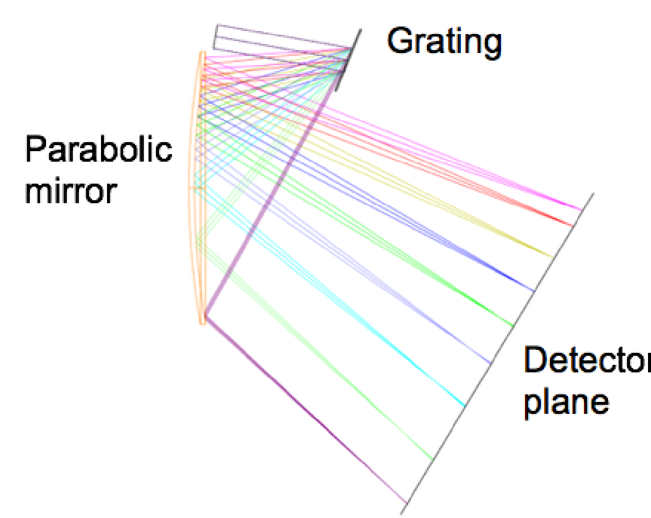
> Currently under construction.



Beamsplitters,
e.g. Indium Tin Oxide:



Grating beamsplitter:



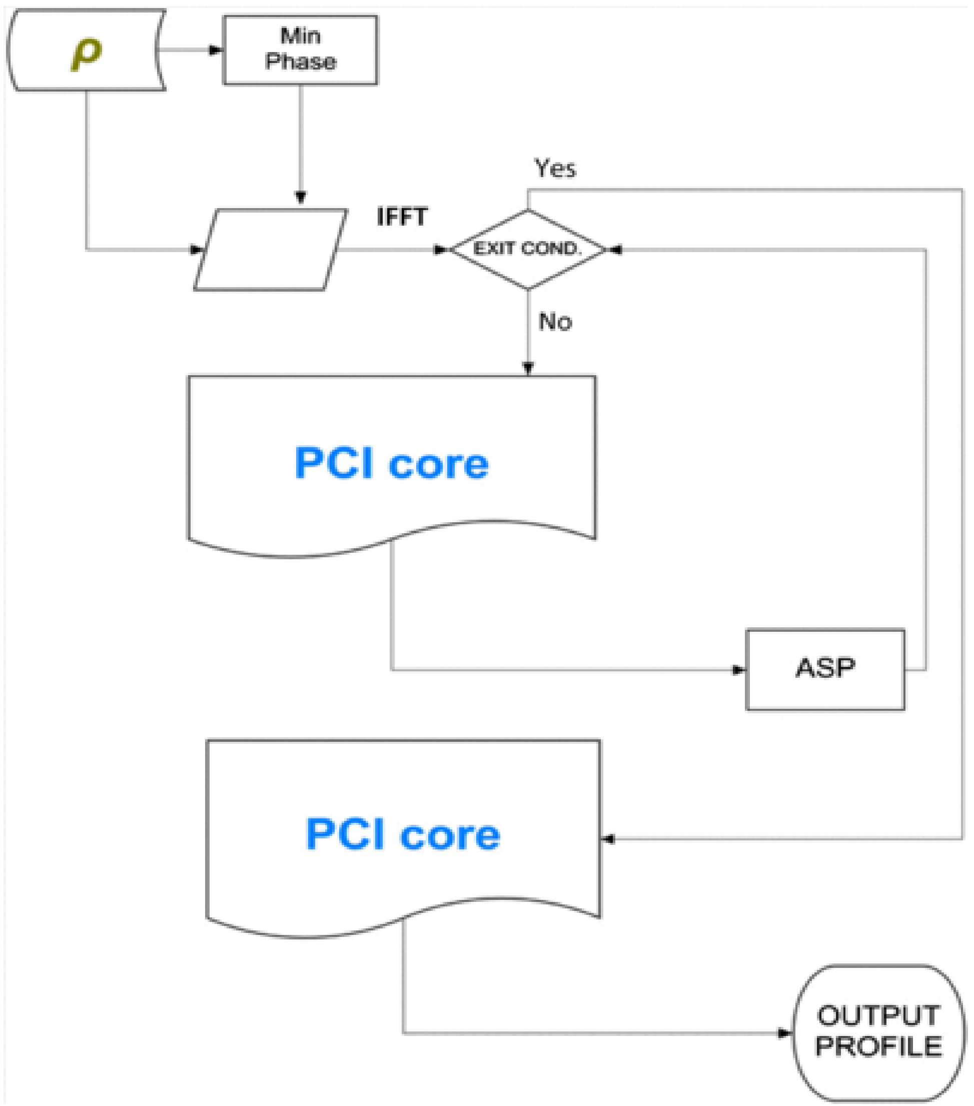
erlands.

Three spectrometers → a wide range of wavelengths
Most components for TR are available
(chamber, diamond window, spectrometers)

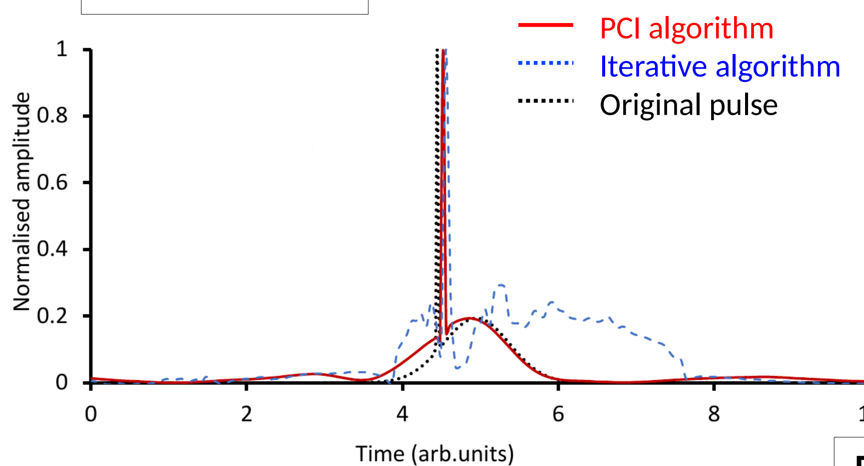
Phase-Constrained Iterative Algorithm (PCI)

F. Taheri *et al.* *PRSTAB* **19** (2016) 032801

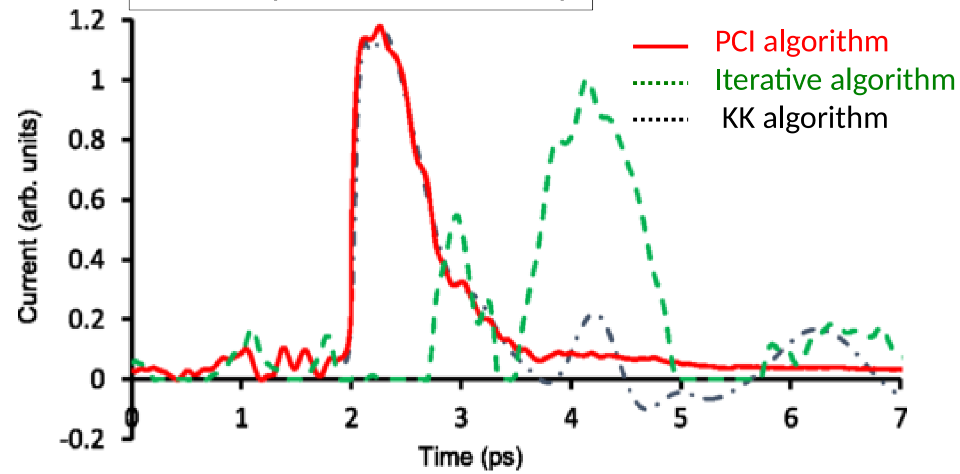
- Reconstruction of the longitudinal profile (phase retrieval) is a fundamental problem for "radiation-based" diagnostics (transition radiation, Smith-Purcell radiation)
- A new technique (PCI) was proposed



Simulations



Data (FACET E203)

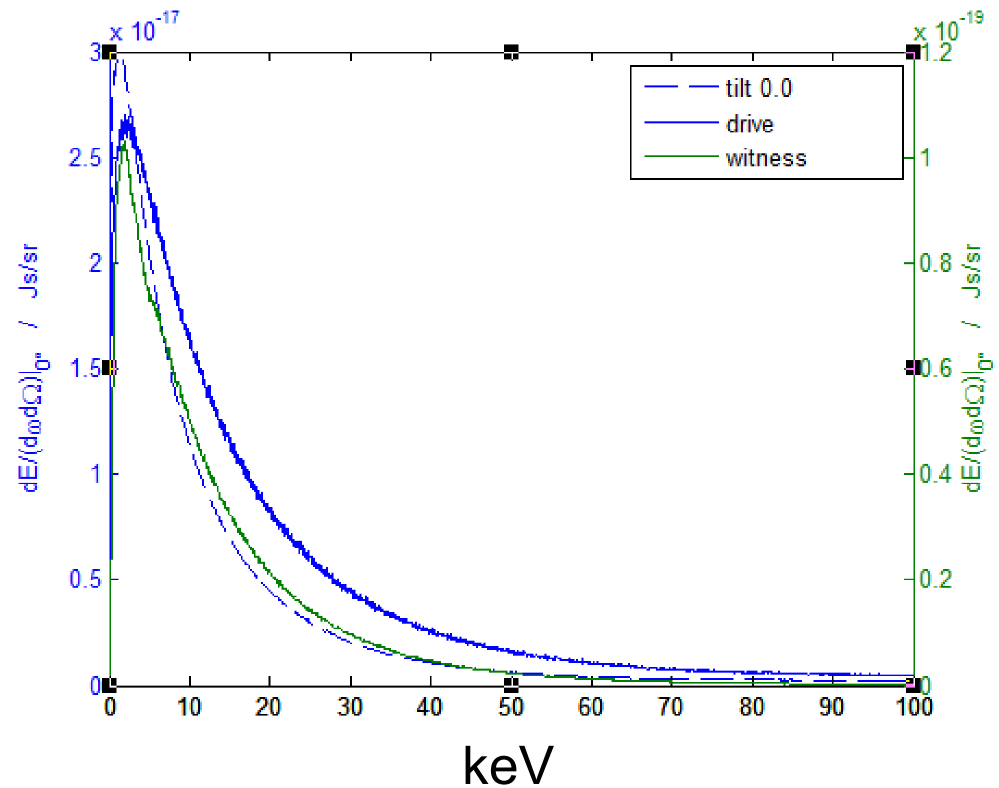


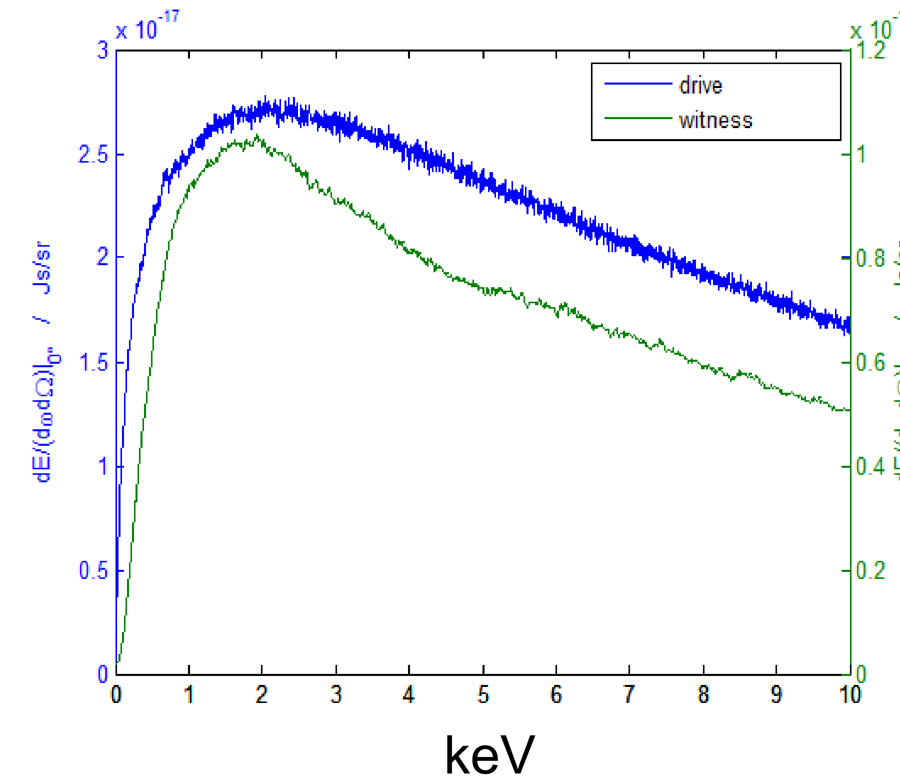
Reliable reconstruction with fewer assumptions

Betatron radiation

> Properties of the radiation needed to design the diagnostics: PIC simulations (HiPACE)

> Driver: γ_0~2000, Q~500 pC, witness: γ_{fin}~5000 , Q~13.5 pC





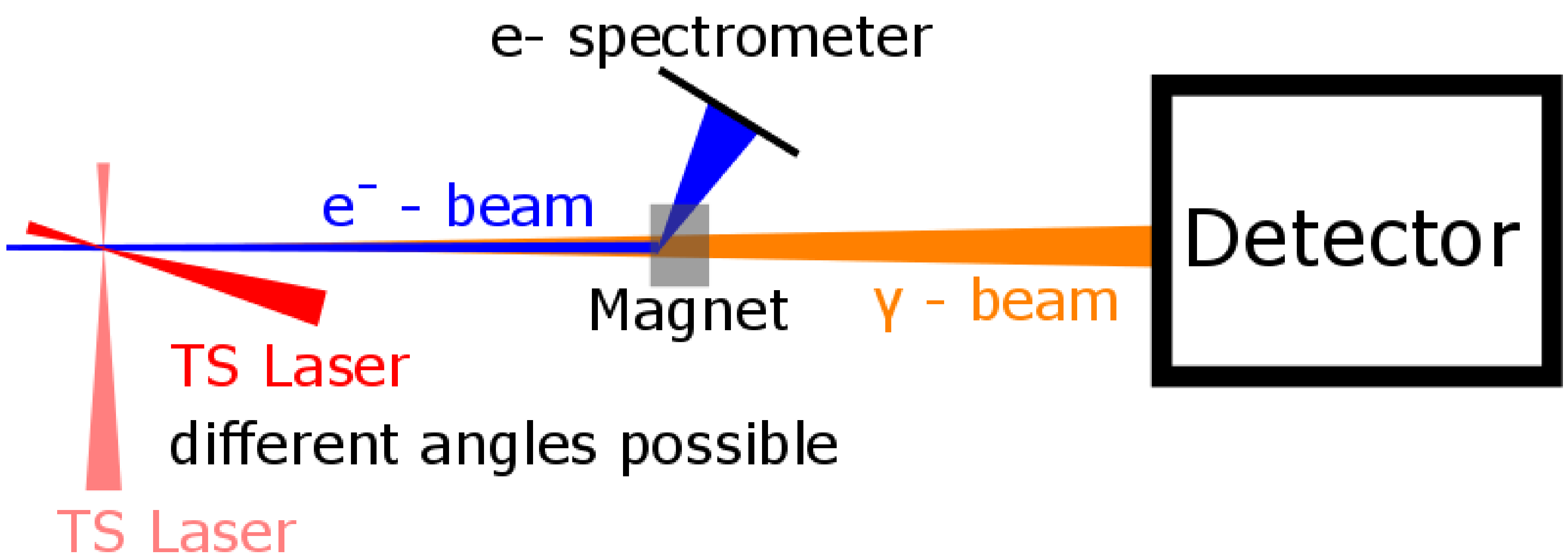
> Similar spectra → difficult to distinguish driver/witness

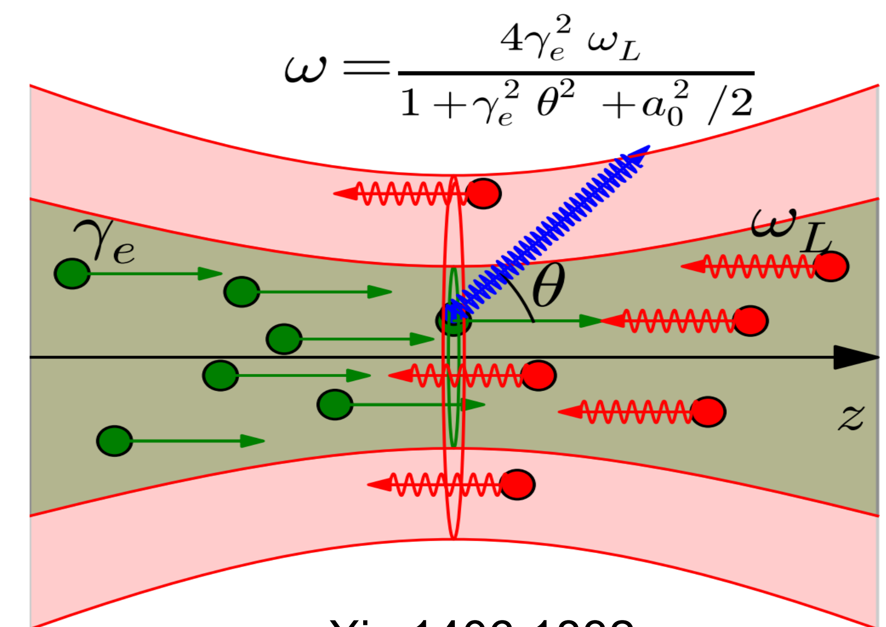
> Spectra peak at few keV → can use a direct detection device

> Experimental setup in progress (ordering an X-ray CCD camera etc.)

Inverse Compton Scattering (ICS)

- Laser pulse scattered from e⁻ beam produces γ-rays whose spectrum/ divergence are related to those of e⁻ beam
  → might be used as a diagnostic tool
- In transverse geometry also sensitive to longitudinal structure of e⁻ beam





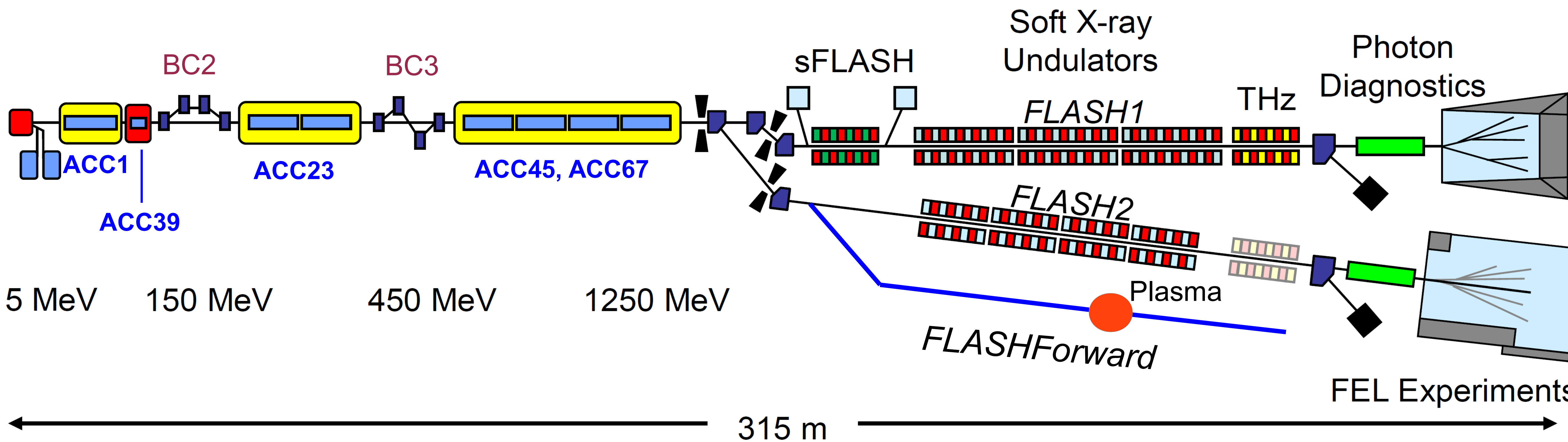
arXiv:1406.1832

- For a given θ, ω depends only on γ_e
  → reconstruct e⁻ energy distribution by measuring the photon spectrum
- Opening angle ~ $1/\gamma_e$ ($\sigma_{x'}=0$) and related to $\sigma_{x'}$ if $\sigma_{x'} >> 1/\gamma_e$
  → reconstruct e⁻ divergence by measuring γ-beam divergence

Setup ready to be tested in the BOND lab (scintillator array as γ-detector)

See talk C. Palmer

Beam dynamics simulations



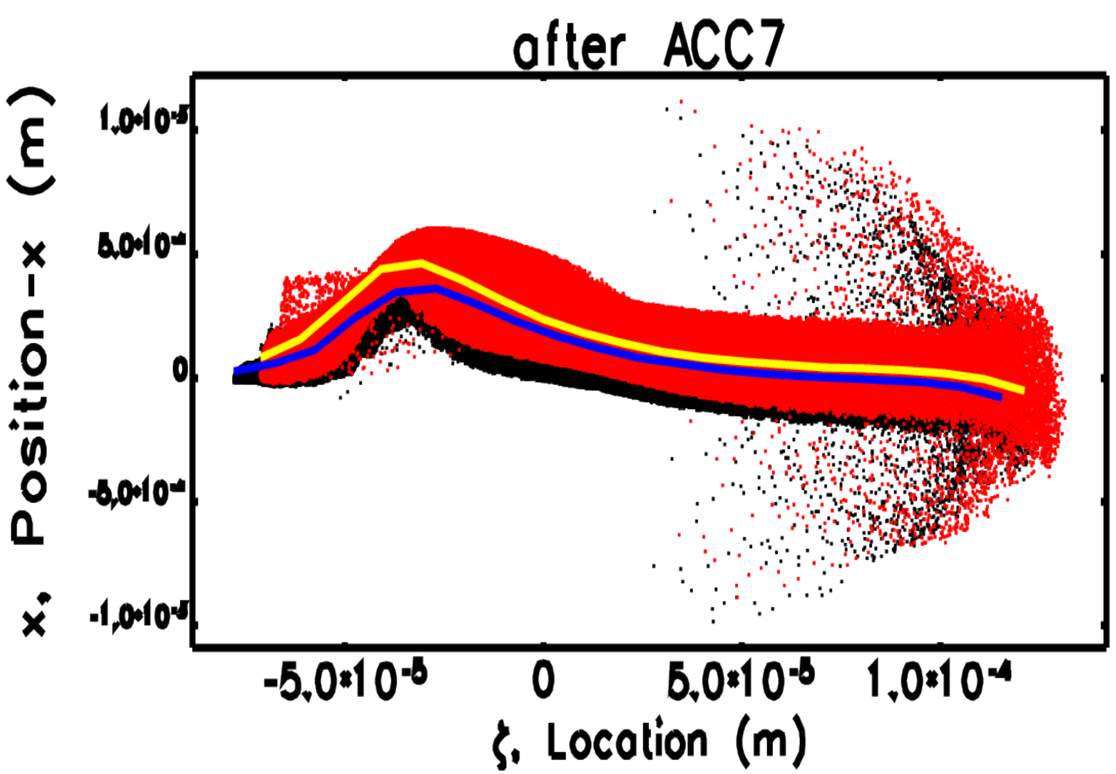
The global goal: start-to-end simulations
Gun → FLASH → FLASHForward → PLASMA → Undulator

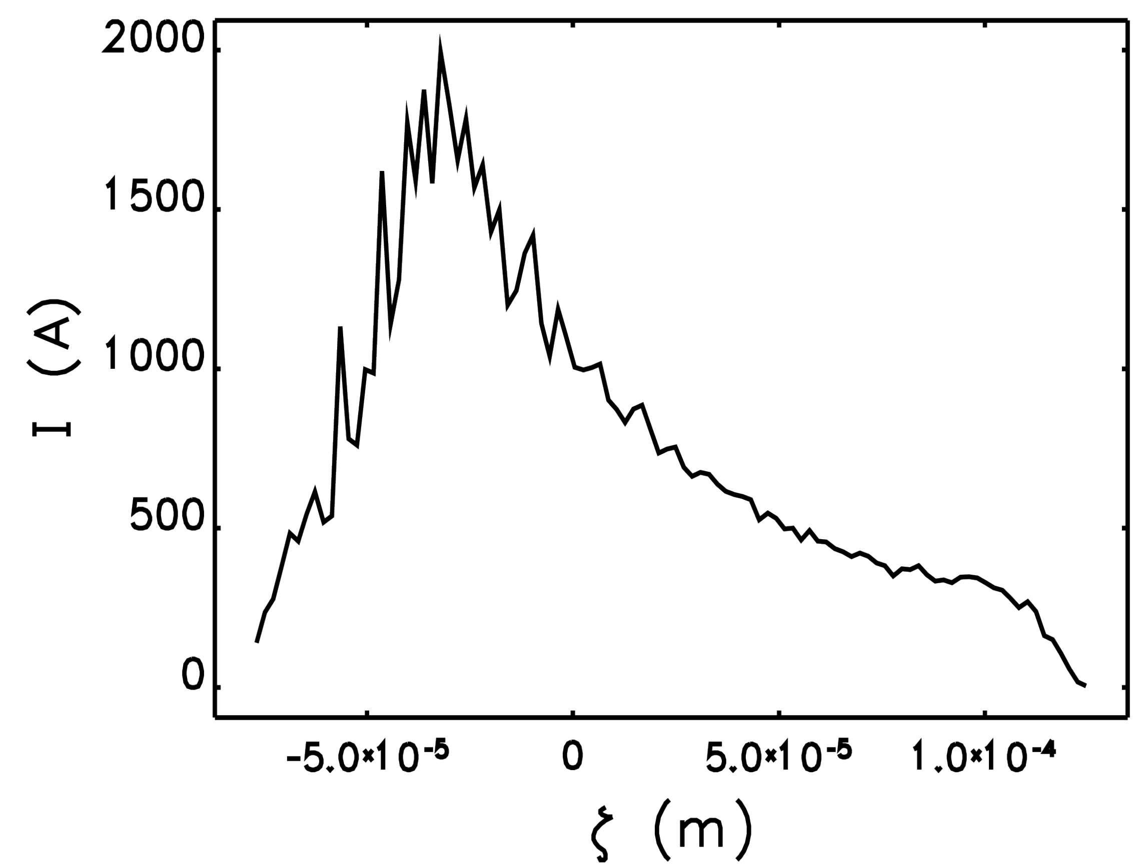
- Which beam parameters are realistic?
  - typically high currents, ramped profile, small spot, … are desired for PWFA
- What are the accelerator settings to achieve them?

Coherent synchrotron radiation (CSR)

> CSR is a limiting factor for high-current electron beams
  > Centroid offsets are developed during compression in chicanes → **hosing instability**

See talk
A. Martinez





> Work is ongoing to define a mitigation strategy
  > Options: beam optics; tailored beam profiles; transverse-longitudinal mixing; emittance spoiling
  > **Beam time at FLASH later this year**

Summary and Outlook

- WG2 is a platform to discuss **beam dynamics** and **instrumentation** for FLASHForward

- Pre-plasma beam line is in advanced state, started installations end of 2015, will continue in 2016
  → Commissioning expected to start in July 2017

- Technical design of the post-plasma beamline in progress

- Standard diagnostics ordered or delivered
  → Beam position monitors, charge monitors, profiling screens
- Special diagnostics design in progress
  → Transition radiation, betatron radiation, inverse Compton scattering

- Beamline simulations including FLASH linac show strong CSR effects
  → concentrating now on mitigation CSR while maintaining high current

Thanks for your attention!

Extra material

Where we are (milestones)

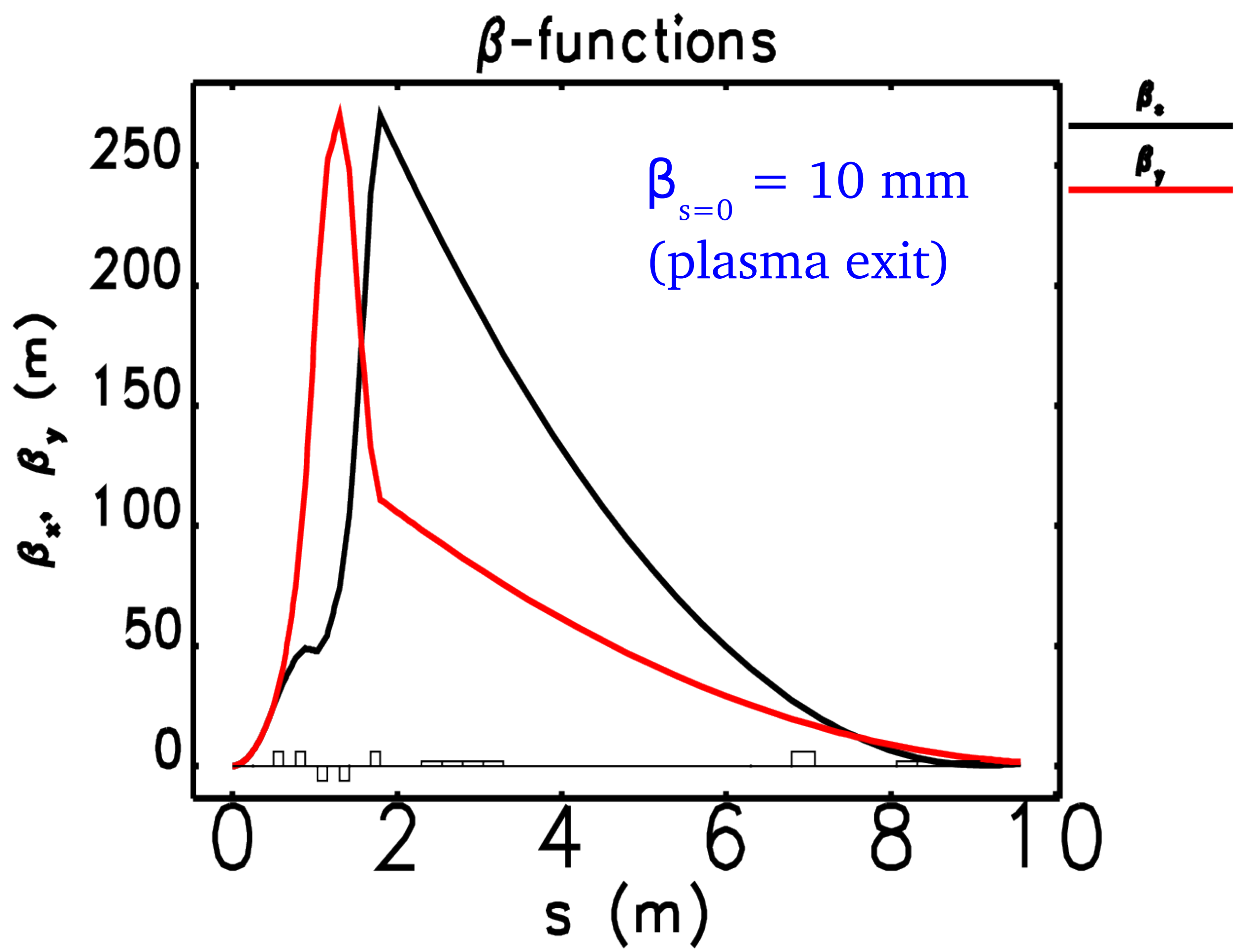
Q3 2013	Establish VI WG 2
Q3 2013	Conceptual design of the post-plasma beamline for Phase I
Q2 2014	Conceptual design of the beam capturing section
Q4 2014	Concept for generic beam diagnostics
Q3 2015	Conceptual design for transition radiation diagnostics
Q3 2015	Concept for betatron-radiation diagnostics
Q4 2015	Technical design of the post-plasma beamline, including all diagnostics
Q4 2016	Procurement, installation and commissioning (Phase I)
Q4 2017	Conceptual design of the beamline for Phase II
Q4 2018	Tecnical design of the beamline for Phase II

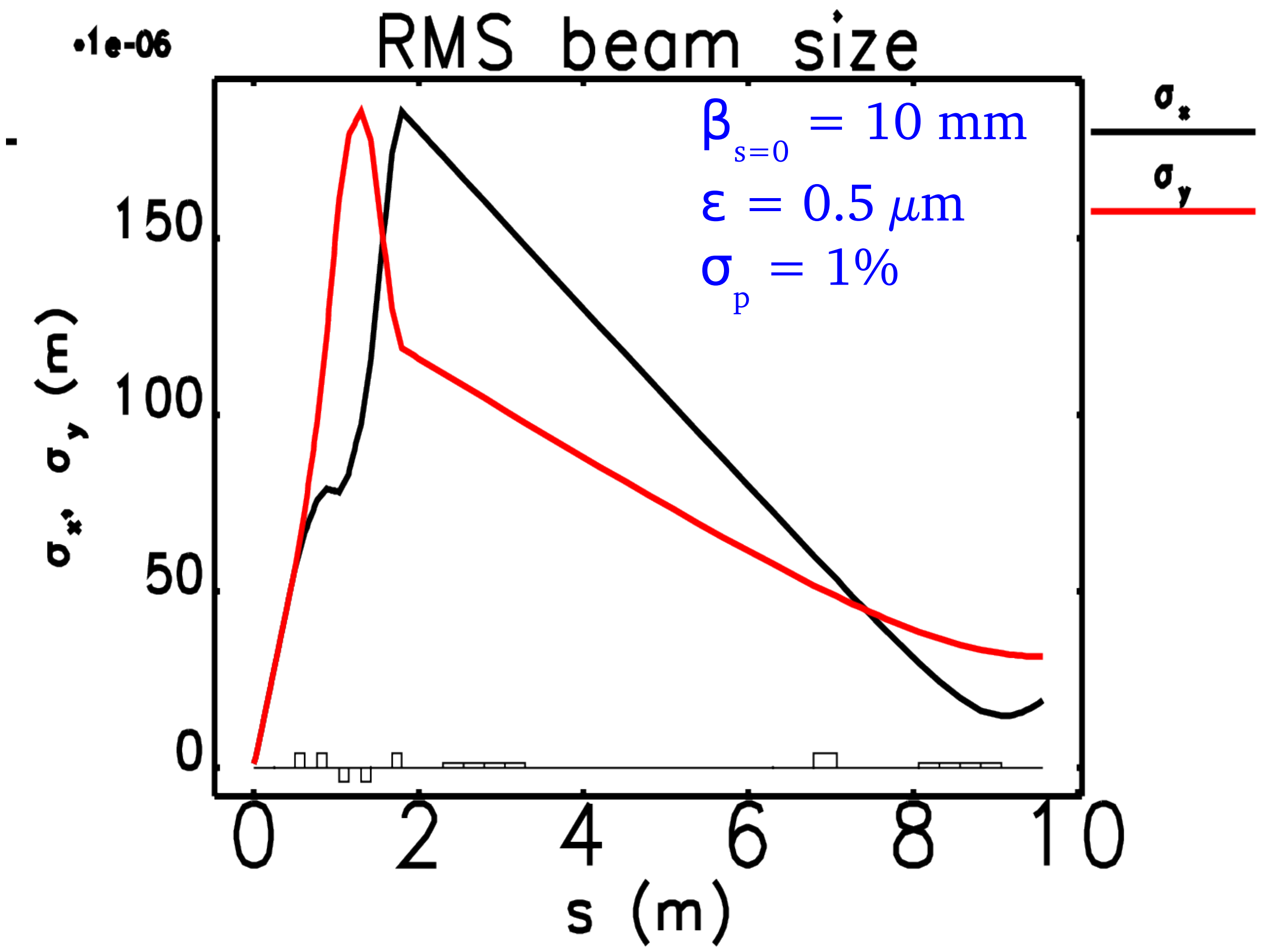
Completed

In progress

To be started

Beam optics

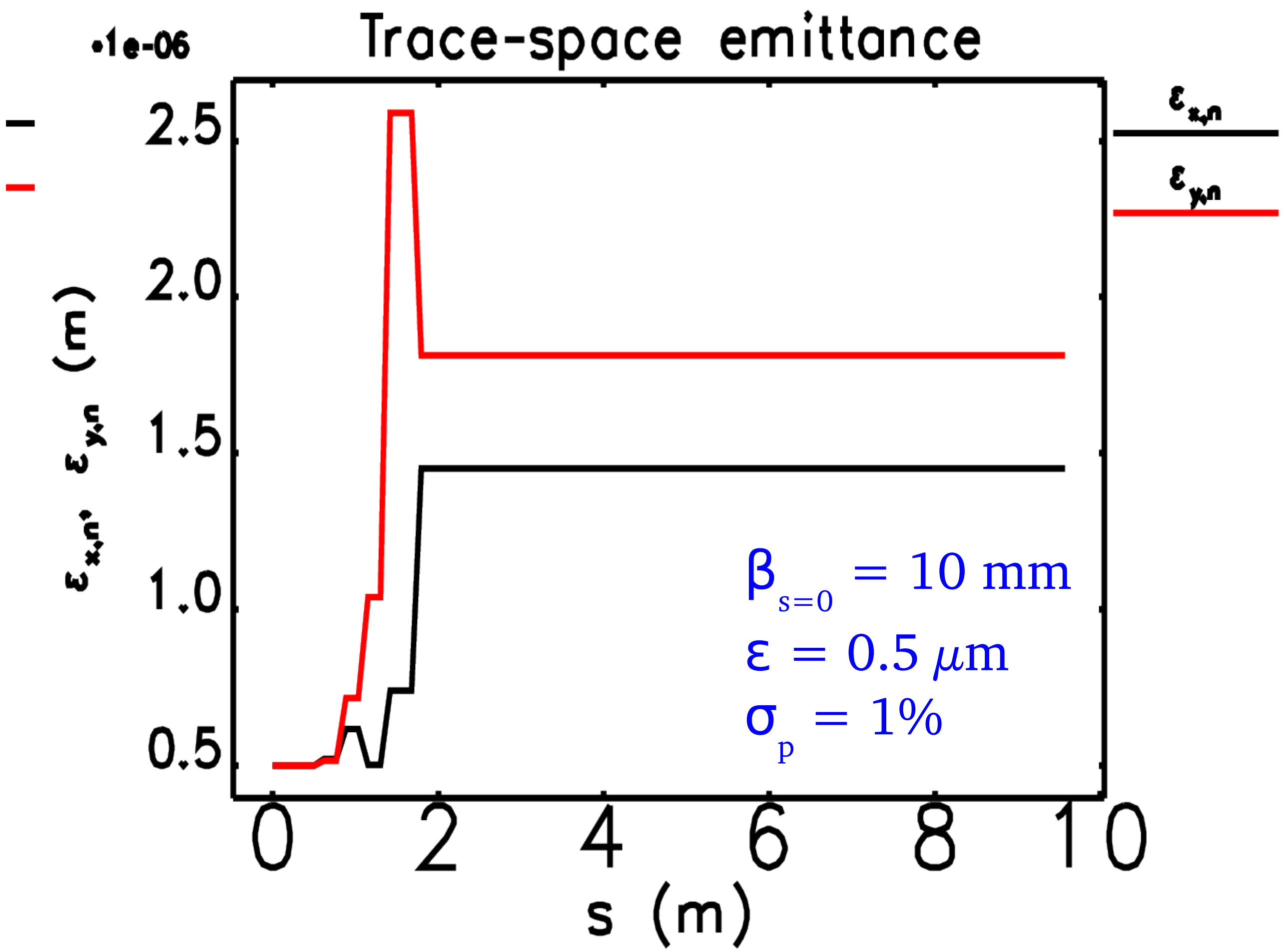


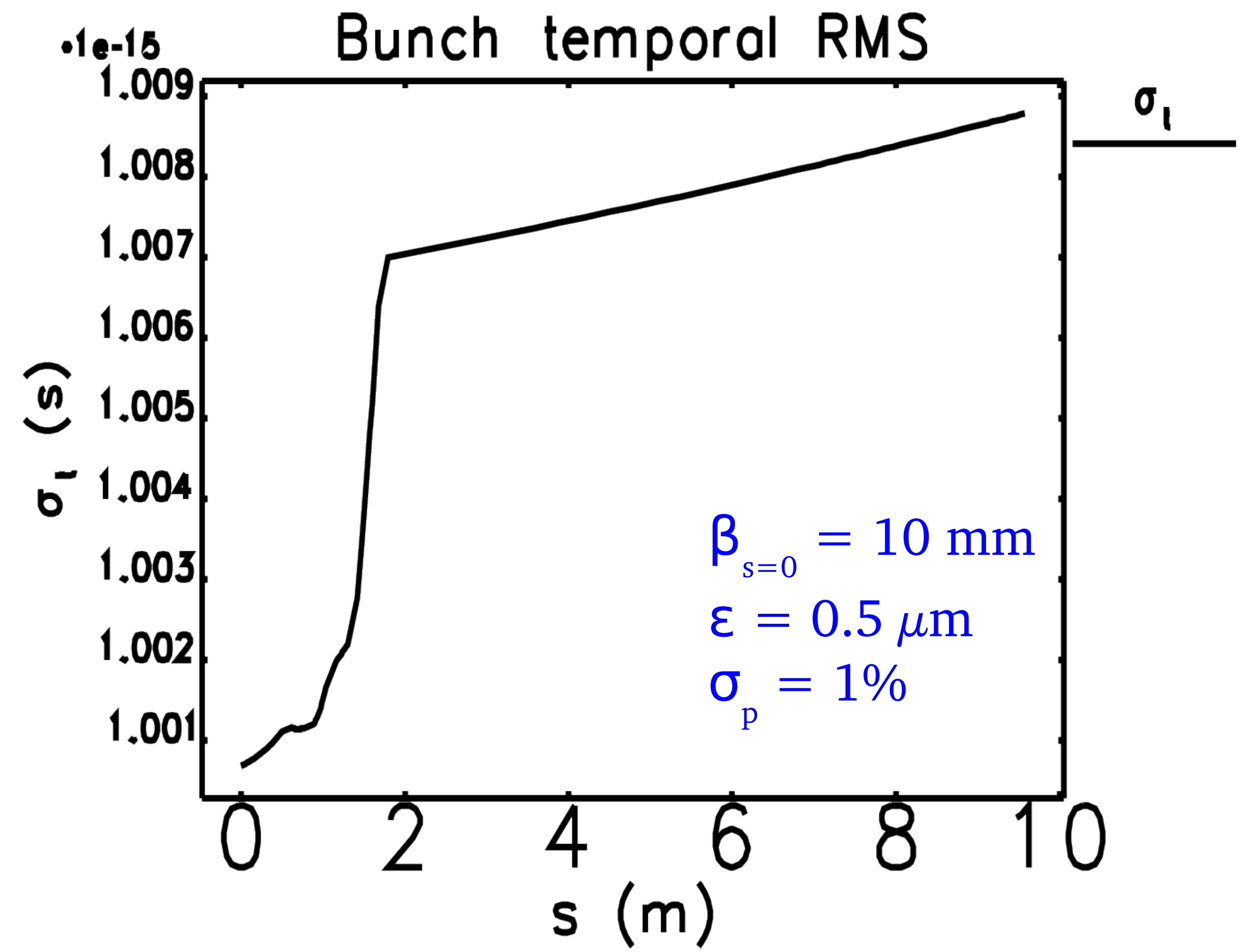


- Electromagnetic quadrupoles, $g^{max}=100$ T/m
- Pairing to achieve stronger focusing
- Designed for energies of up to 2.5 GeV

- Beam size below several hundred micron
- Minimum at 2nd dipole → precise energy measurement

Chromatic and higher-order effects



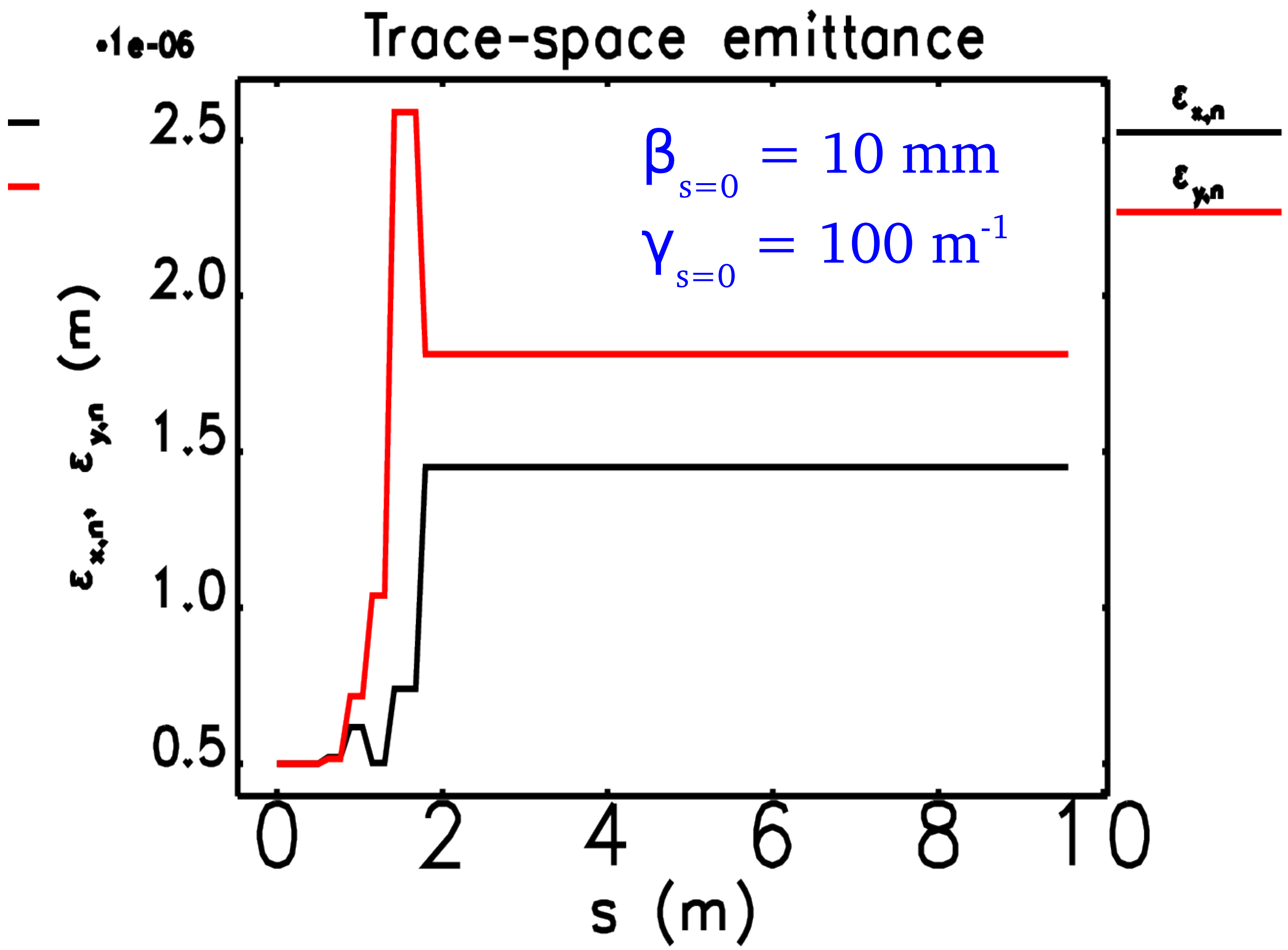


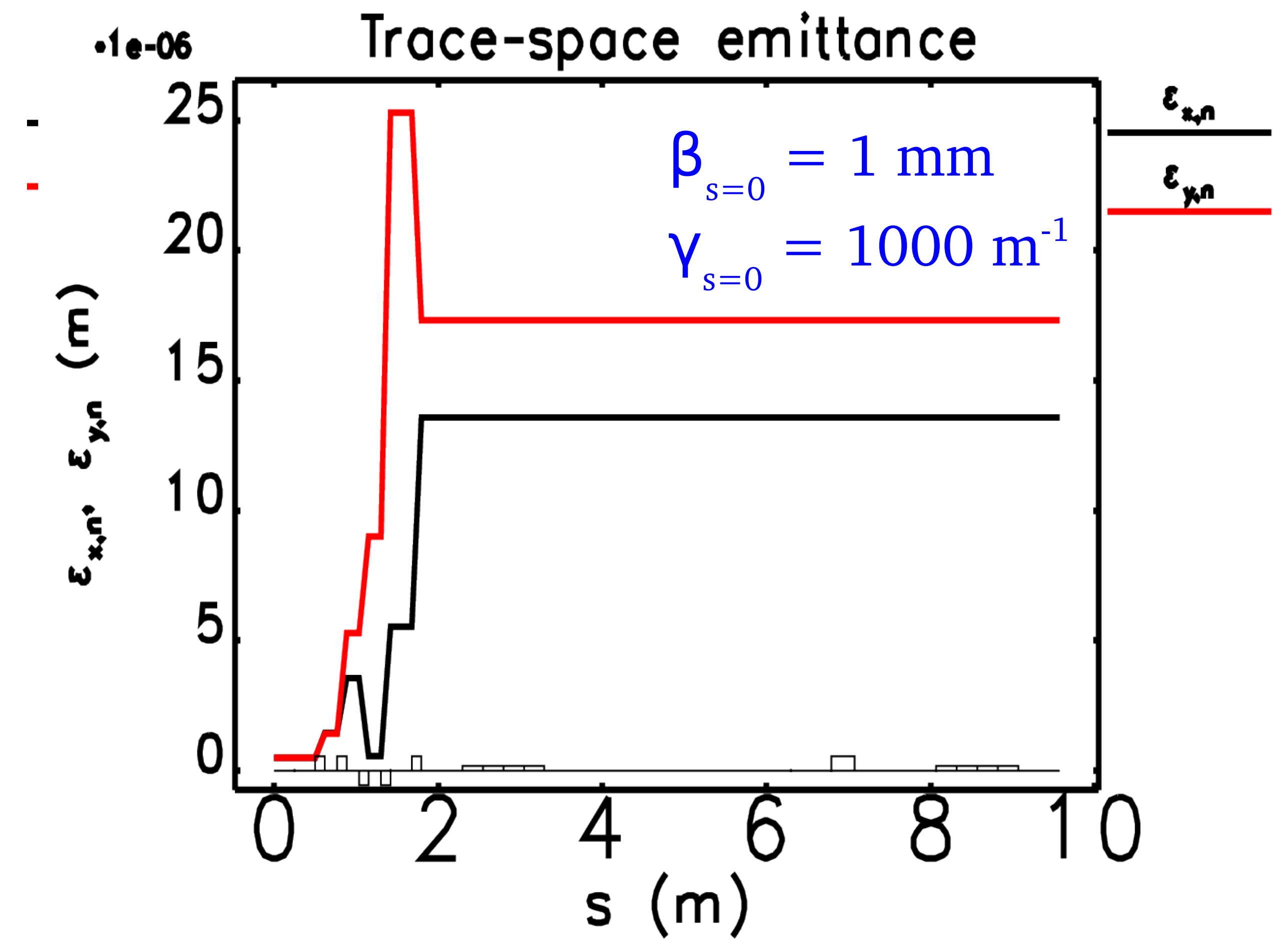
> Emittance growth due to strong quadrupoles and large energy spread

> Bunch elongation due to 2nd-order geometric effects

Quality preservation

> Initial Courant-Snyder parameters are important for beam transport

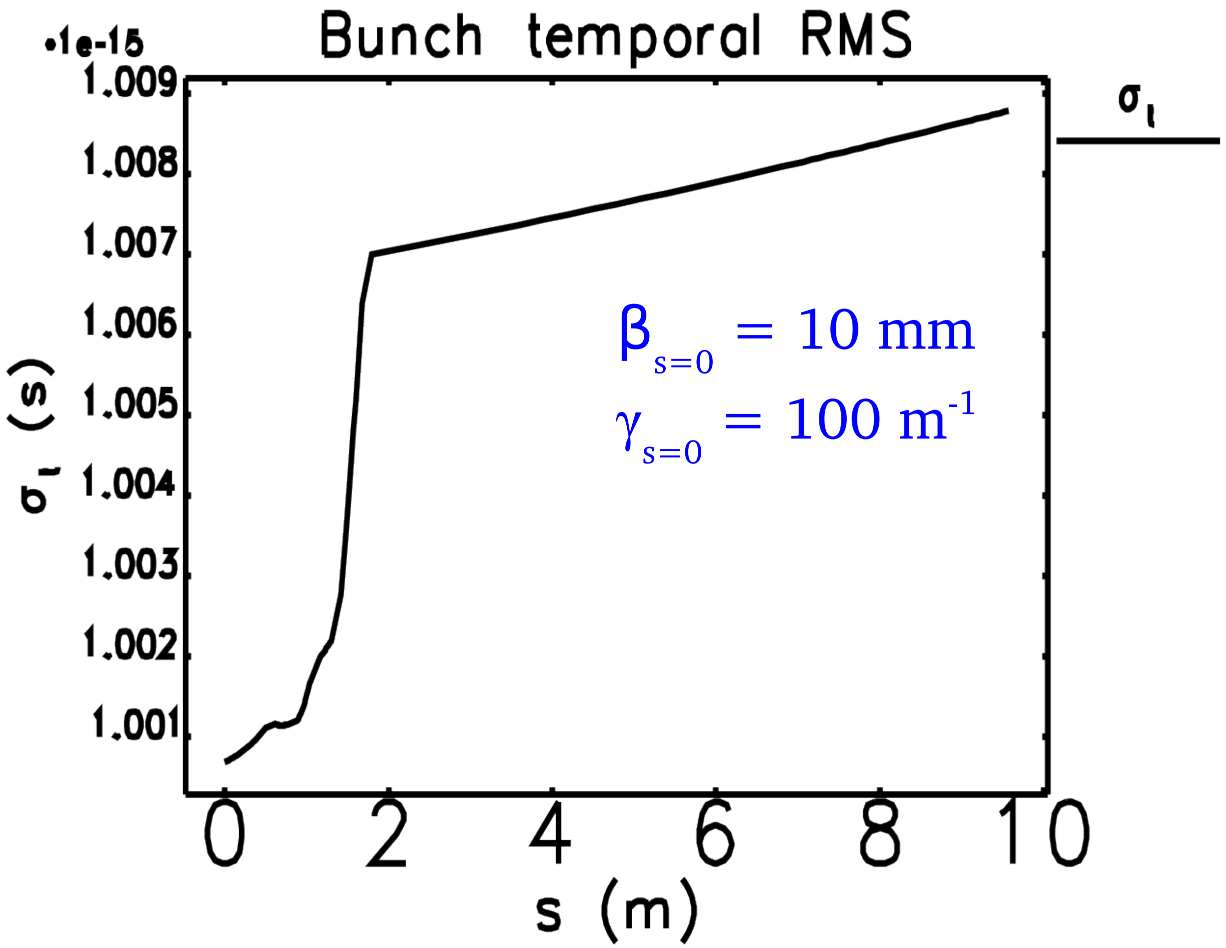


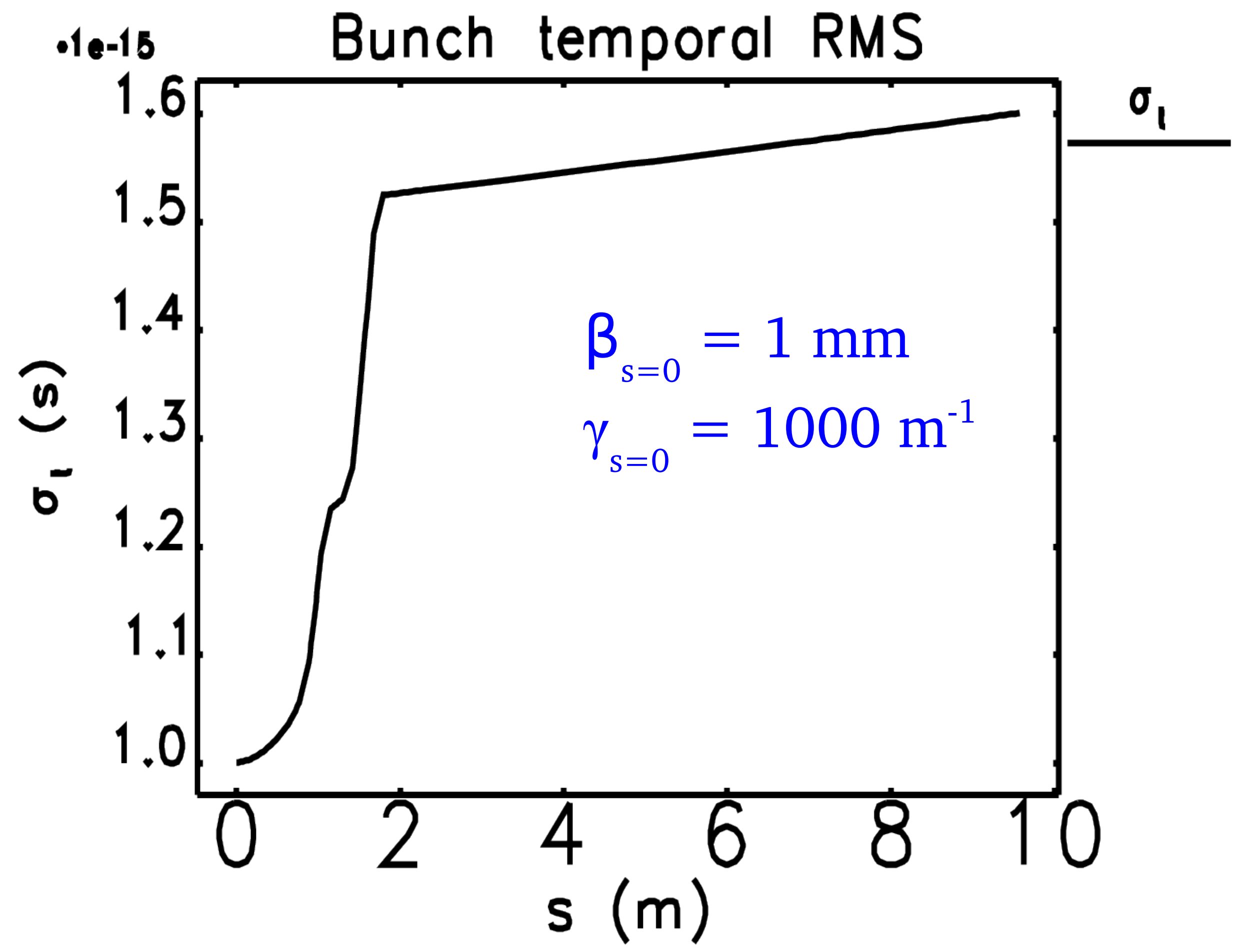


> much more severe growth

Quality preservation

> Initial Courant-Snyder parameters are important for beam transport

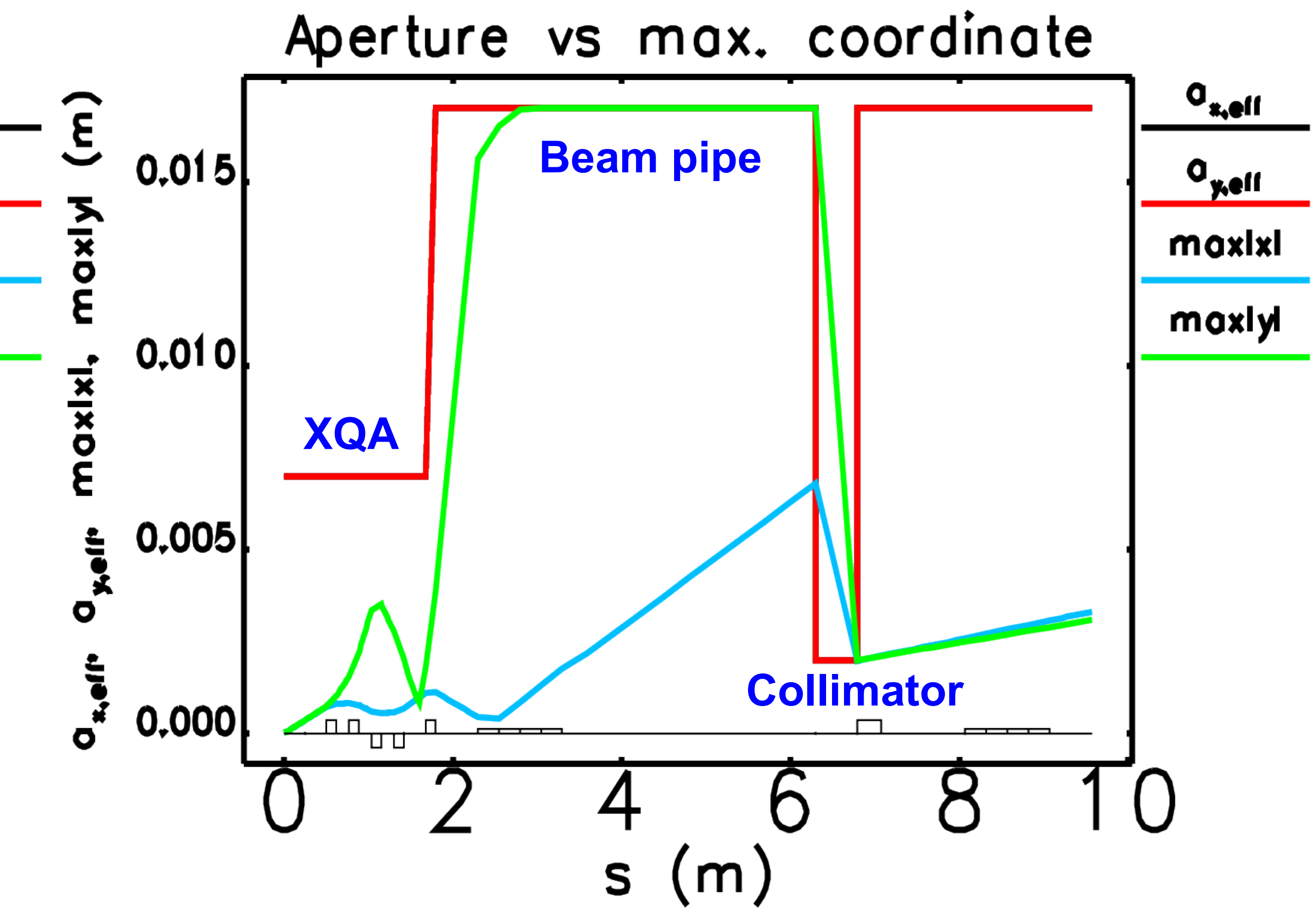


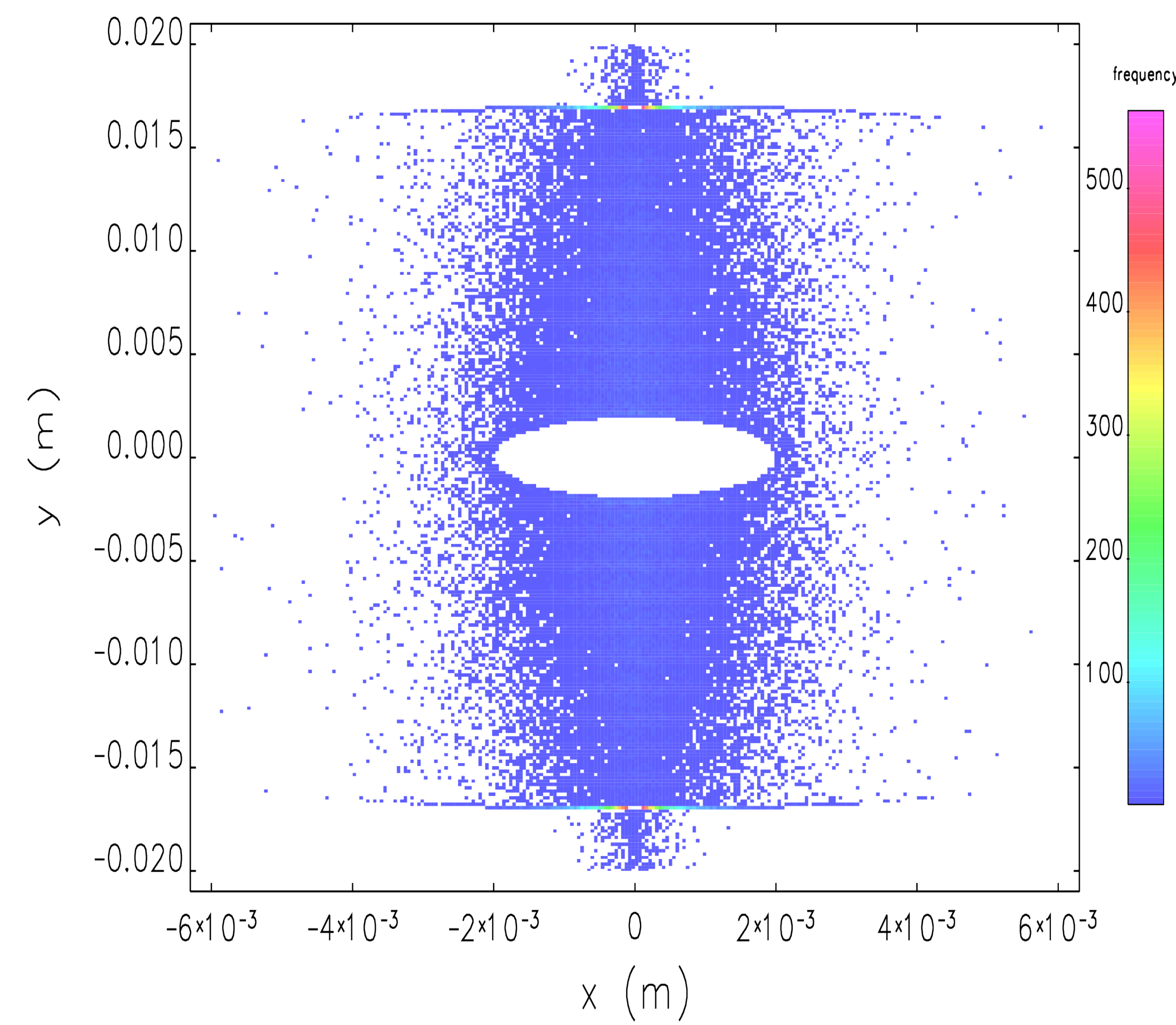


> **Controlled release essential, pursued in WG3**

What about the driver?

> Assuming a linear chirp 0-1 GeV

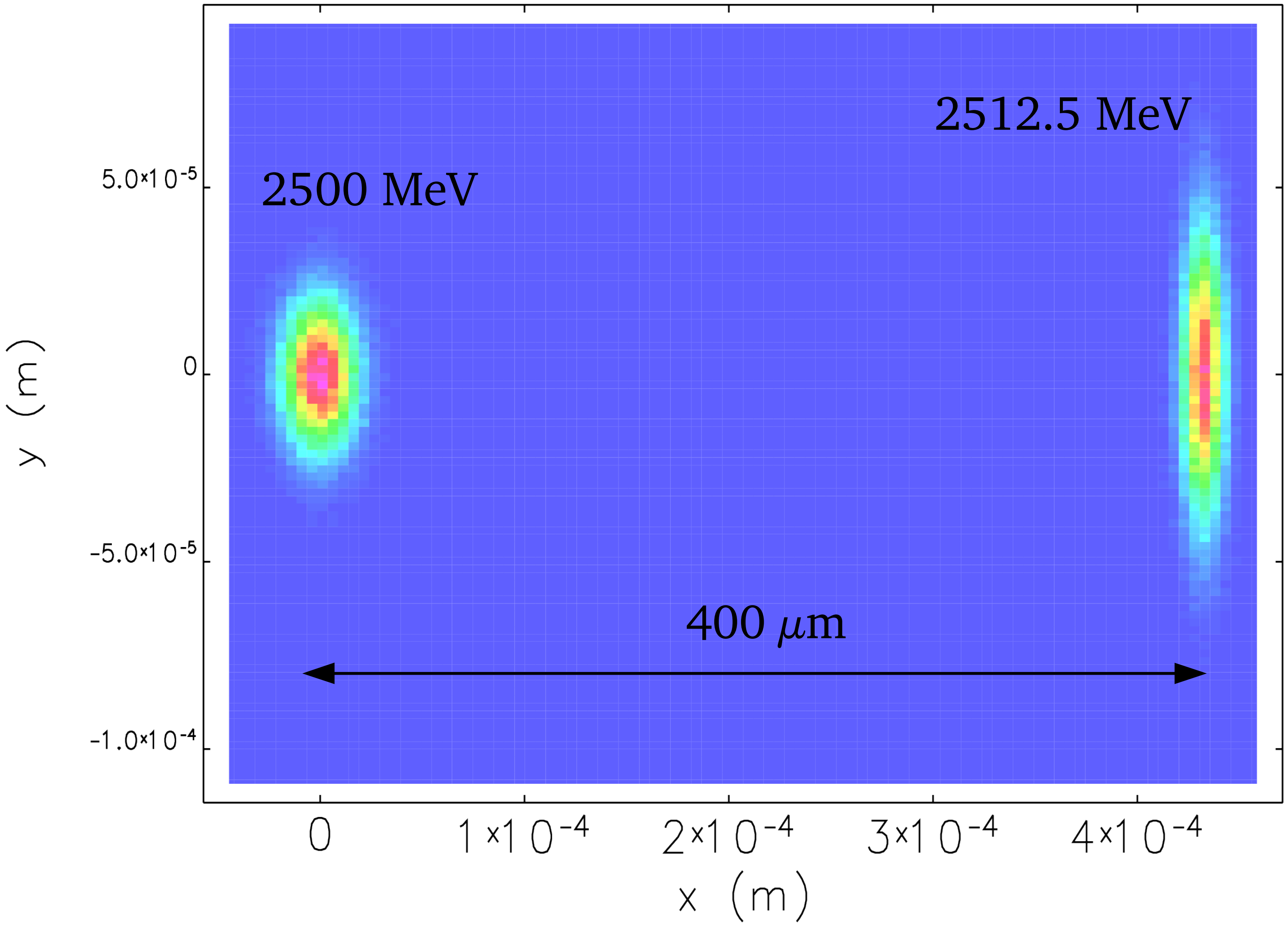




> Eventually fills the available aperture
> Shielding required (predominantly vertical plane)

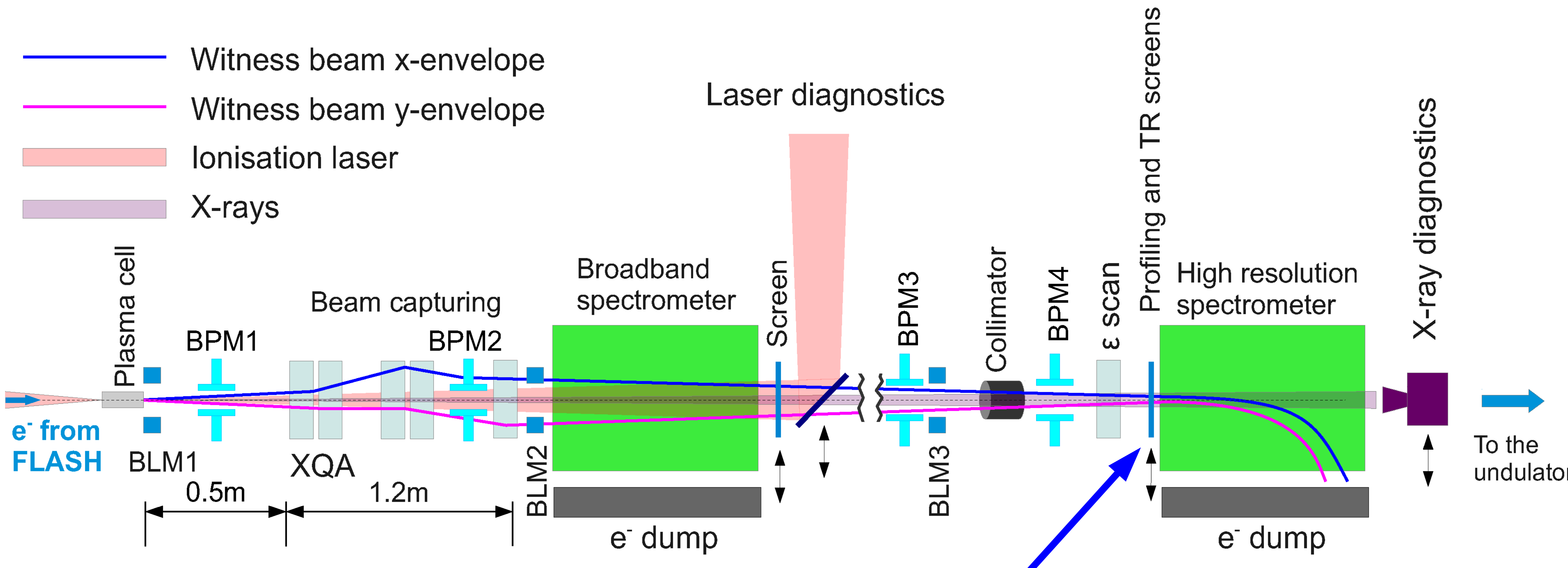
> A collimator helps to remove most of the residual driver (~80%)

Energy measurement (witness)



$400\ \mu m/0.08m=0.005 = 0.5\%$

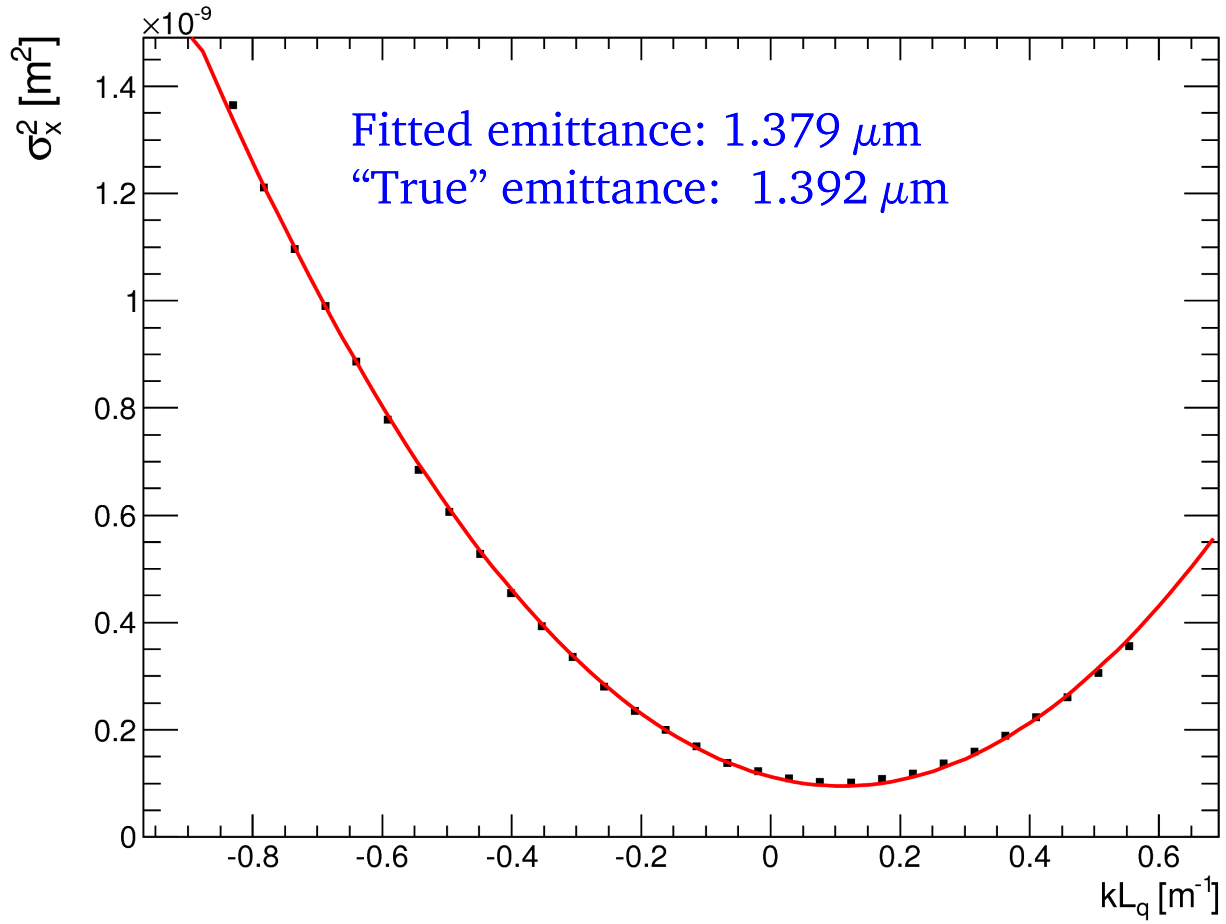
Emittance measurement

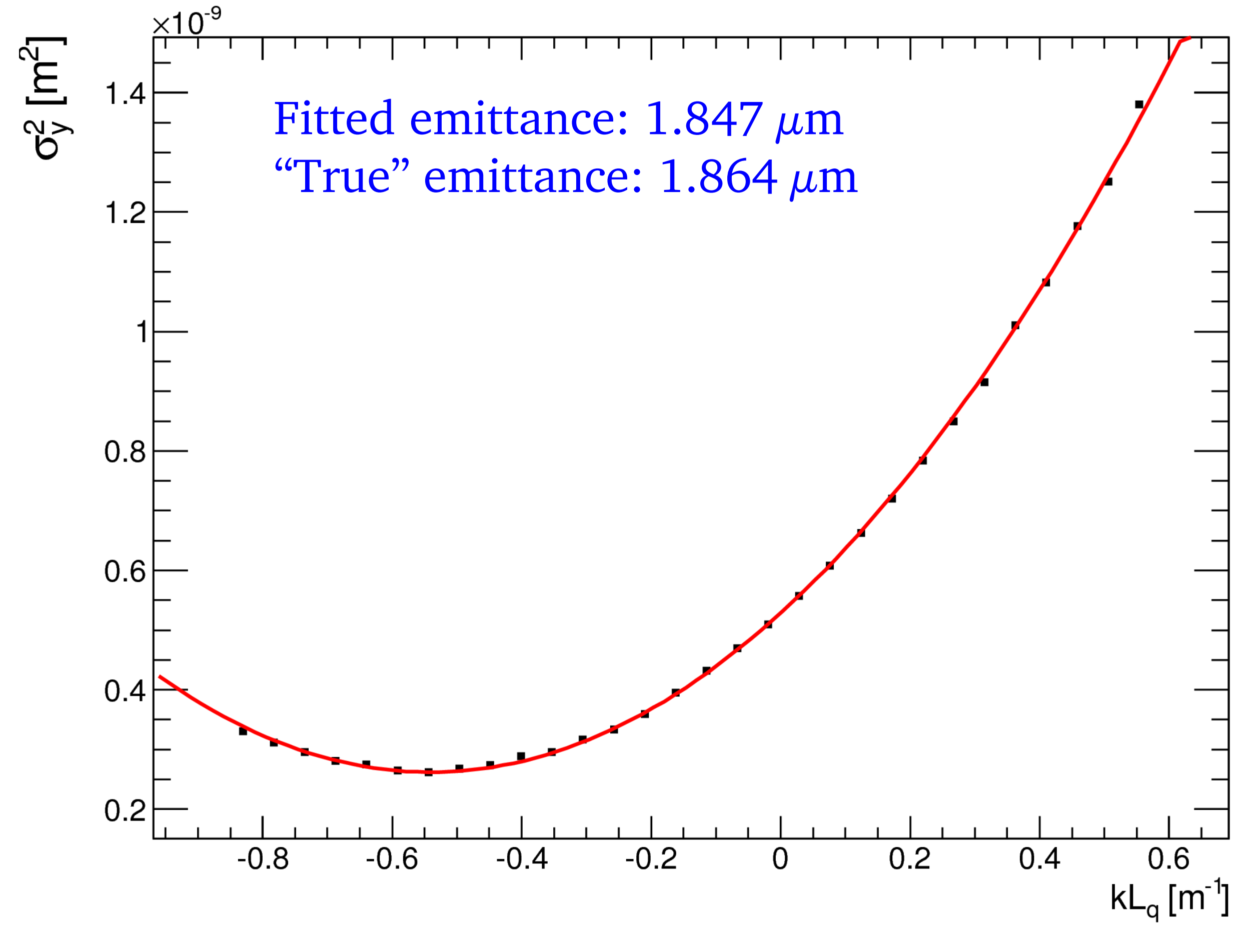


Screen chamber for ε and TR diagnostics

Emittance measurement

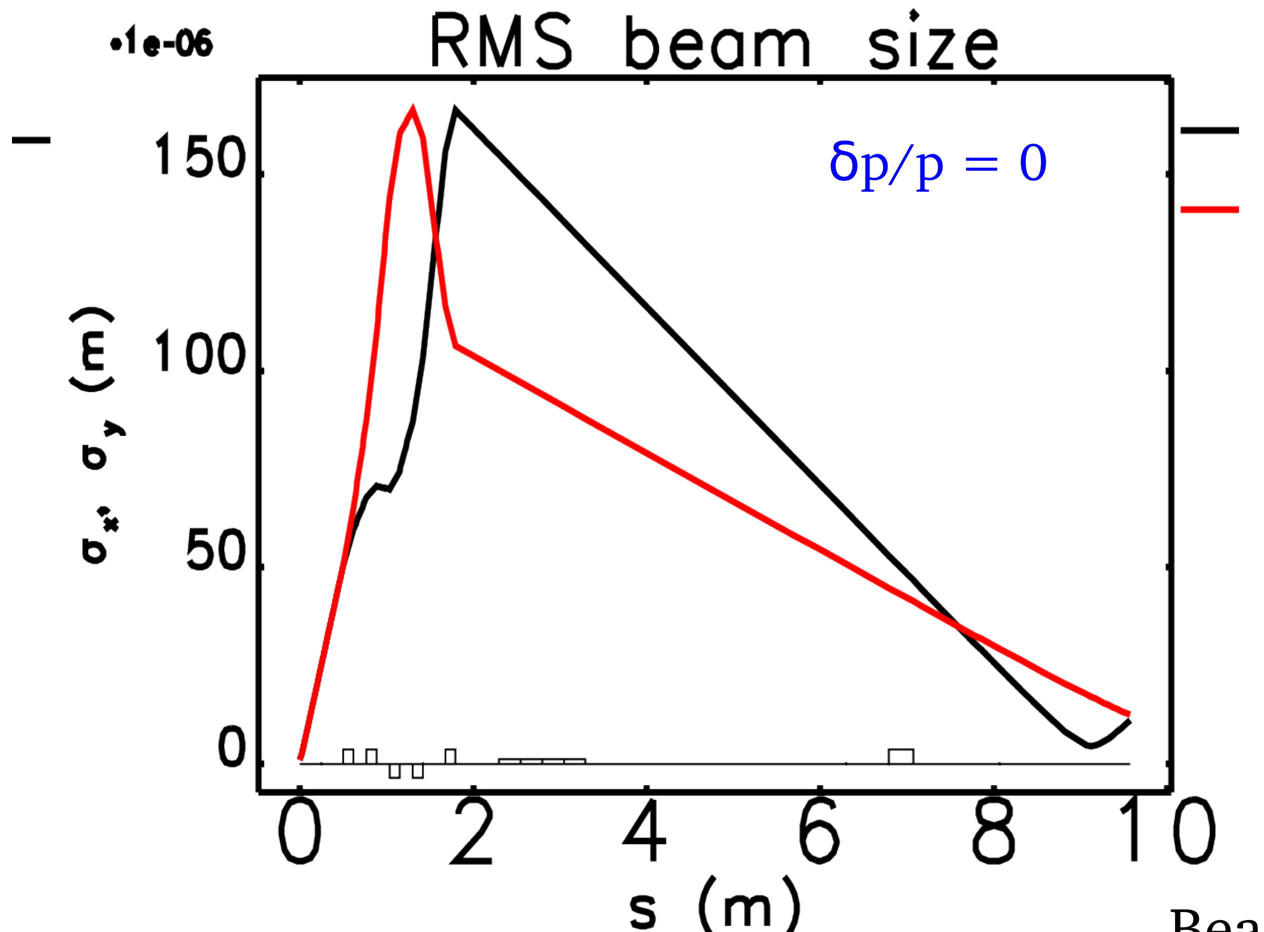
- Single quadrupole scan
- Special optics setting: waist at the screen in both planes → simultaneous measurement

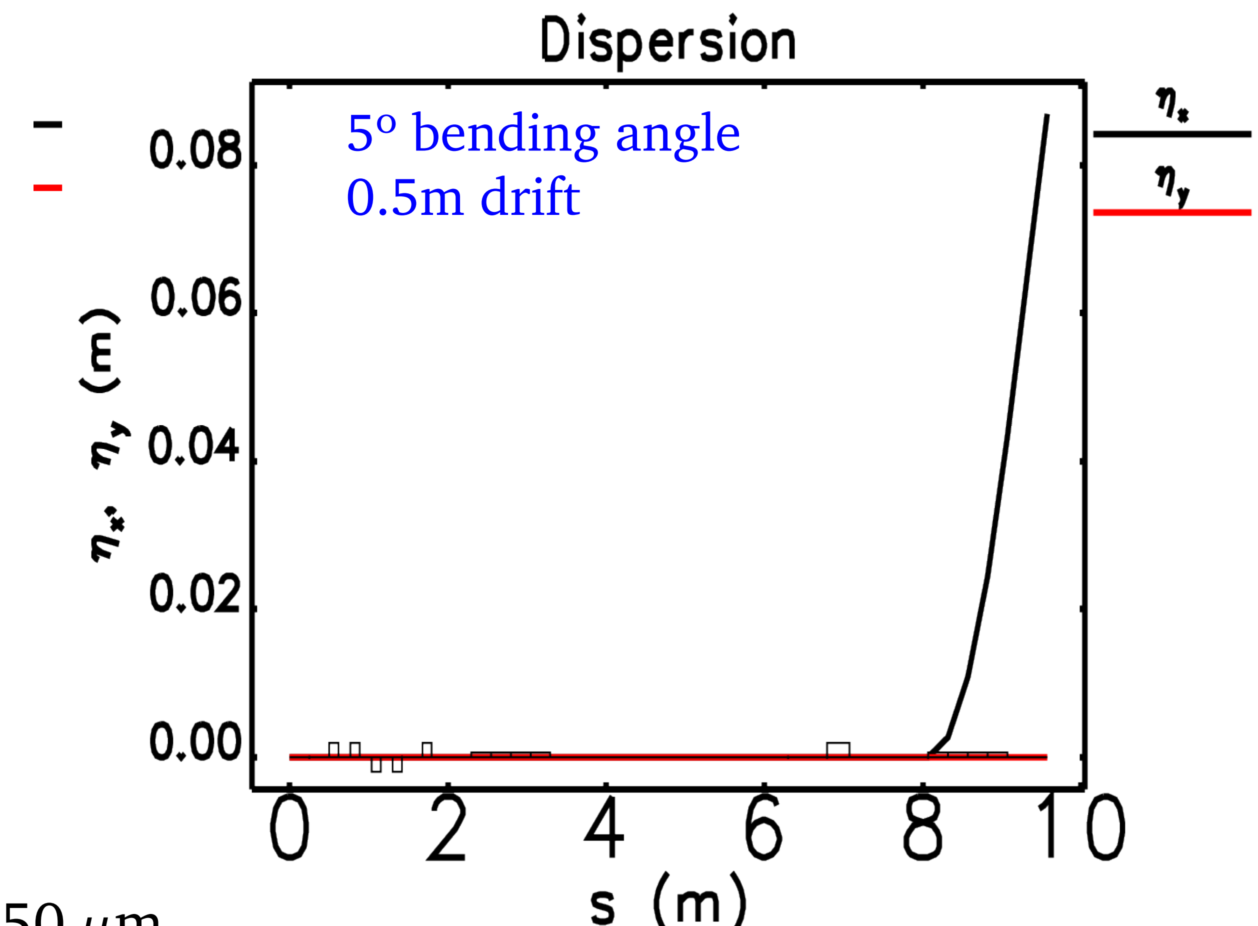




- Excellent match between fitted and "true" emittance
- Note: emittance at the plasma exit is 0.5 μm

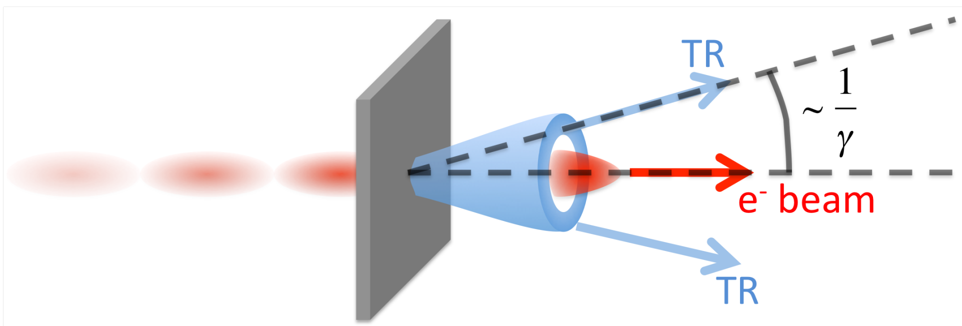
Energy measurement (witness)





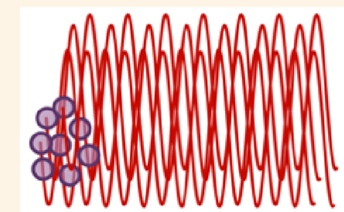
Beam size $< 50\ \mu$m
Dispersion ~ 0.08m
→ Resolution ∼1‰

Transition radiation (TR) as a longitudinal bunch diagnostic



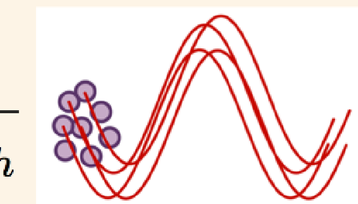
INCOHERENT TR:

$$\omega \gg \frac{1}{\tau_{bunch}}$$

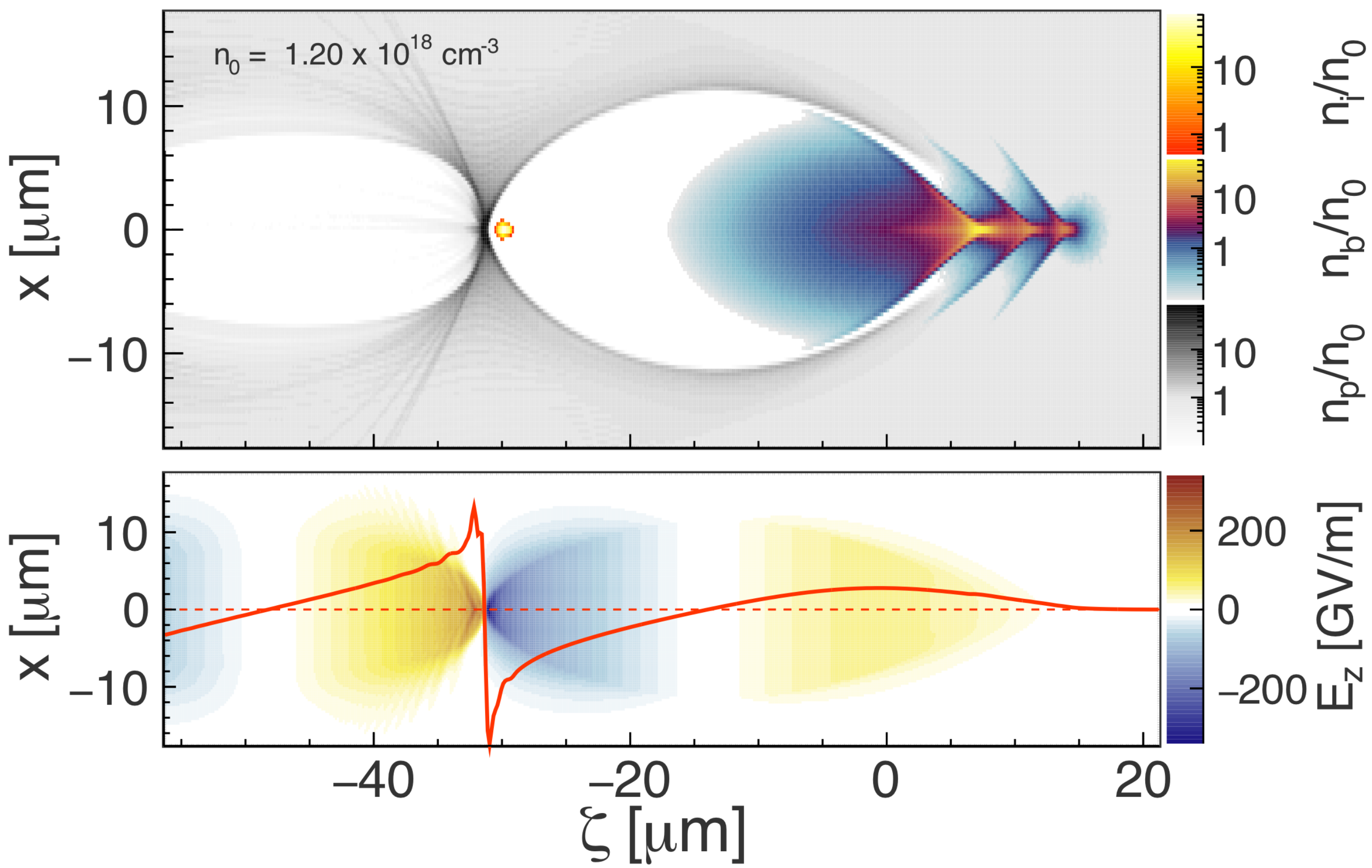


COHERENT TR:

$$\omega \ll \frac{1}{\tau_{bunch}}$$



TR for ultra-short electron bunches from PWFA



HiPACE

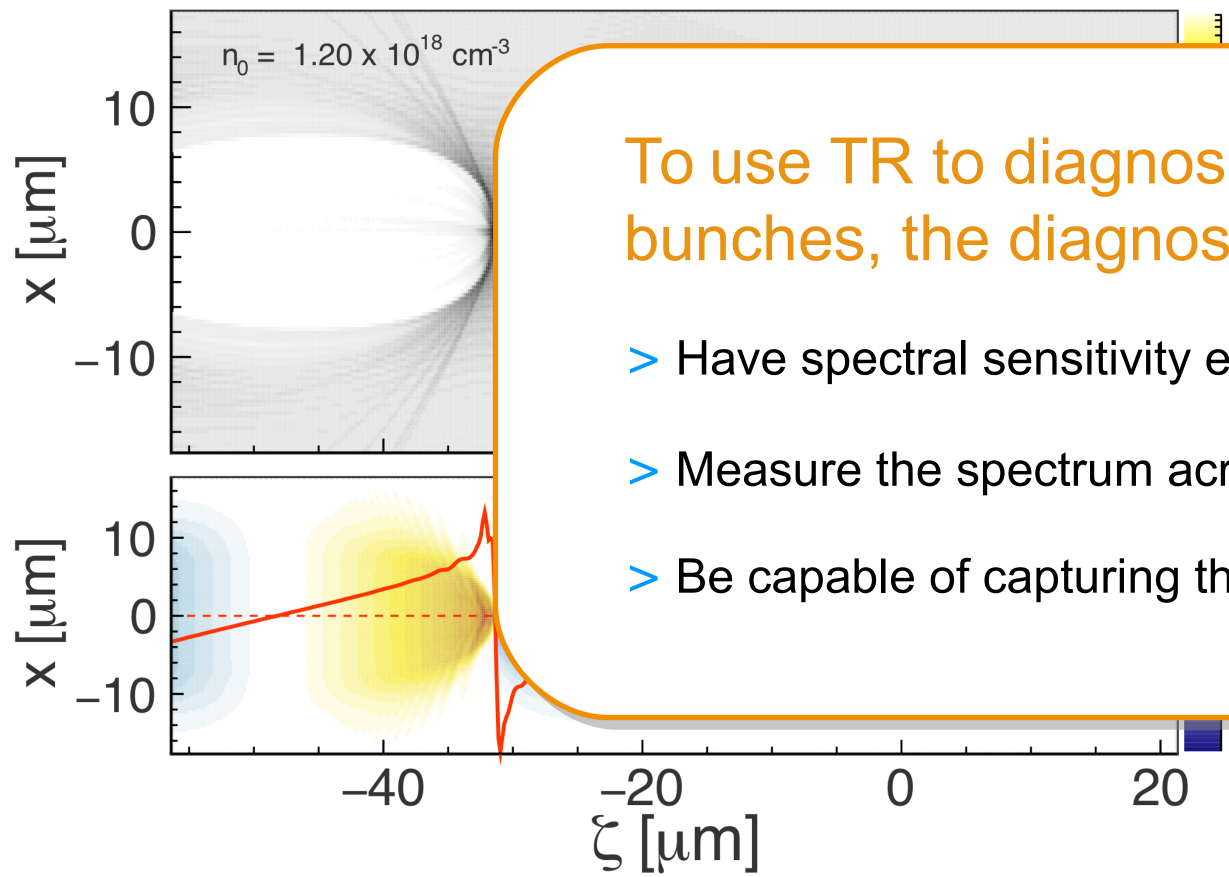
UCLA osiris v2.0

> Size of accelerating structure in PWFA is ~ 10s-100s microns (scaling with plasma electron density).

> Witness bunch duration typically limited by wakefield size.

Intrinsically short (fs) electron bunches.

TR for ultra-short electron bunches from PWFA



PWFA is ~ 10s-100s

on density).

limited by wakefield

tron bunches.

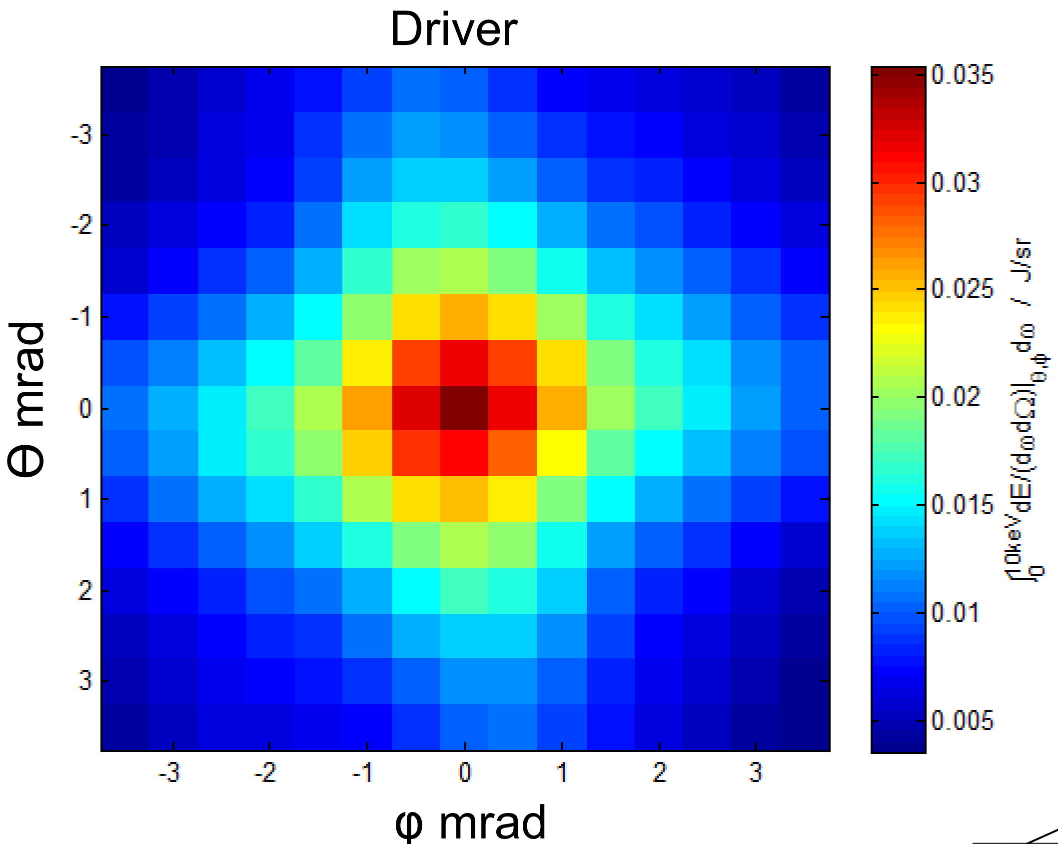
To use TR to diagnose these fs PWFA electron bunches, the diagnostic must:

> Have spectral sensitivity extending into the visible/UV.

> Measure the spectrum across a broad frequency range.

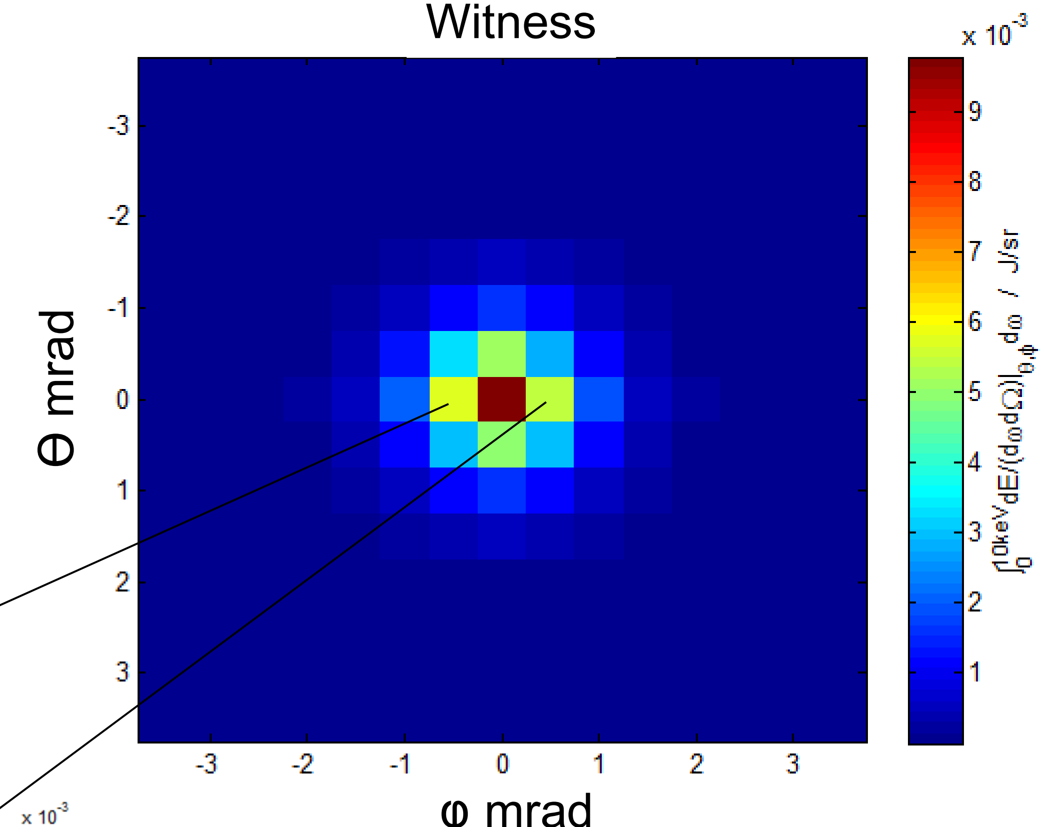
> Be capable of capturing this broad spectrum within a single shot.

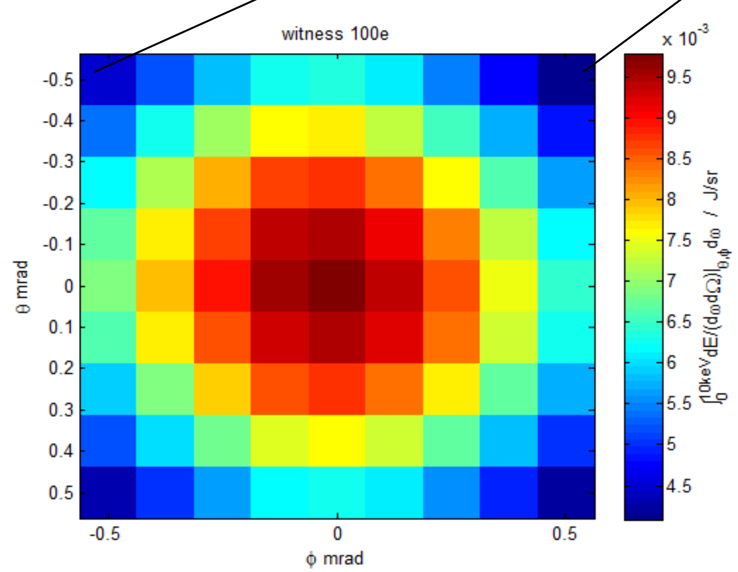
HiPACE simulations – angular distributions



Θc~2.5mrad

Ntot(50fC): 2.3e9



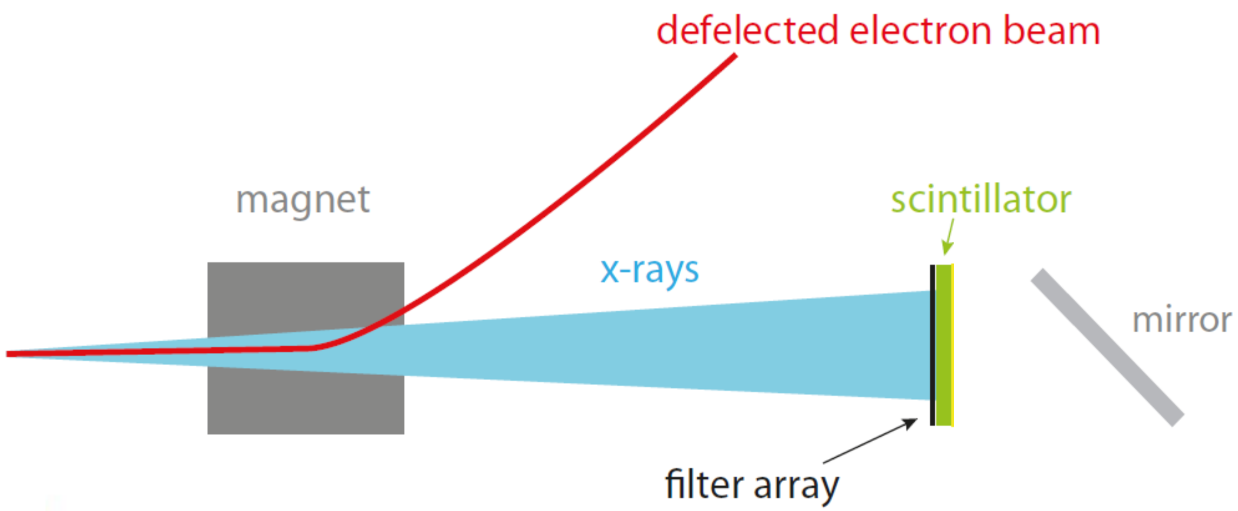


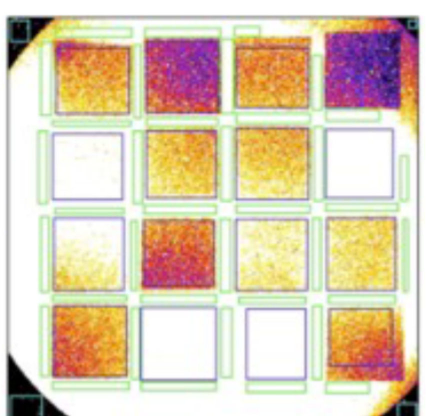
Θc<1mrad

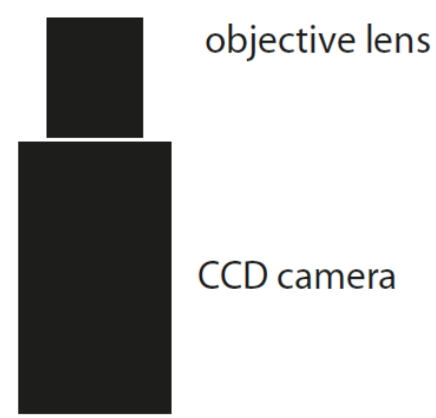
Ntot(50fC): 7.4e7

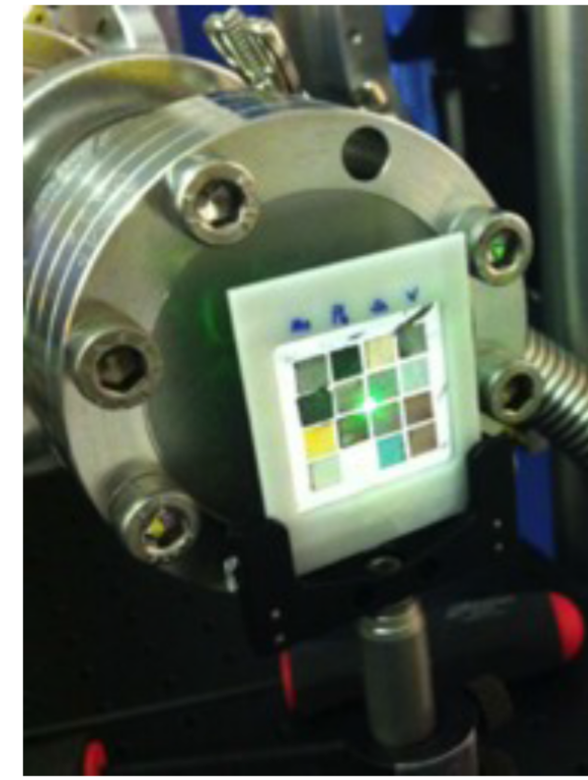
Indirect detection of hard x-rays

> Above ~10 keV → scintillator + camera



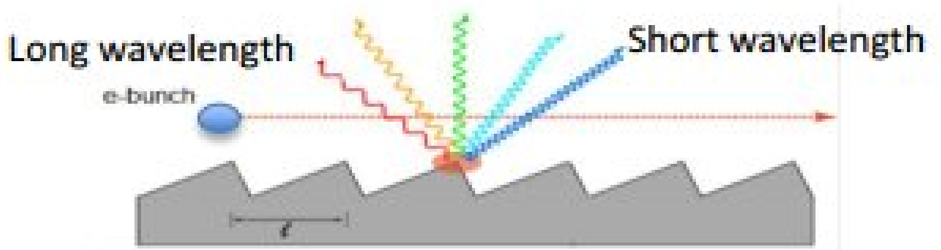






> Scintillator options:
- CsI(Tl) (Hamamatsu), testing at REGAE
- Lanex
- FastLanex

Smith-Purcell radiation monitor



$$\lambda = \frac{\ell}{m}\left(\frac{1}{\beta} - \cos\theta\right)$$

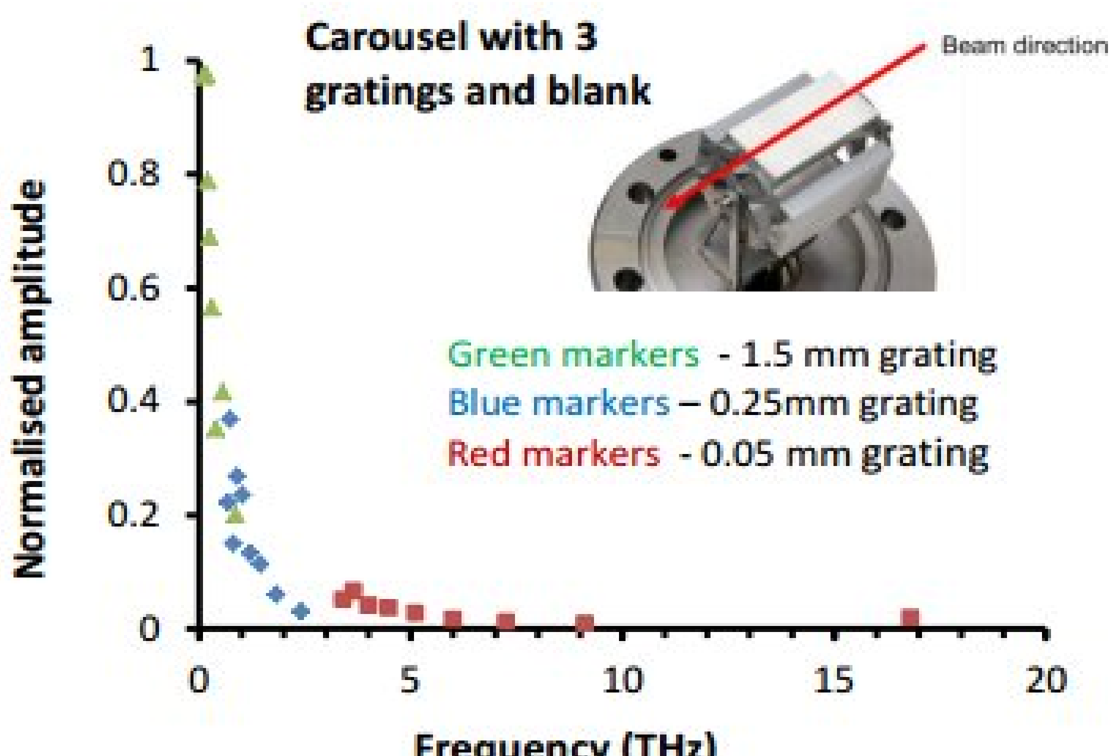
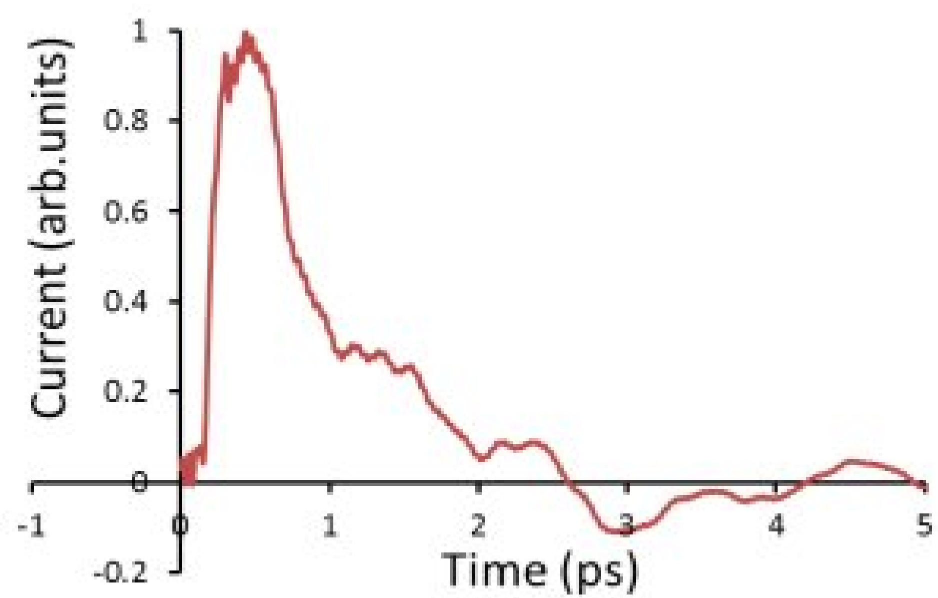


Image is ready in 1-hour

Reconstructed bunch profile (FACET)

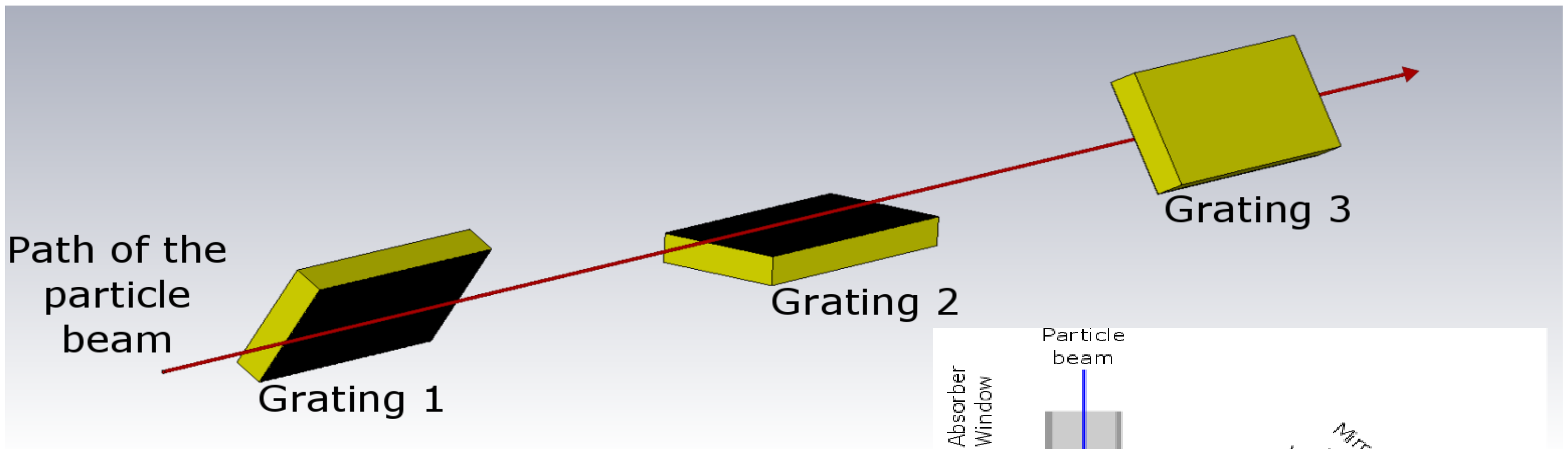


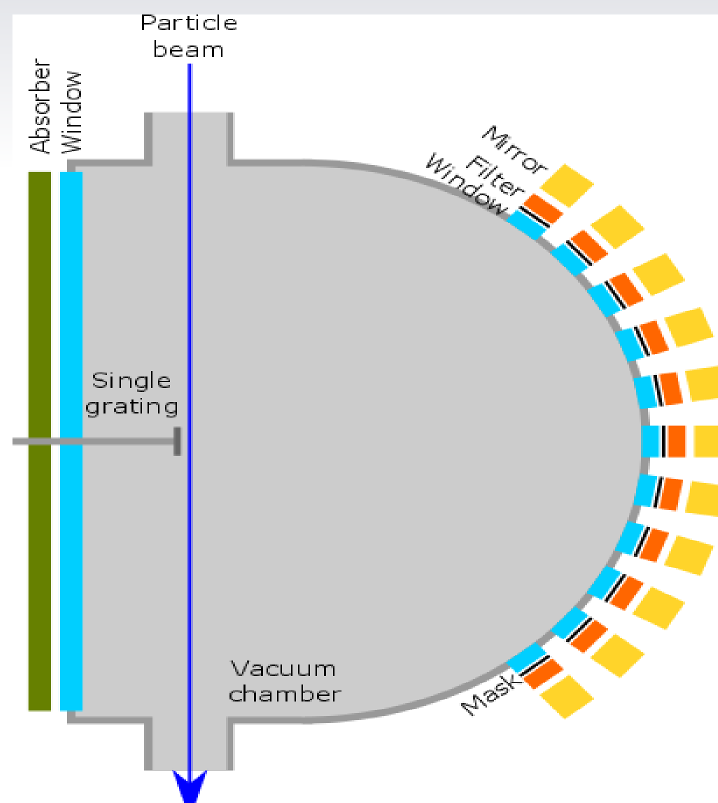
> Electron bunch passing by a grating emits electromagnetic radiation

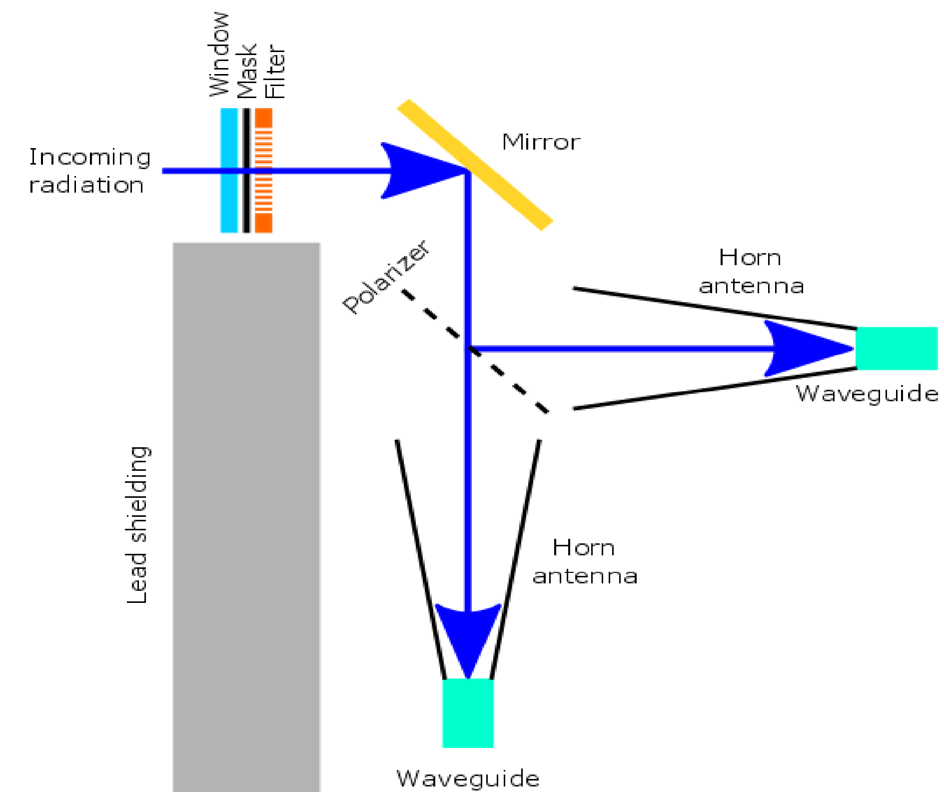
> Spectrum depends on the bunch longitudinal profile → diagnostics tool

Development of a single-shot Smith-Purcell Monitor

> Grating step defines the wavelength range
> For a single-shot measurement, need several gratings







Design of a single-shot device is in progress
Could be potentially used at FLASHForward (Phase II)