MANCHESTER 1824

The University of Manchester

CI Seminars

2 November 2015

A selection from the

Activities on beam driven plasma wakefield acceleration

in the University of Manchester

Dr Öznur Mete

The University of Manchester

The Cockcroft Institute of Accelerator Science and Technology

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Team

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- Yangmei Li (PhD Student)
- Thomas Pasey (PhD Student)
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- Michael Wigram (MPhys Student)
- Matthew Dover (MPhys Student)
- Jaihui Zhang (MPhys Student)

Outline

- AWAKE Project
  - Witness production
  - 3D simulations for unresolved phenomena in 2D
- Future collider studies based on PDPWA
  - Possible layouts using existing infrastructure
  - Design issues
- Plasma Acceleration Research Station (PARS) Project
  - Optimisation for various regimes of CLARA
  - Plasma sources
- iMPACT Proposal
  - Multi-bunch PWA
  - PIC simulations for CLARA and CLARA Front End
- Instrumentation
  - 2D mask based emittance diagnostics (a.k.a pepper-pot) for space charge dominated beams
  - Phase space tomography
  - Novel emittance diagnostics
  - Beam spectrometer terminated with a segmented beam dump
  - Plasma lens

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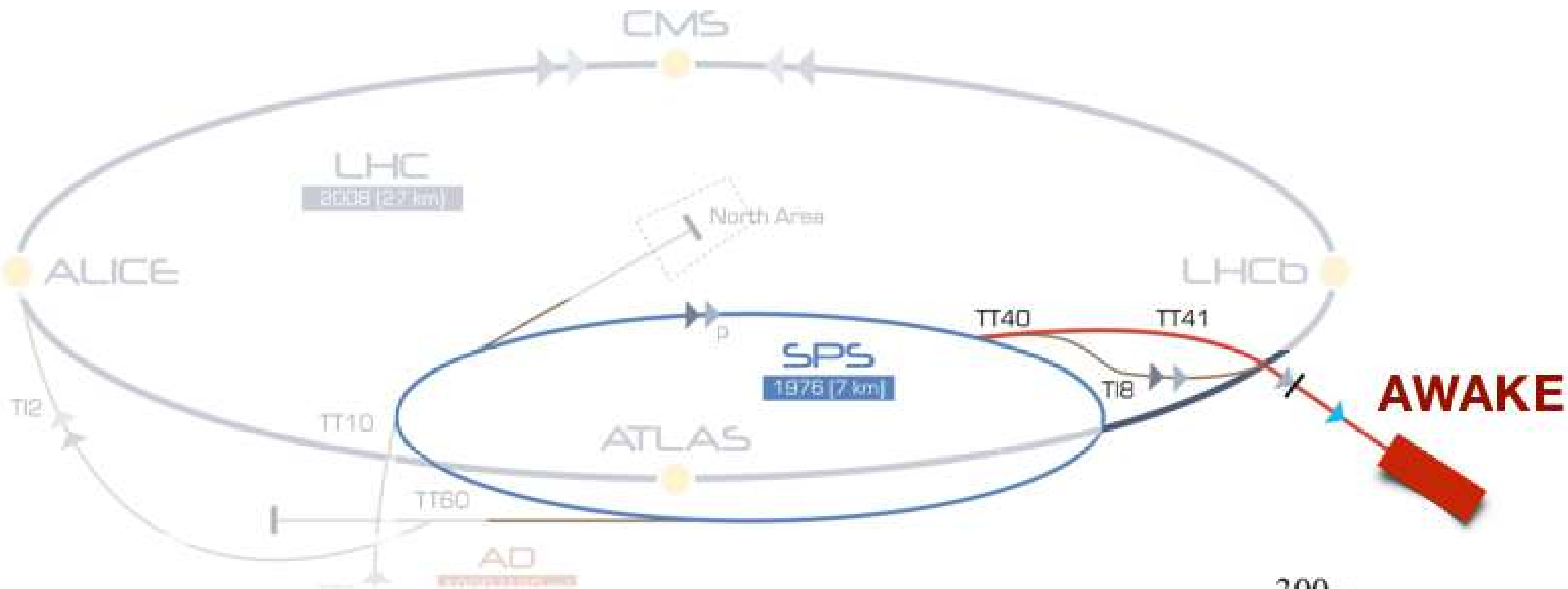
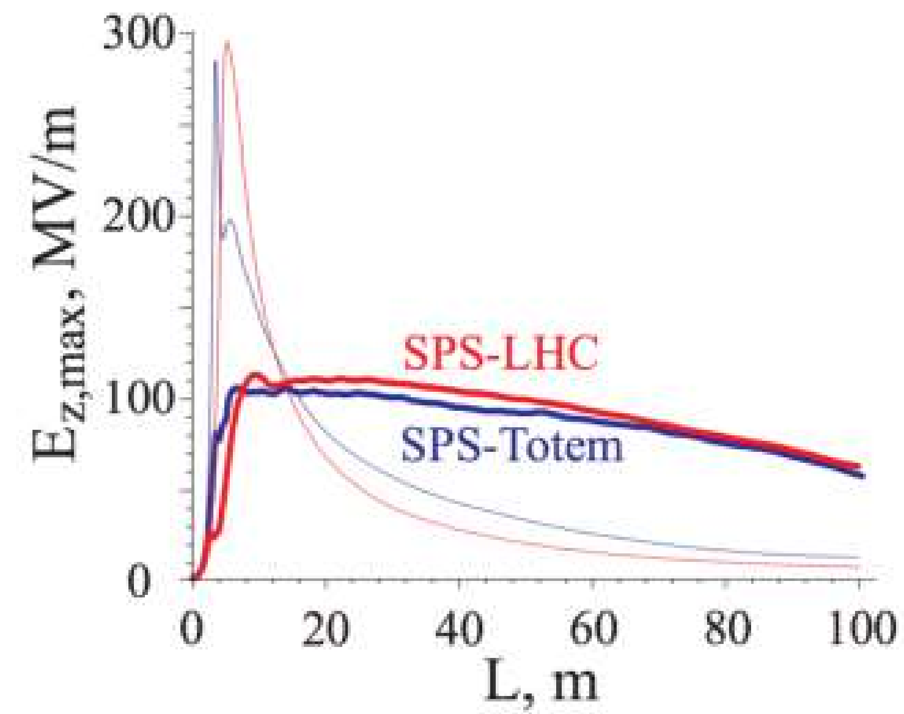
AWAKE Project



AWAKE project, a proton driven plasma wakefield acceleration (PDPWA) experiment is approved by CERN. The PDPWA scheme consists of a seeding laser, a drive beam and a witness beam to be accelerated. The primary goal of this experiment is to demonstrate acceleration of a 16 MeV single bunch electron beam up to 1 GeV in a 10m of plasma.

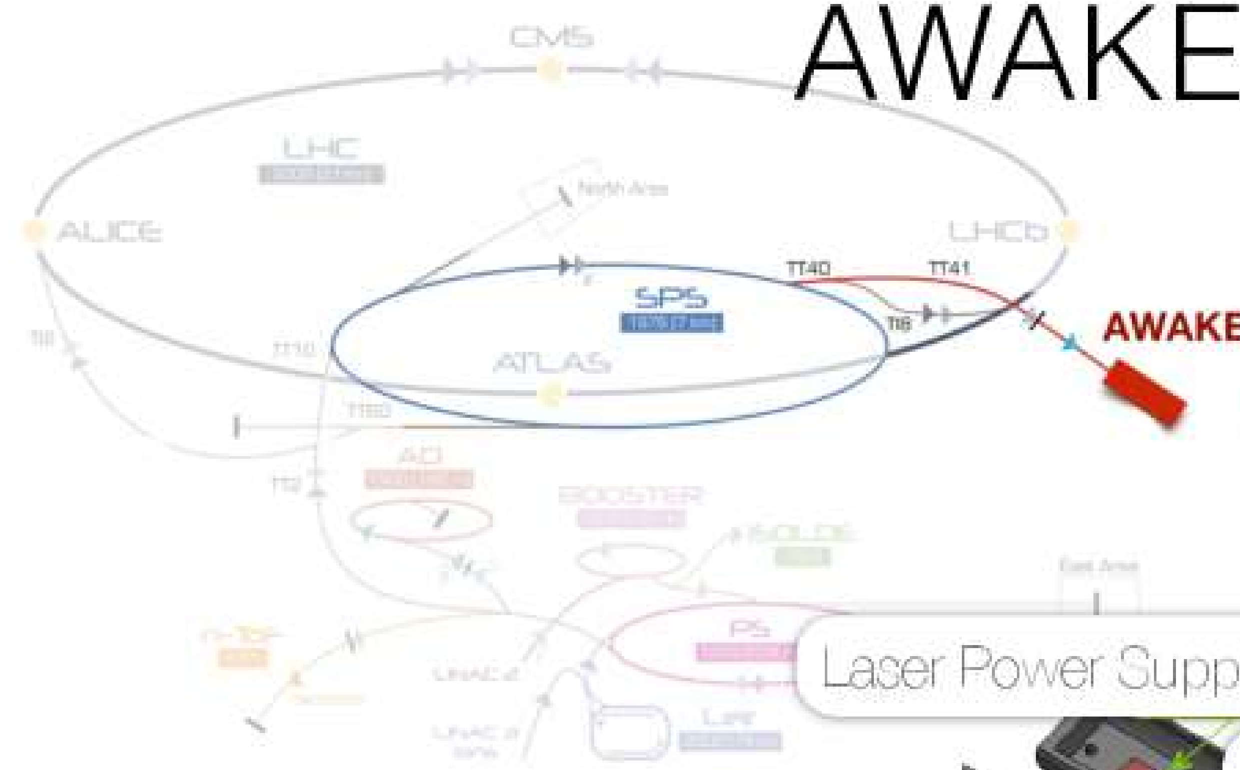


A. Caldwell, K. V. Lotov, PHYSICS OF PLASMAS 18, 103101 (2011).

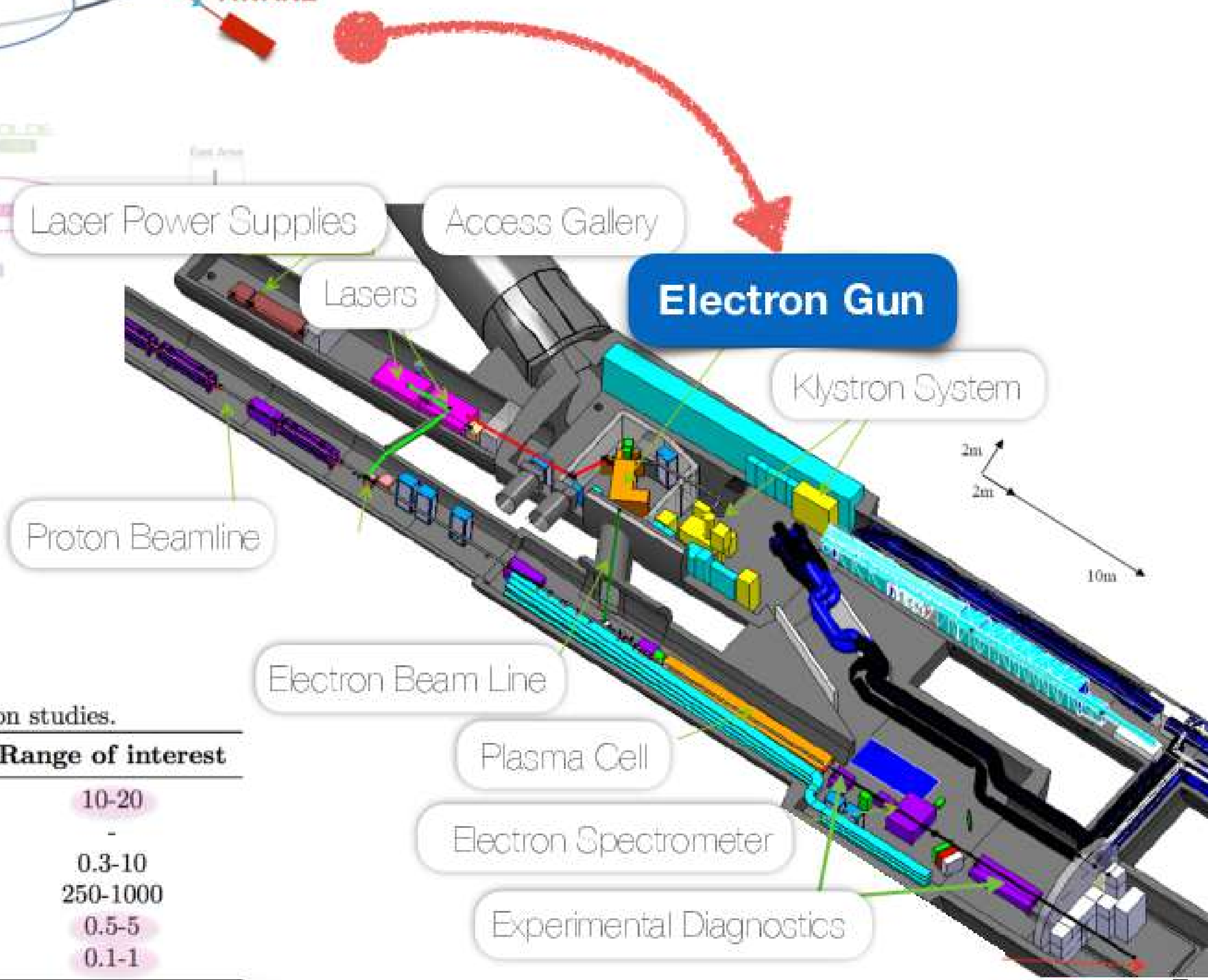
AWAKE Facts

- 2013
    - **Approval** of project at CERN including funding profile.
- 2014-2015
    - Design, procurement and installation of the equipment, development of **plasma cells**.
    - Modification and installation of the **beam line and the experimental facility.**
- 2016
    - **First proton beam** to the AWAKE experiment, beam–plasma commissioning.
    - Beginning taking data
- 2017
    - **Installation of the electron source and beam line and diagnostics.**
    - **Delivery and installation of the electron photo-injector,** commissioning of the magnetic spectrometer.
- **More data taking!**
- International Effort
- 16 institutions in 9 countries across Europe and Asia.

AWAKE Project



Production of a Witness Beam



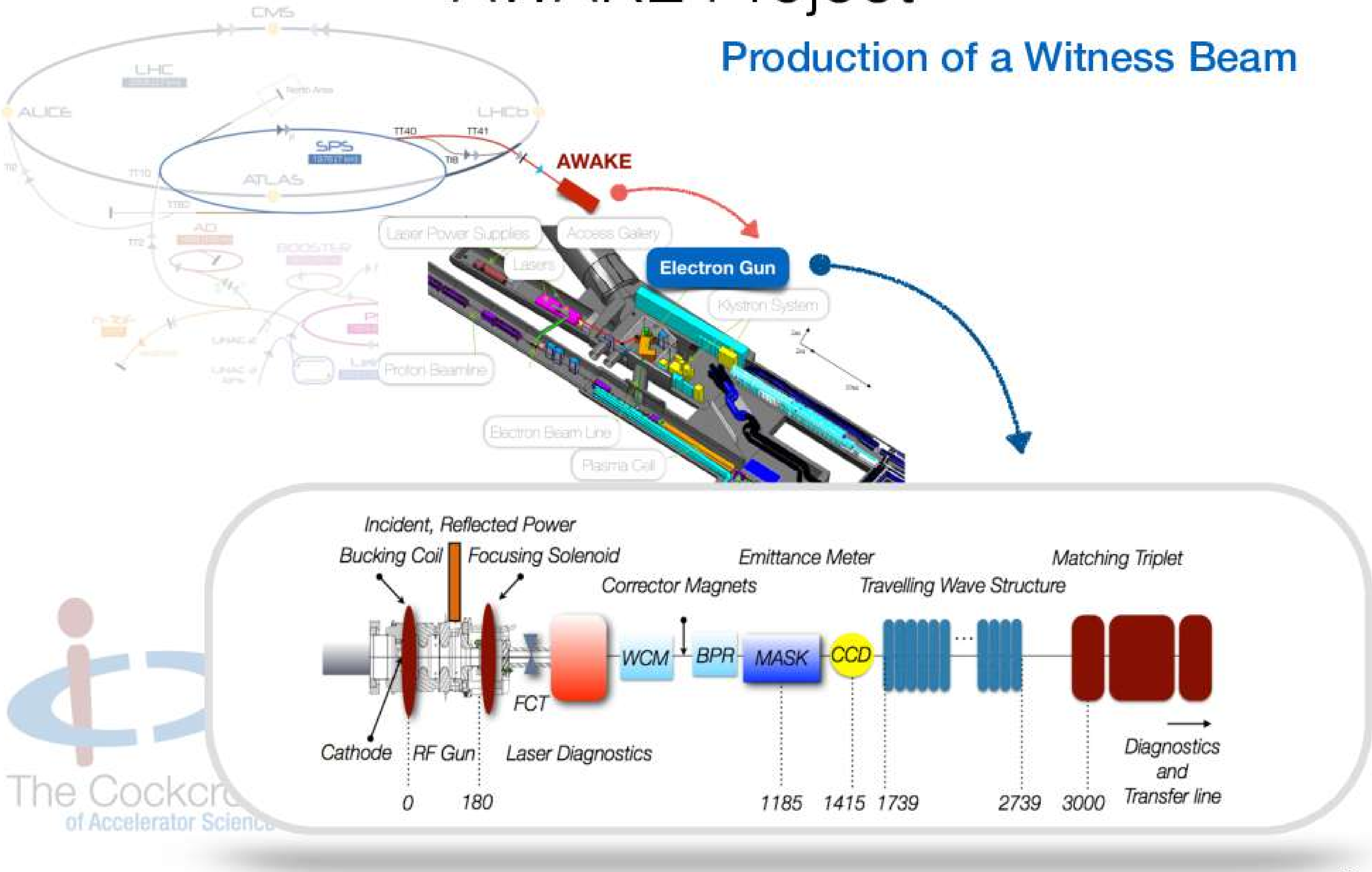
Baseline specifications for AWAKE e⁻ beam.

Table 1: Specifications for the simulation studies.

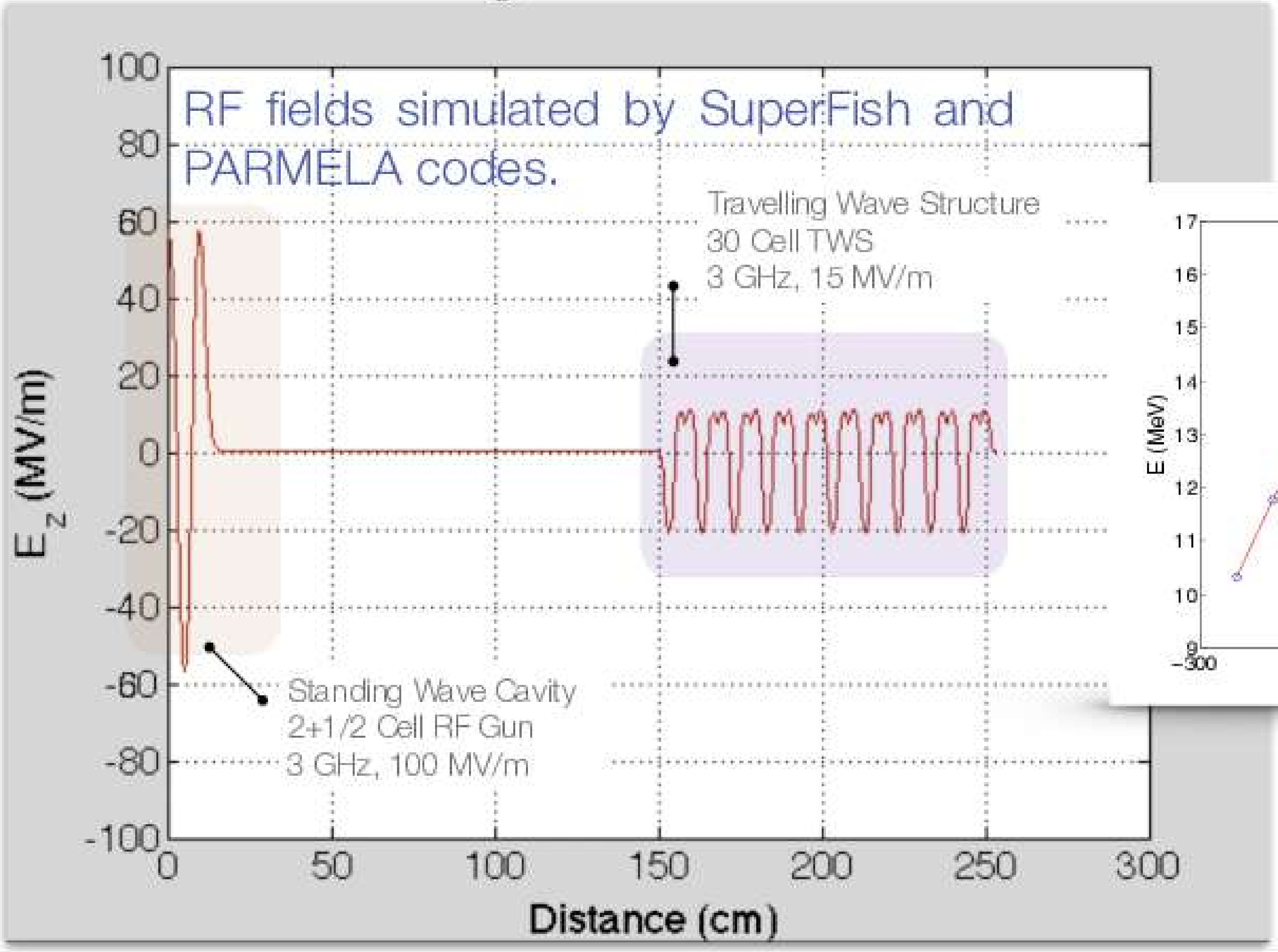
Parameter	Baseline	Range of interest
Beam energy (MeV)	16	10-20
Energy spread (σ, %)	0.5	-
Bunch length, (σ, ps)	4	0.3-10
Beam focus size, (σ, μm)	250	250-1000
Norm. emittance (rms, mm-mrad)	2	0.5-5
Bunch charge, (nC)	0.2	0.1-1

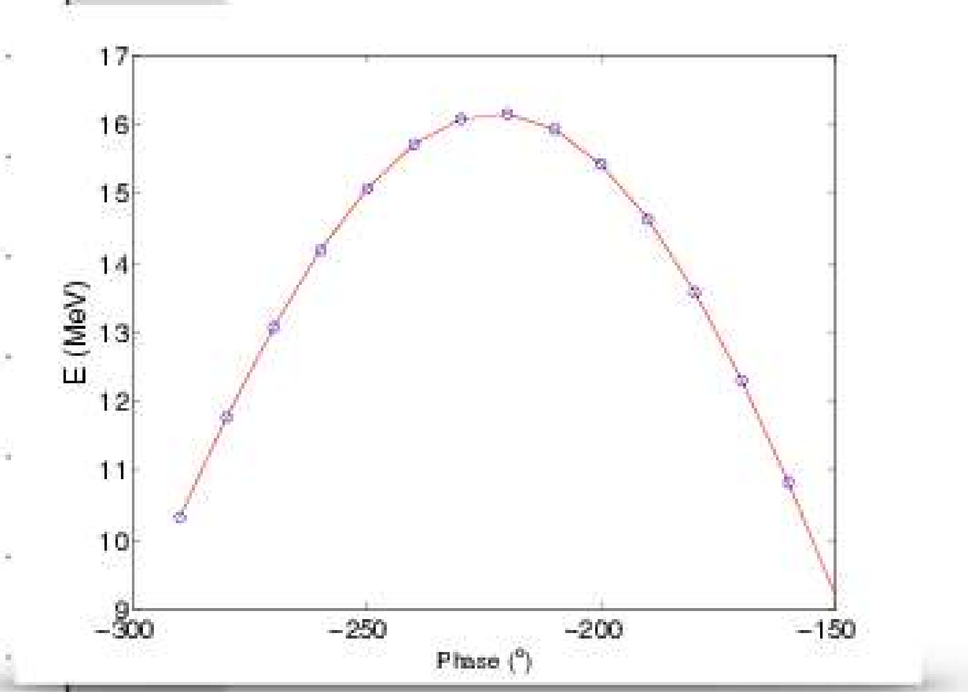
AWAKE Project

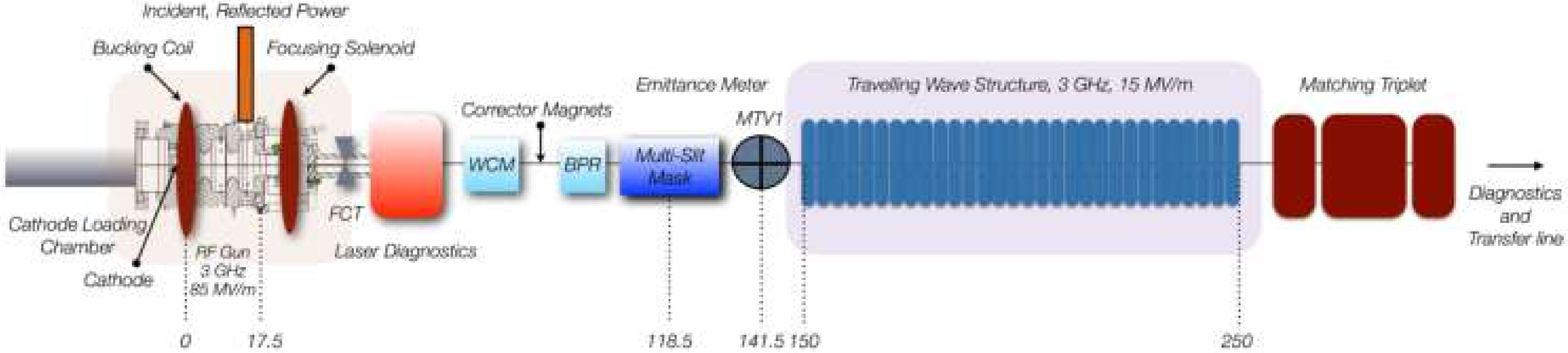
Production of a Witness Beam



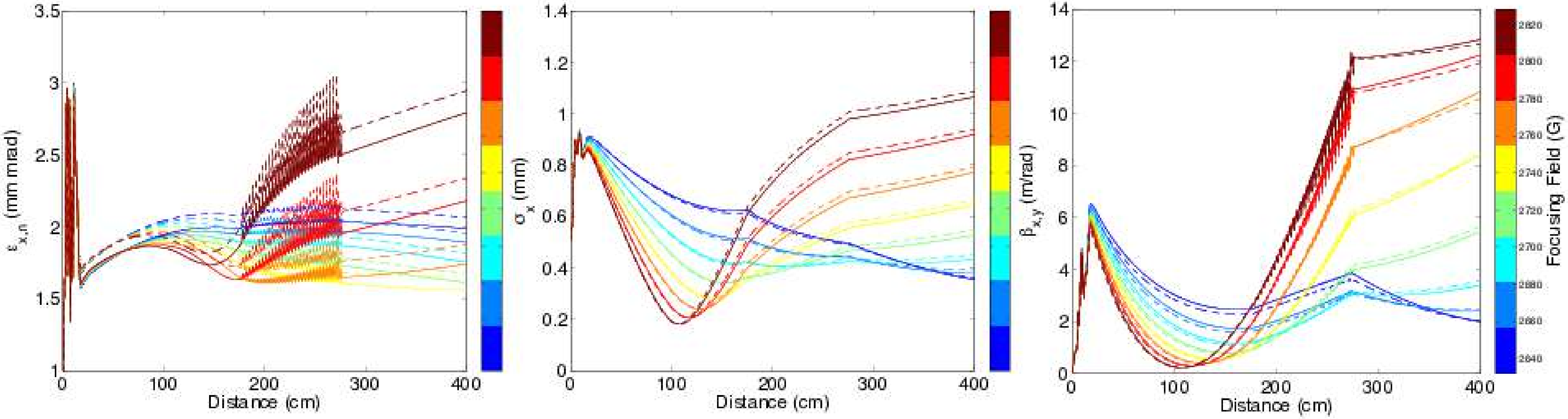
Baseline Design for AWAKE Witness Beam







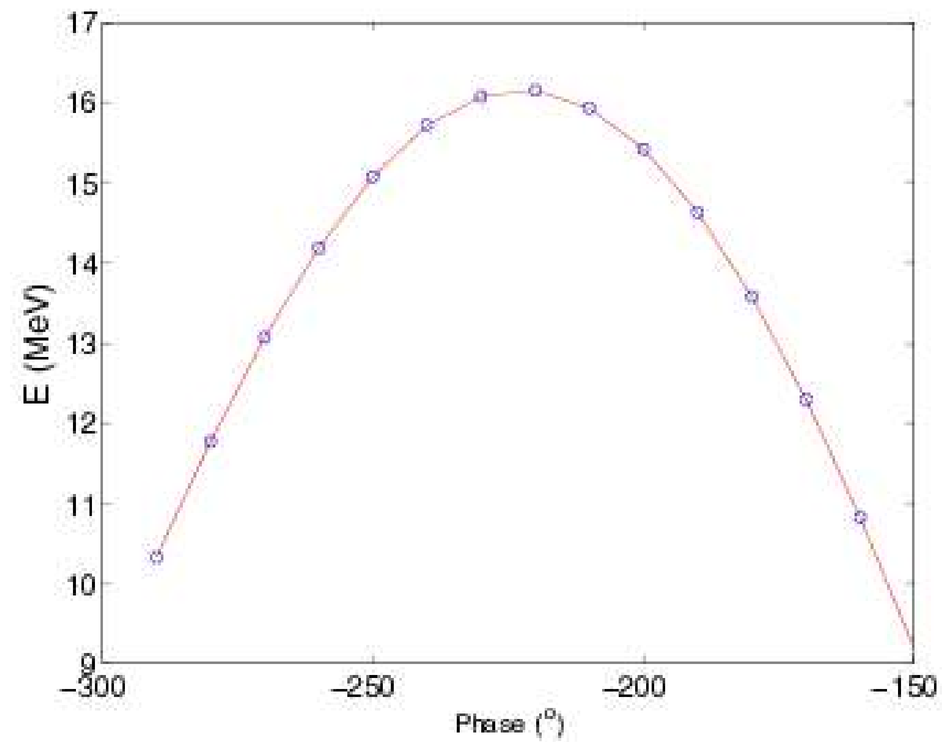
Baseline Design for AWAKE Witness Beam



TWS Exit (2770 mm)

$\beta_{x/y}$ (m/rad)	6.1/ 6.3
$\alpha_{x/y}$	-0.6 / -0.6
$\sigma_{x/y}$ (µm)	556 / 577
$\varepsilon_{x/y}$ (mm mrad)	1.6 / 1.7
E(MeV)	16.16
ΔE (%)	0.3

Magnetic field for compensation solenoid is 2744 Gauss.

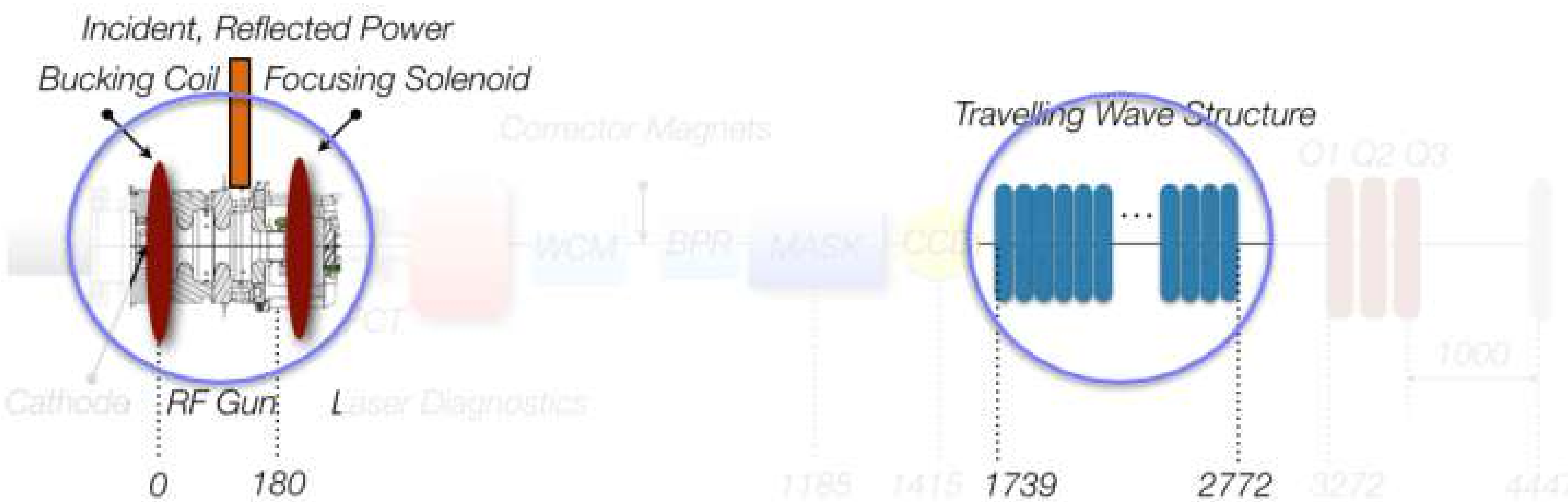


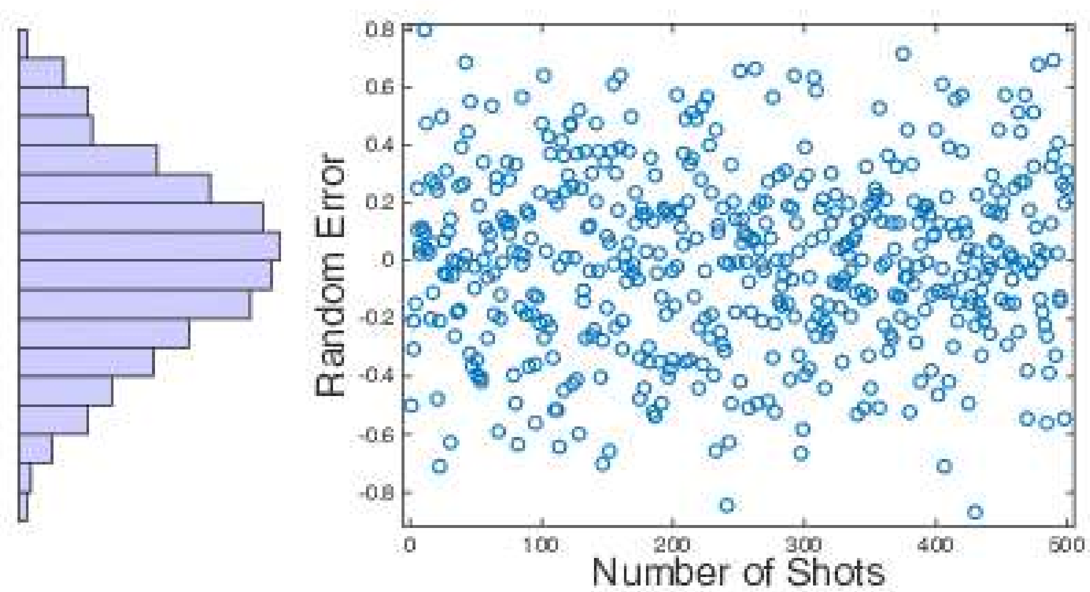
O. Mete et al., AWAKE Tech. Note, CERN EDMS 1516468

Effects of phase jitter on beam dynamics

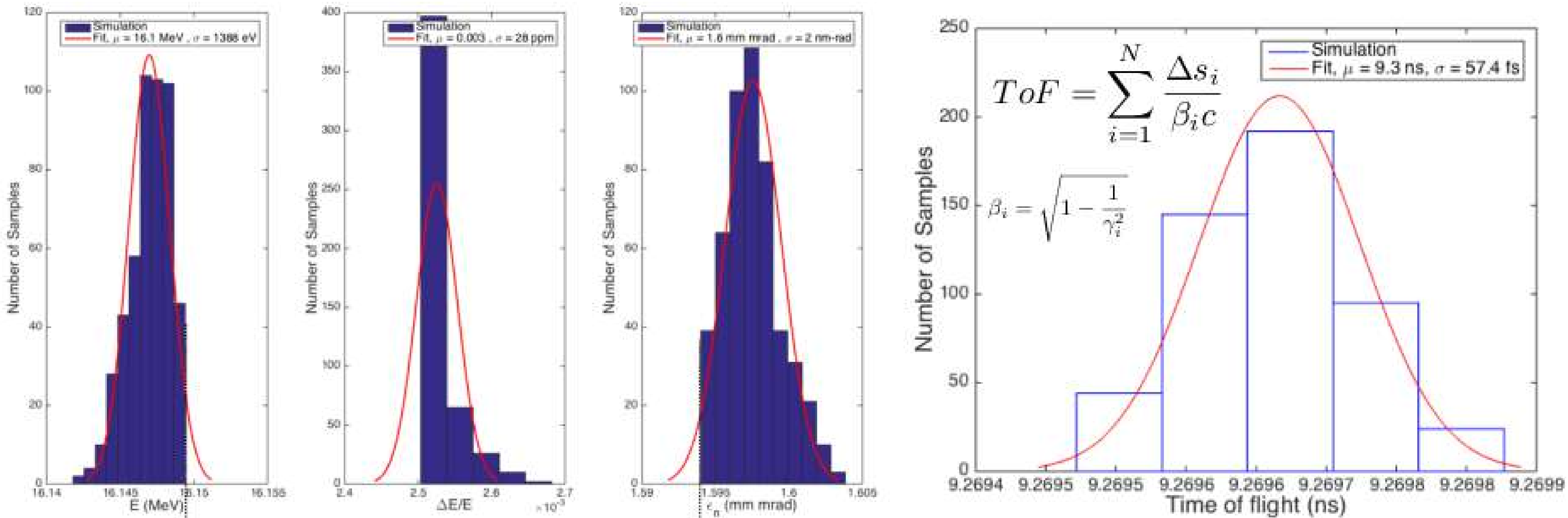
In simulations, phase error can be generated as the phase difference between the beam and the RF.

- Klystron is the common source of error for both SW and ATS,
- 2.99855 GHz, 1° corresponds to ~1ps, measured phase jitter in CTF3 ~200fs,
- Phase jitter simulations for AWAKE injector; 300fs (1σ) over 500 samples around -1° off-crest phase (~46h to simulate with Parmela).





Effects of phase jitter on beam dynamics



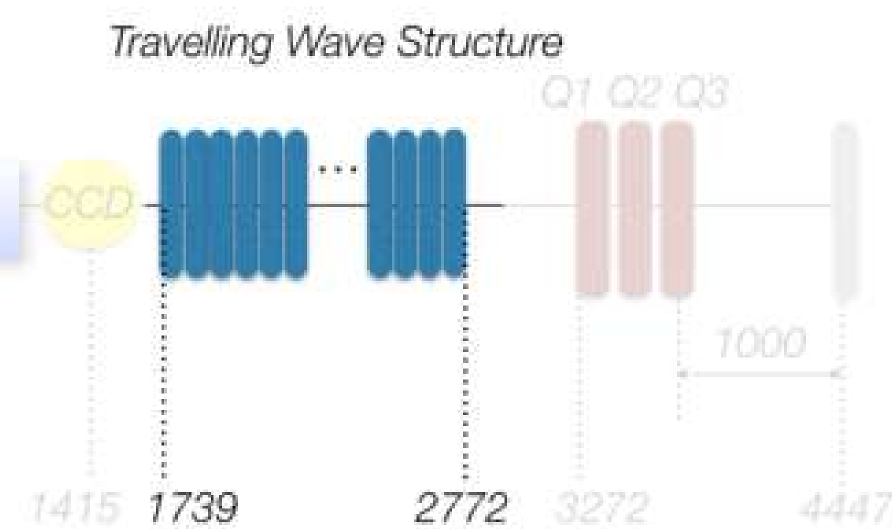
On-crest limit

Compensation limit

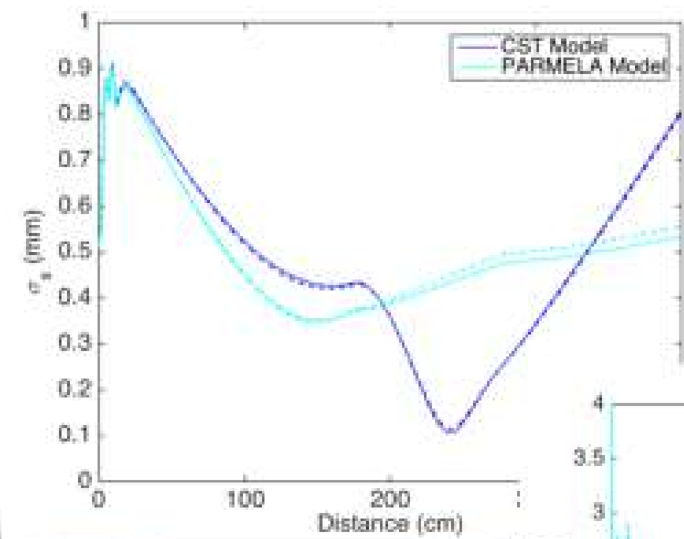
Parameter	Reference Value	μ (300fs)	σ (300fs)	**Error**
εx	1.6 mm mrad	1.6 mm mrad	2 nm-rad	**7 nm/deg**
E	16.15 MeV	16.1 MeV	1388 eV	**5 keV/deg**
σE	0.3%	0.3%	28ppm	**93 ppm/deg**
ToF		9.3 ns	57 fs	**190 fs/deg**

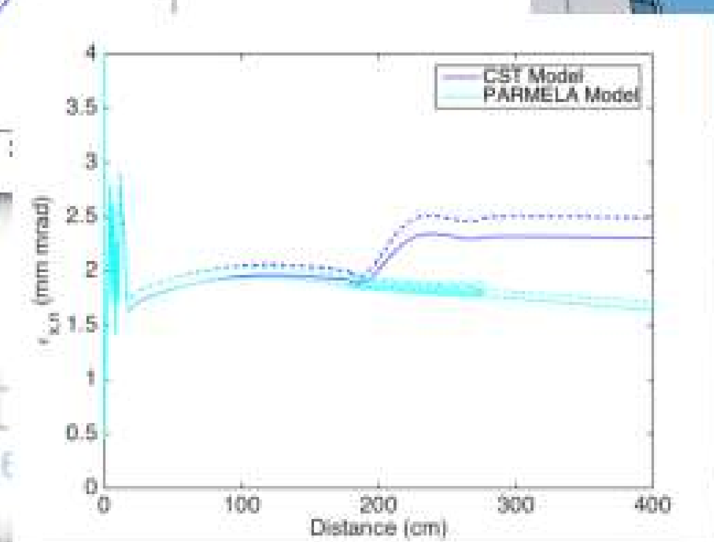
Effects in plasma to be simulated.

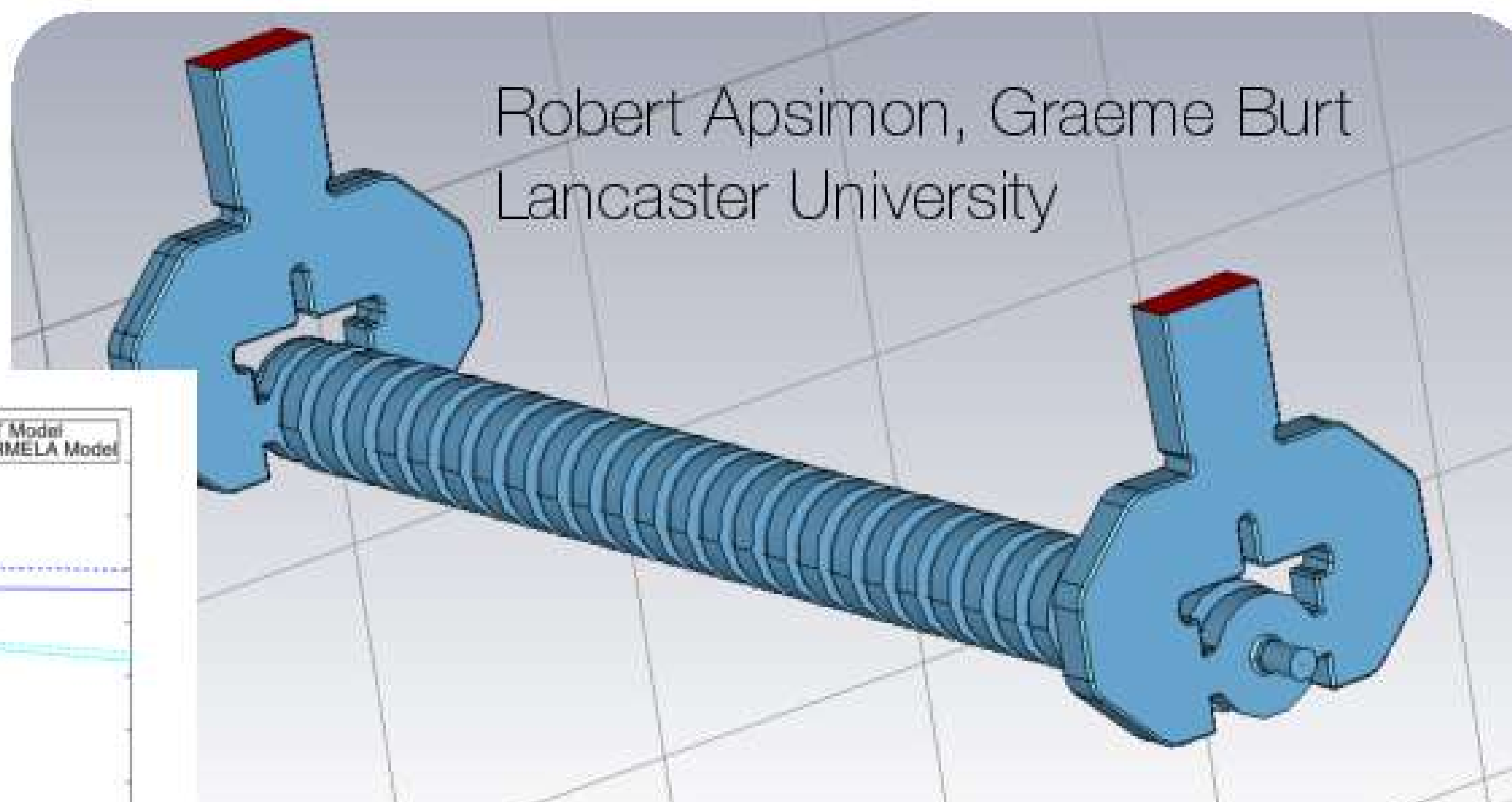
Booster Section from 5 to 10-20 MeV



- ATS = Accelerating Travelling wave S-band,
- 15 MV/m constant gradient, 2π/3 phase advance and at 2.99855 GHz,
- 30 cells is just under 1 metre long.

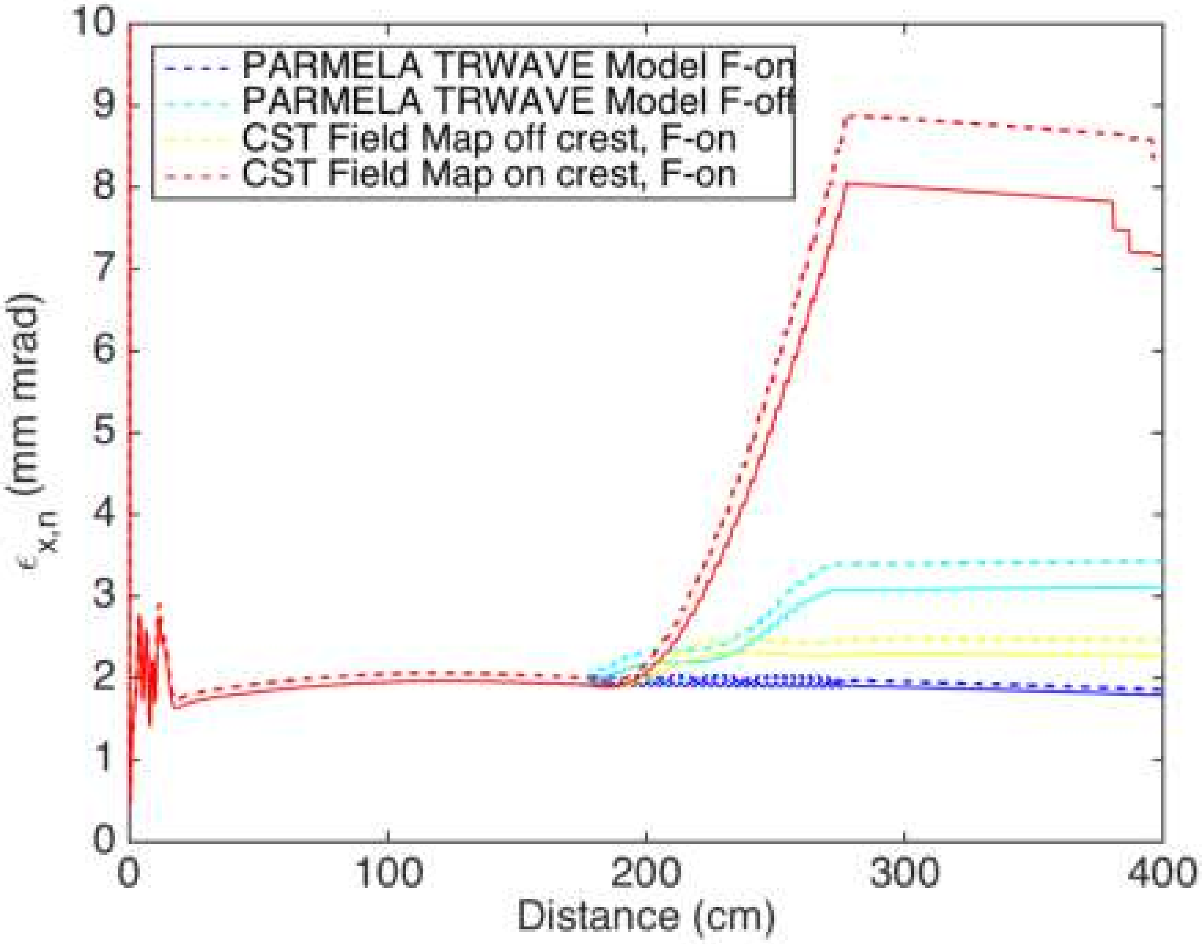


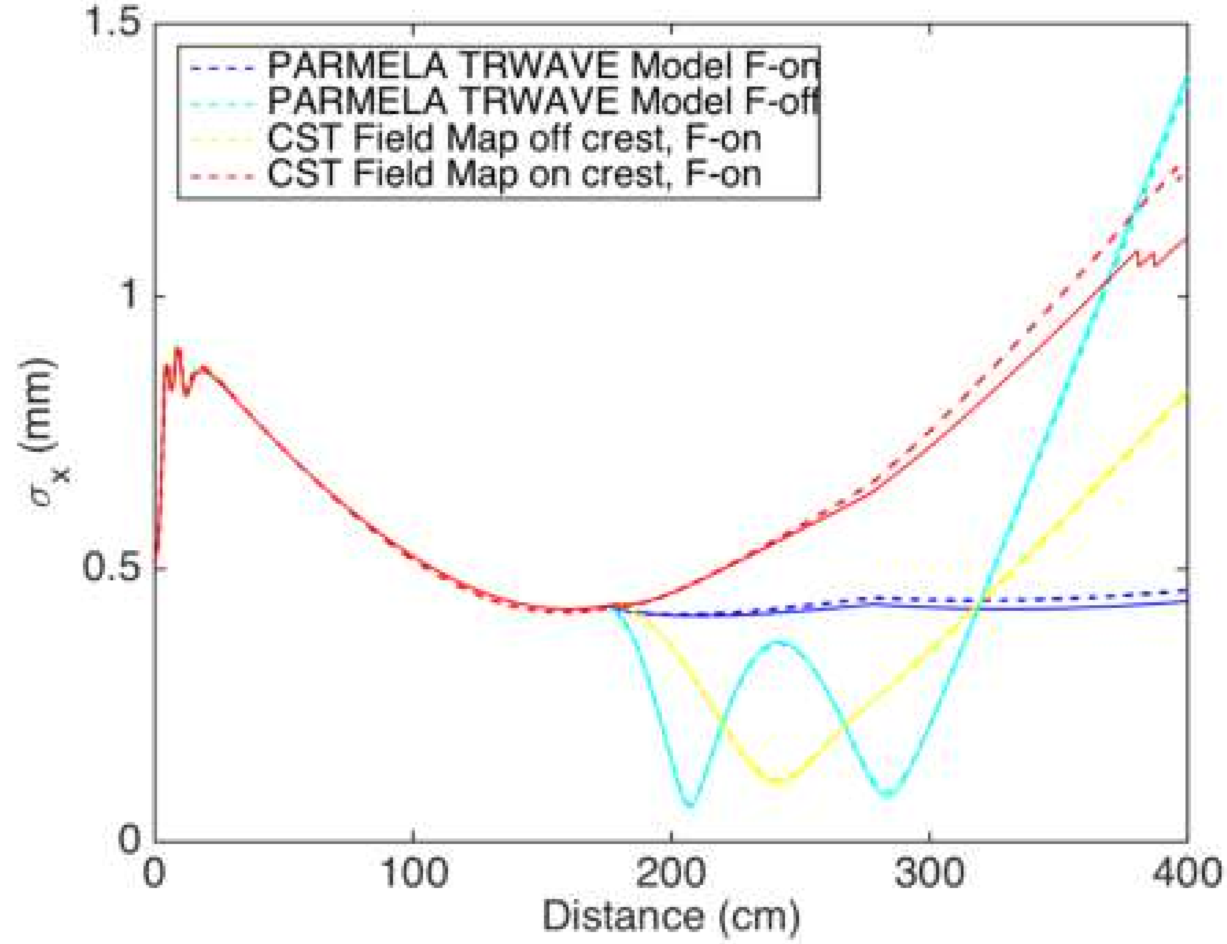




…in collaboration with Graeme Burt, Rob Apsimon (Lancaster University)

Effect of Fringing Fields and Phase

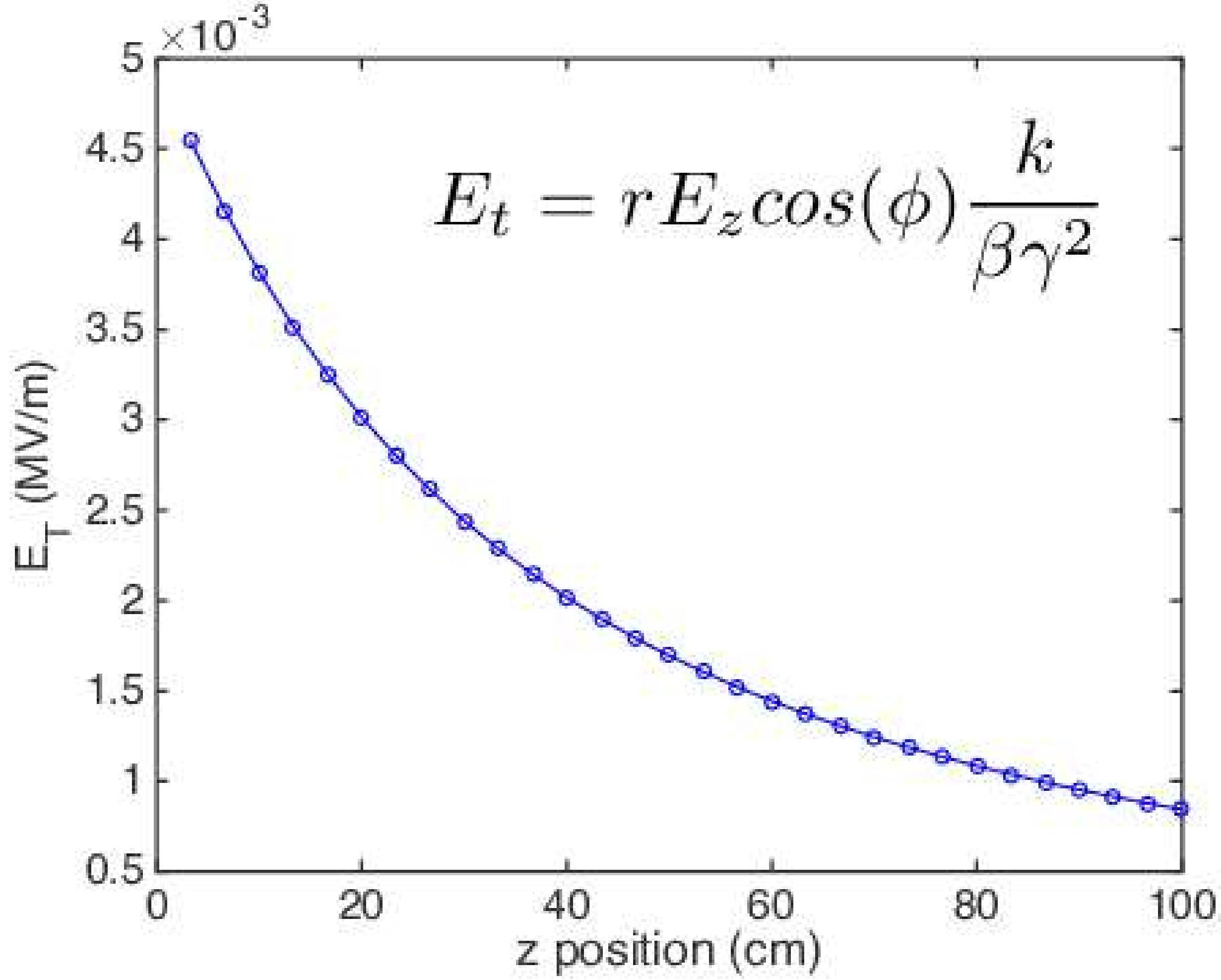




- Fringing fields on/off in PARMELA,
- CST model: **no transmission** through the structure when fringing fields were not included,
- CST model: on crest results in 8 mm mrad.
- CST model: minimum emittance occurs 15° off the crest (2.3 mm mrad), compromises the energy spread (~1.2%, next slide). - Closest to the "perfect (reference PARMELA model)" model.

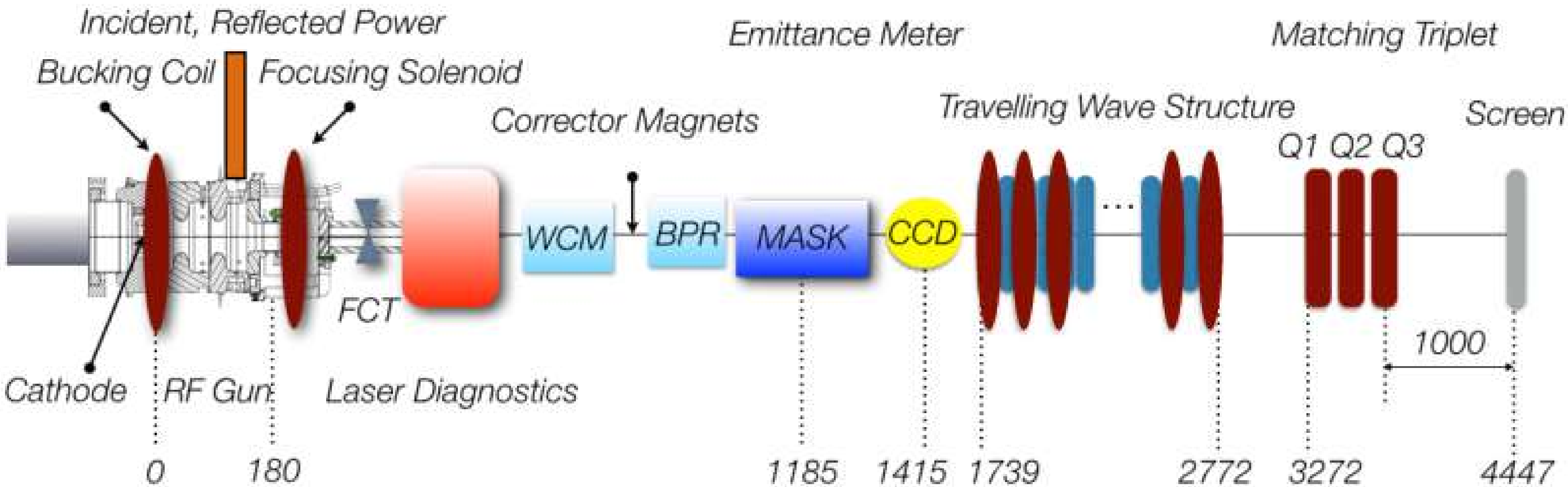
Radial Field

- Transverse electric field induced due to the changes in longitudinal field in radial direction - Panofsky-Wenzel theorem.

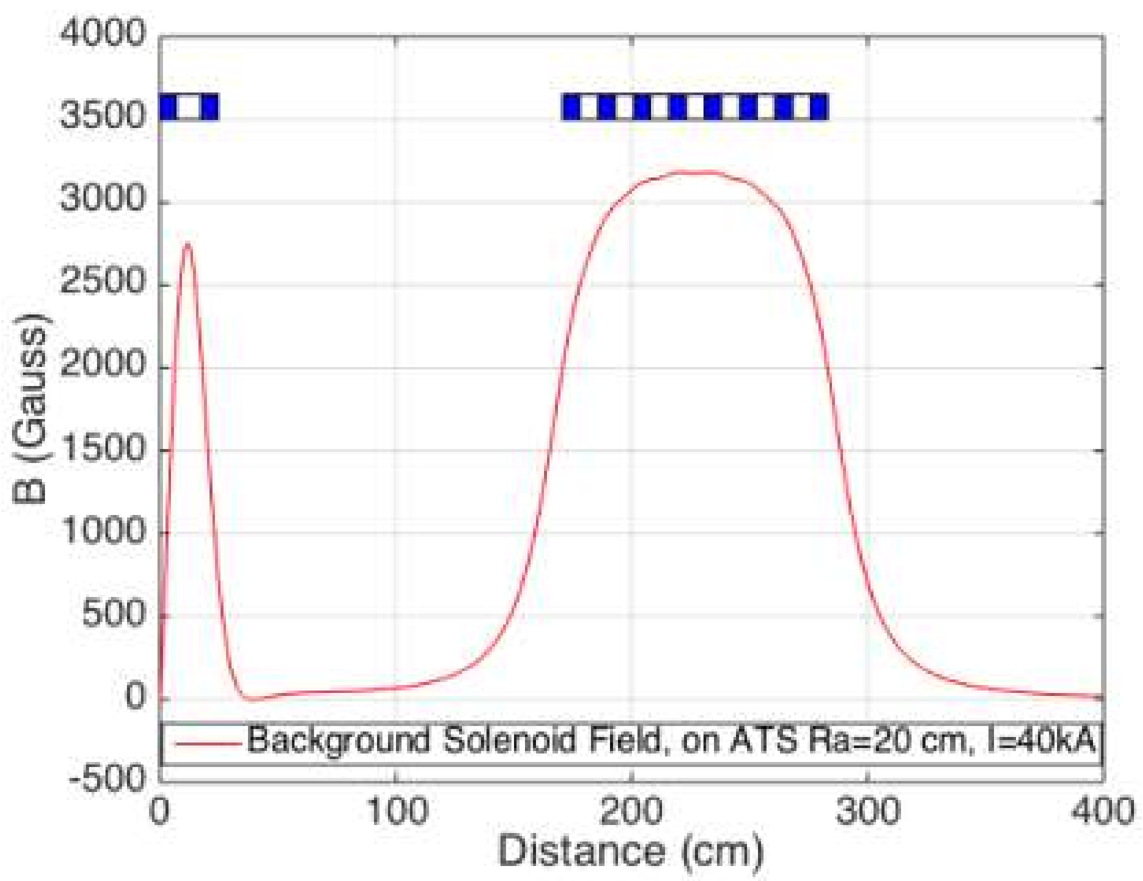


- Non-negligible radial fields in the order of several keV can be induced through field change due to the small iris (~10mm).
- This might cause a "kick" especially in the entrance of the structure where the gamma is lower.

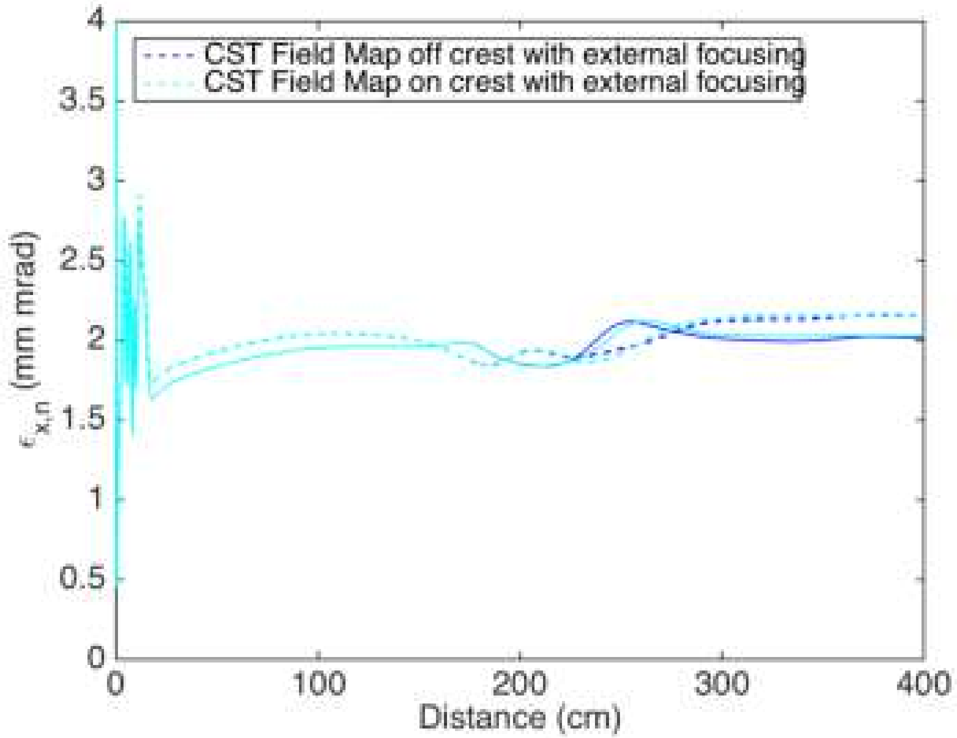
Mitigation: External Focusing

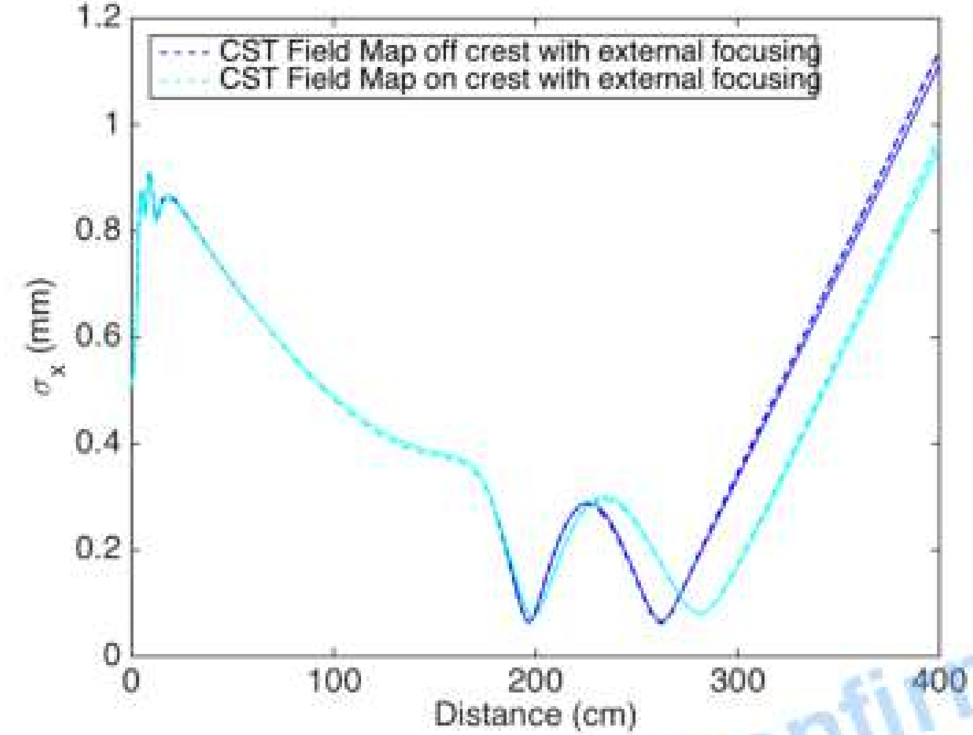


- Mitigation might be achieved by implementing solenoids throughout the ATS.
- Solenoids were evenly distributed - aiming field uniformity across the structure.
- Current on each solenoid, 40kA, aperture 20cm.

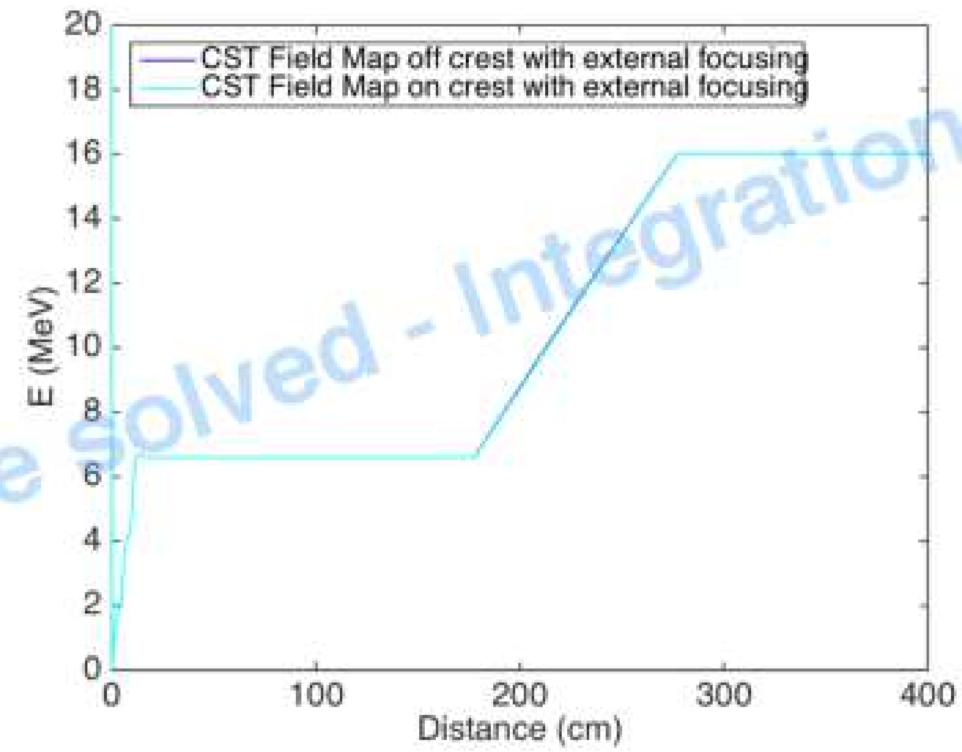


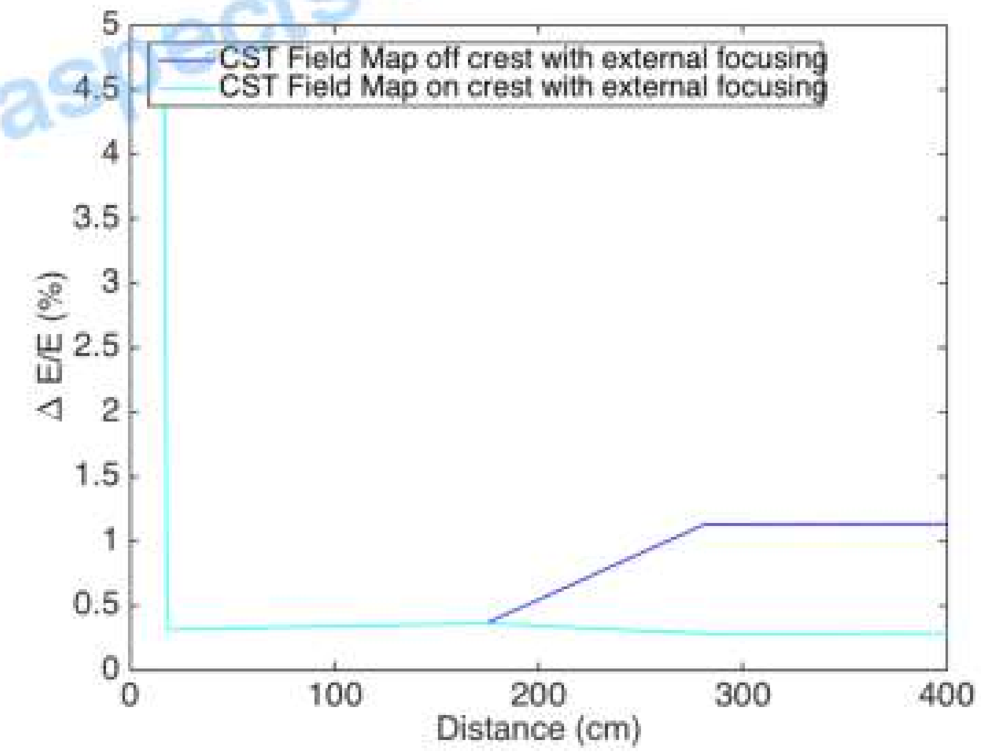
Mitigation: External Focusing





- Solenoids can compensate against the transverse electric field at both on and off crest phases



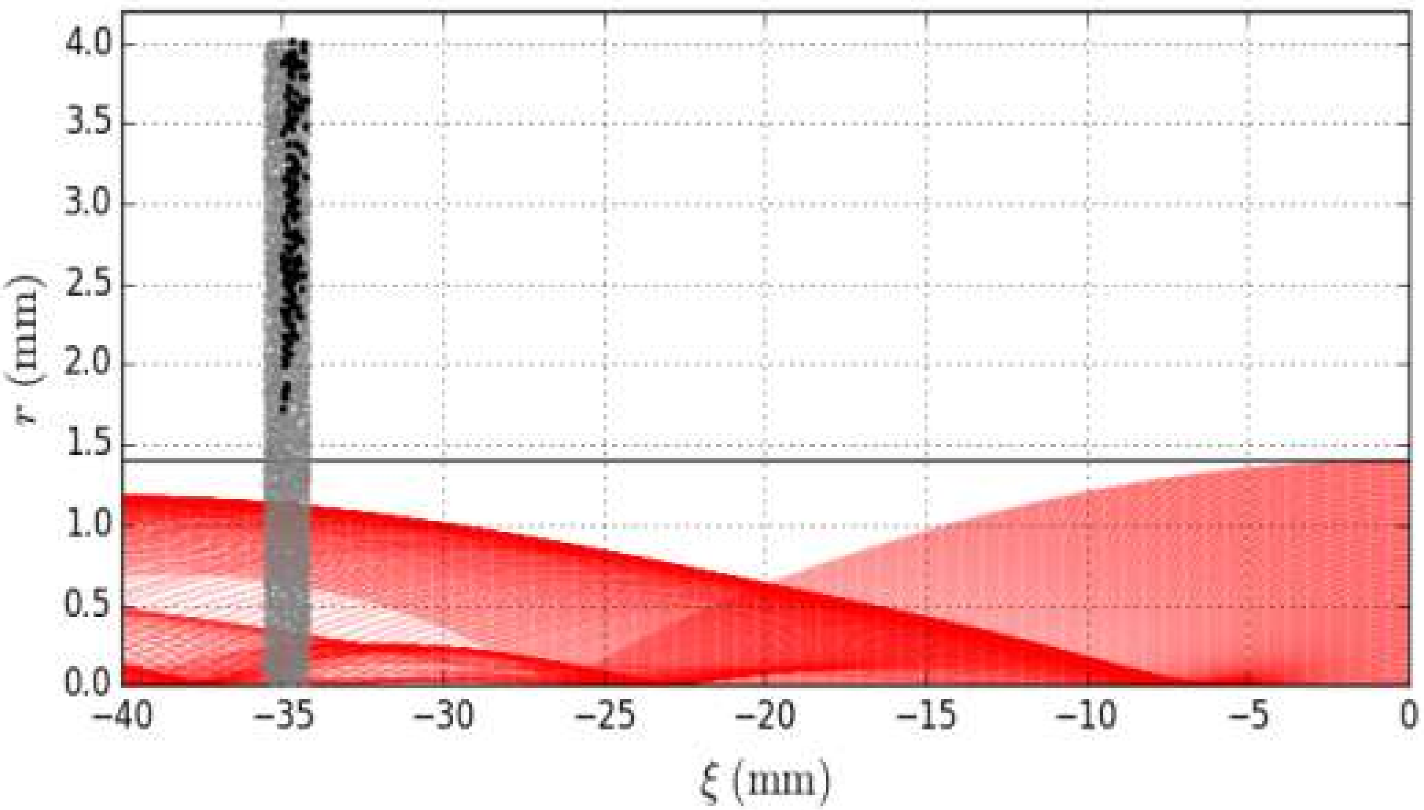


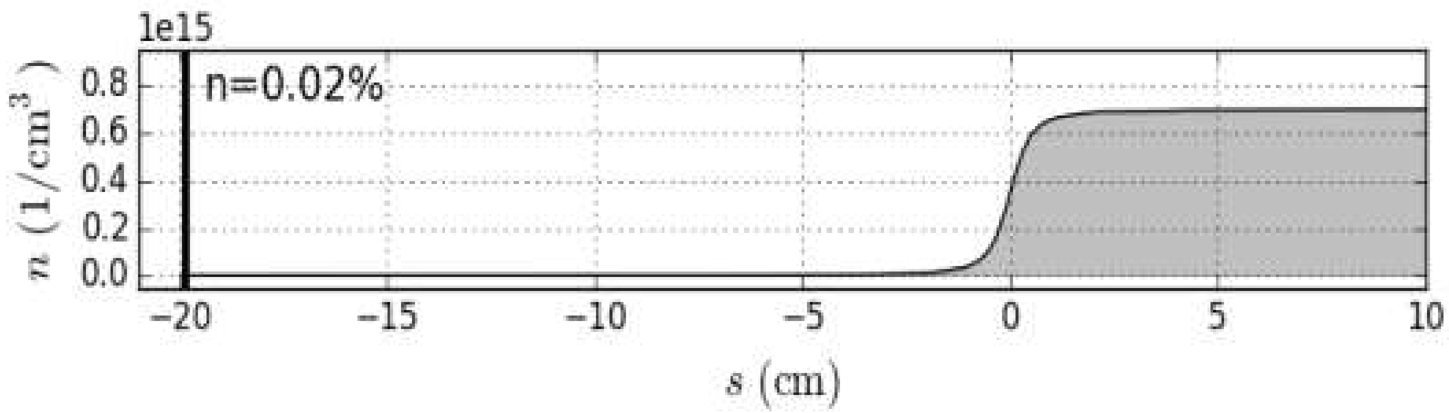
3D Simulations for Unresolved Phenomena in 2D

Slide from Alexey Petrenko (CERN).

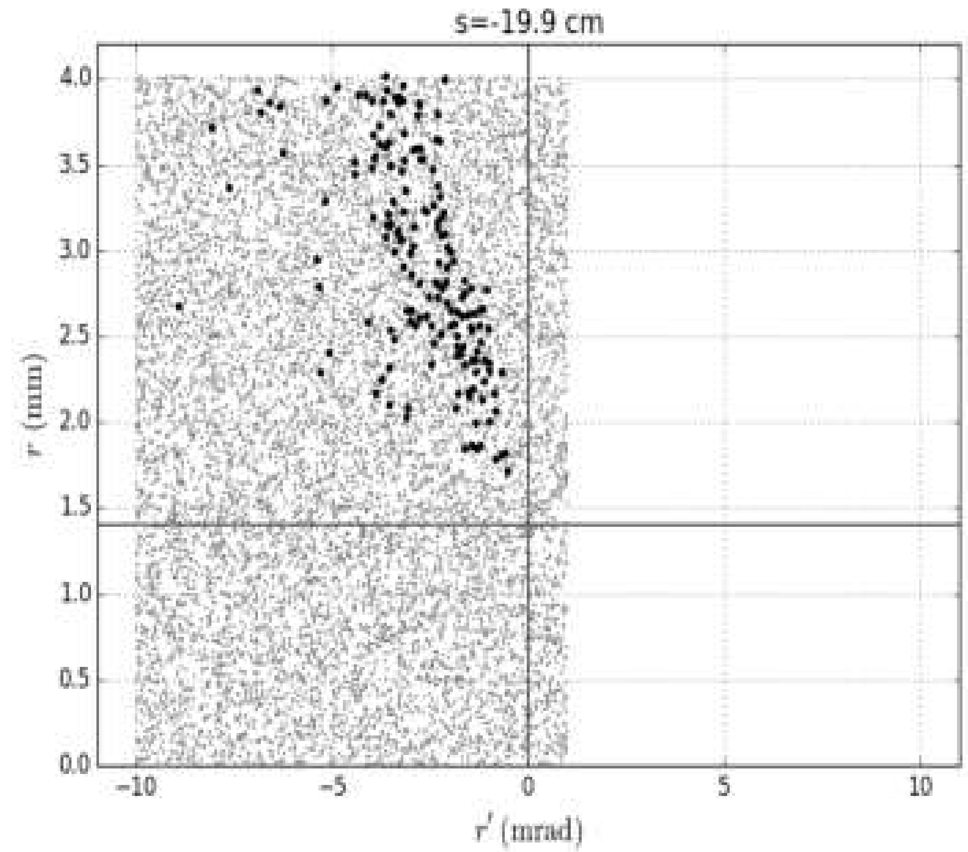
Action of radial forces on test electrons

Red lines show the trajectories of plasma electrons. Dots show the 16 MeV electrons from the injected beam.





Injected electrons marked by the black dots will be captured eventually:



Plasma electrons are ejected from plasma at the density ~0.1% of nominal (~10^{-12} 1/cm^3). This results in strong focusing electric field extending for several mm outside plasma.

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  - Novel emittance diagnostics tests in Argonne for space charge dominated regime
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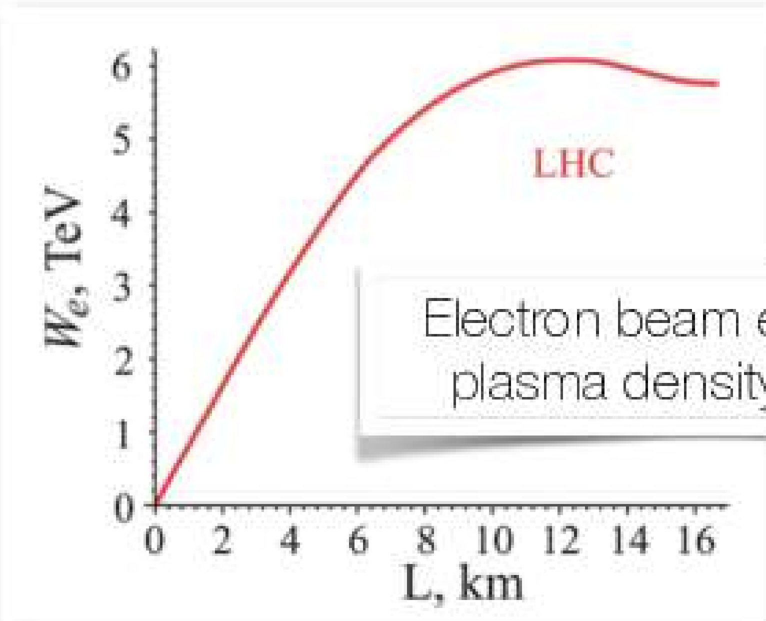
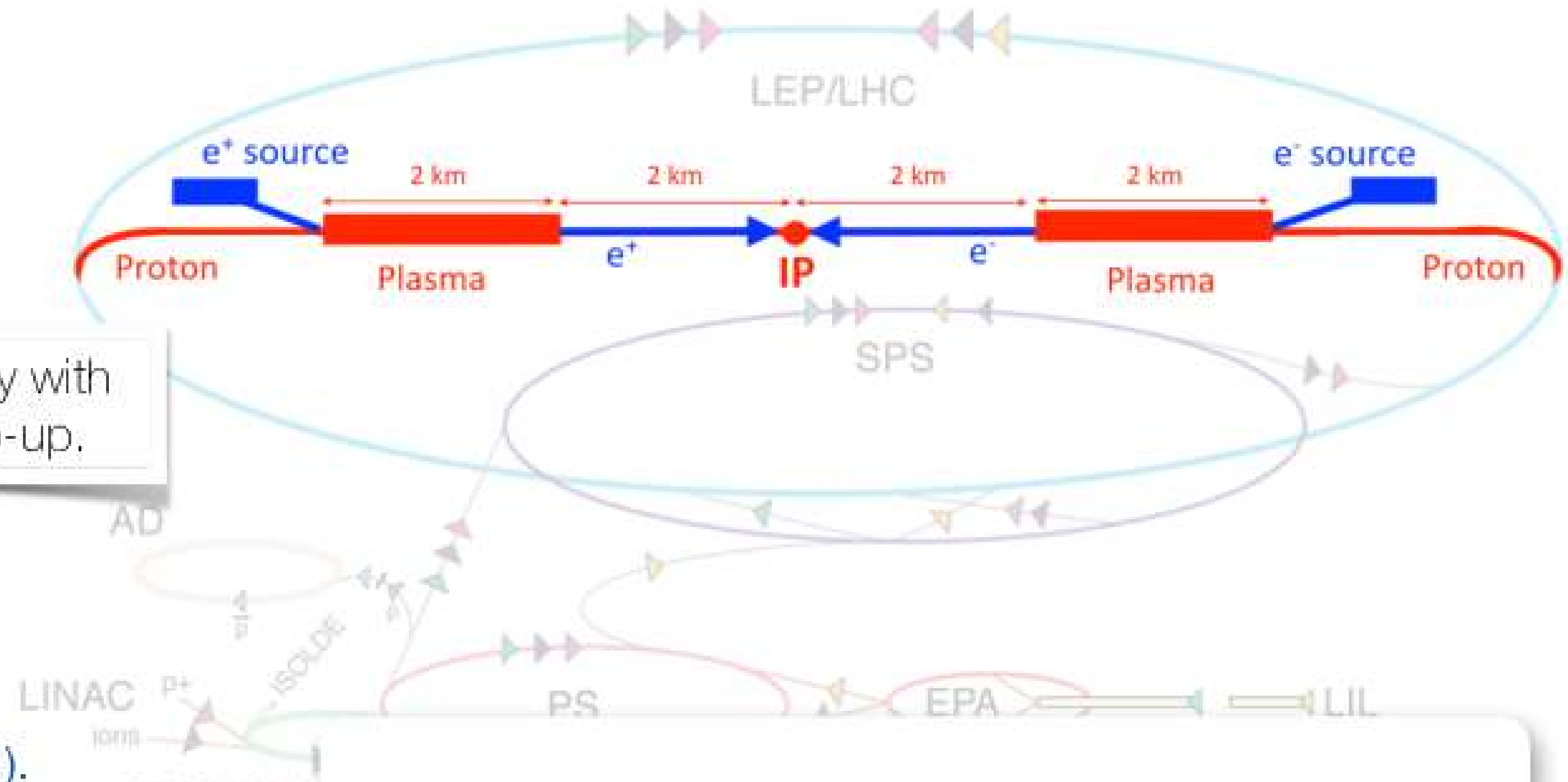
An electron-positron collider



Electron beam energy with plasma density step-up.

A. Caldwell, K. V. Lotov,
PHYSICS OF PLASMAS 18, 103101 (2011).



For this PDPWA-based e^+e^- collider design, half of the LHC bunches (1404 bunches) are used for driving electron acceleration and the other half for positron acceleration. Taking into account that the ramping time of the LHC is about 20 min and assuming that the loaded electron (and positron) beams have a bunch charge of 10% of the drive proton bunch, i.e. electron (and positron) bunch charge of $N_e = 1.15 \times 10^{10}$, and the beam spot sizes at IP are the same as that of the CLIC beam, as shown in Table 1, the resulting luminosity for such an e^+e^- linear collider is about 3.0×10^{31} cm^{-2} s^{-1}, which is about three orders of magnitude lower than that of the ILC or the CLIC.

G. Xia, O. Mete et al.,
NIMA Volume 740, 11 March 2014, 173–179

1 TeV e^+/e^- beam in 2 km of plasma

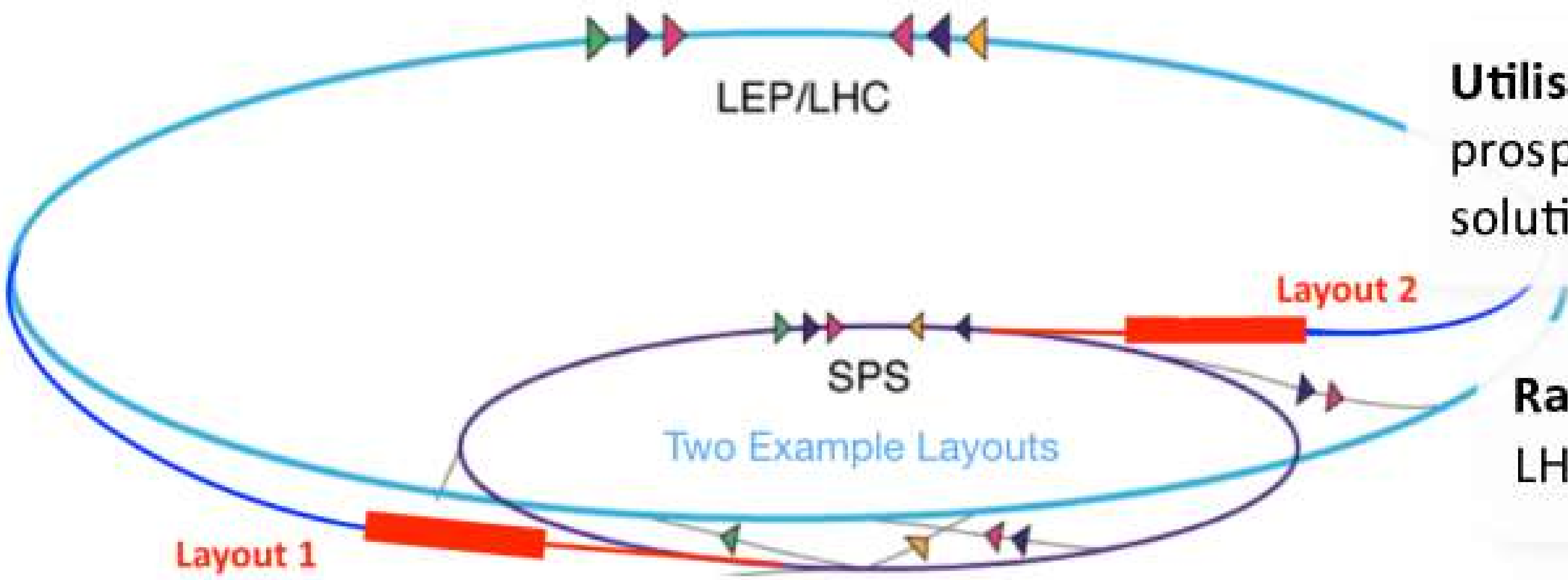
- Via plasma step up and self modulation instability.

LHC radius, 4.3 km

- Transfer and matching of protons&plasma.
- Dedicated e^- source
- 2 km plasma section (0.5 GeV m^{-1}).
- 2 km beam delivery and final focusing section.
- "Used" protons to be extracted, dumped or may be recycled.

Towards the Future

An electron-proton collider



Utilisation of existing CERN infrastructure
prospects of a cheaper and more compact solution than LHeC.

Ramping times
LHC ➟ 20 mins, LHC pre-injectors ➟ 2 s.

SPS protons can excite the plasma
PIC simulations: 1 GV m^{-1} ➟ accelerates e^- beam up to 100 GeV in 170 m of plasma.

Parasitic e^-p collisions*
establish collisions between 100 GeV e^- beam and 7 TeV LHC protons.
*LHC collisions can continue in parallel

of the linac. Using the LHC beam parameters, for example, $N_p = 1.15 \times 10^{11}$, $\gamma_p = 7460$, $\beta_p^* = 0.1$ m, $\epsilon_p^N = 3.5$ μm and assuming the electron beam parameters as follows: $Ne = 1.15 \times 10^{10}$ (10% of the loaded drive bunch charge), $E_e = 100$ GeV, $n_b = 288$ and $f_{rep} \approx 15$, the calculated luminosity of the electron proton collider is about 1×10^{30} cm^{-2} s^{-1} for this design, which is about three to

G. Xia, O. Mete et al.,
NIMA Volume 740, 11 March 2014, 173–179

Issues of **Proton Driven** Plasma Wakefield Acceleration

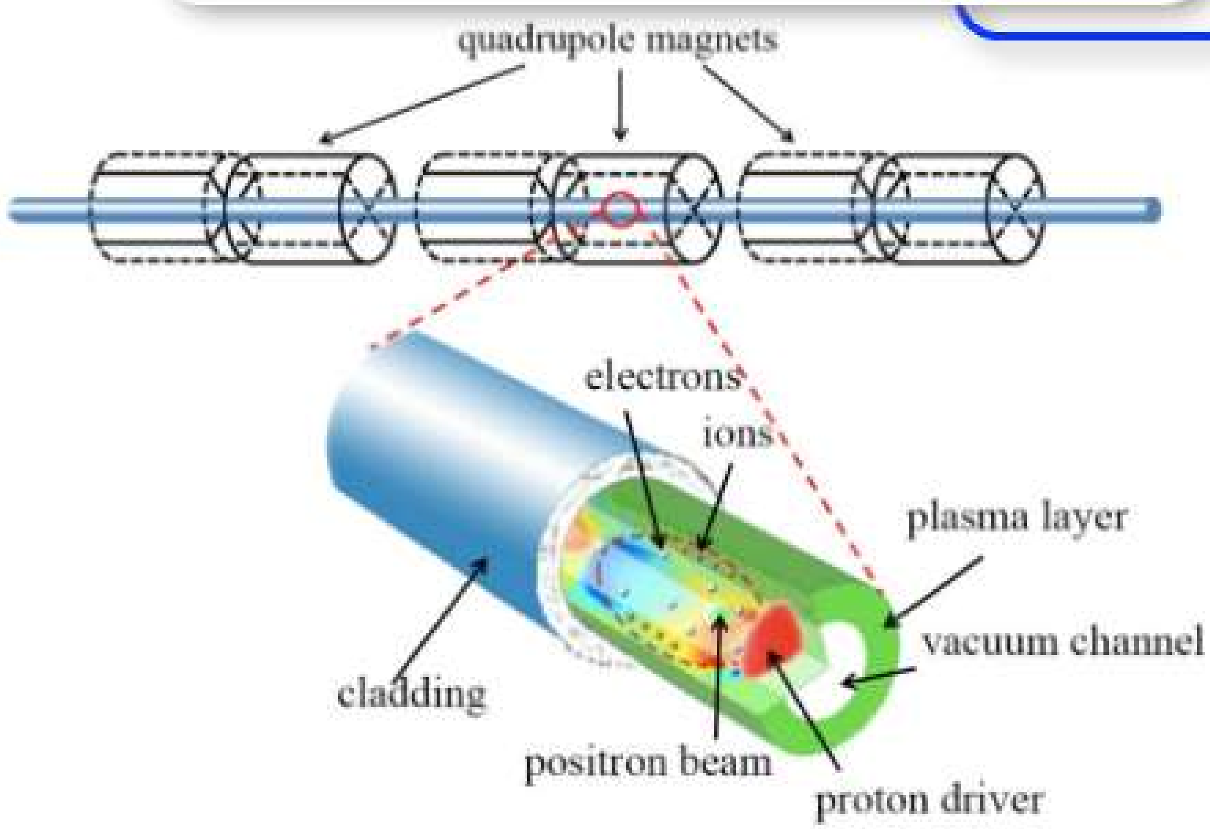
- Phase slippage
- Interaction of “driver” beam with plasma
- Interaction of “witness” beam with plasma
- Positron acceleration (in case of e^-p collider)

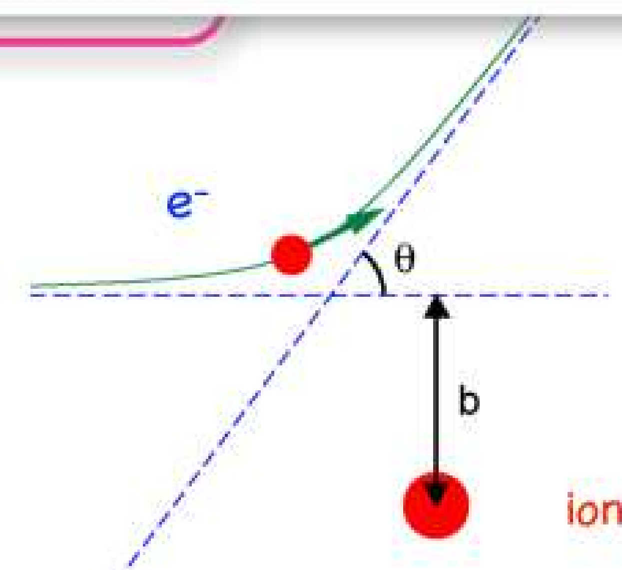
Group velocity of wakefields is the same as the velocity of the driver, protons. **Electrons may overrun the wakefields - no acceleration.**

Bunch lengthening due to energy spread and **focusing** issues of protons.

Production of accelerating field by using a **hollow plasma** for positron acceleration.

Electron beam scattering by plasma electrons and ions - **luminosity degradation through emittance growth**





PHASE SLIPPAGE (DEPHASING)

Key Issues in Collider Design

$$\delta \leq \pi$$

LHC

$$\delta = k_p \Delta s \approx \frac{1}{eE_{acc}/m_e c \omega_p}(\gamma_{ef} - \gamma_{e0}) \left[1 - \frac{(\gamma_{if} - \gamma_{i0})}{\left(\sqrt{\gamma_{if}^2 - 1} - \sqrt{\gamma_{i0}^2 - 1}\right)} \right]$$

otherwise the electrons will overrun the protons.

For a single stage PDPWA based e^+e^- collider design, a 7 TeV LHC proton beam will excite plasma wakefields and accelerate electron bunches to 1 TeV (assuming electron injection energy of 10 GeV which is far less than 1 TeV), $\gamma_{i0} \approx 7000$, $\gamma_{ef} - \gamma_{e0} \approx 2 \times 10^6$. If we assume that the amplitude of wakefields is $eE_{acc}/m_e c\omega_p \sim 1$, then the phase slippage is

$$k_p \Delta s = 2 \times 10^6 \left[1 - (\gamma_{if} - 7000)/(\sqrt{\gamma_{if}^2 - 1} - \sqrt{7000^2 - 1}) \right]$$

The calculation shows that the phase slippage length (or maximum acceleration length) is about ~ 4 km assuming the plasma density of 10^{15} cm^{-3} for a final proton beam energy of around 1 TeV. Therefore a 2 km acceleration channel meets the phase slippage requirement for an e^+e^- collider design.

SPS

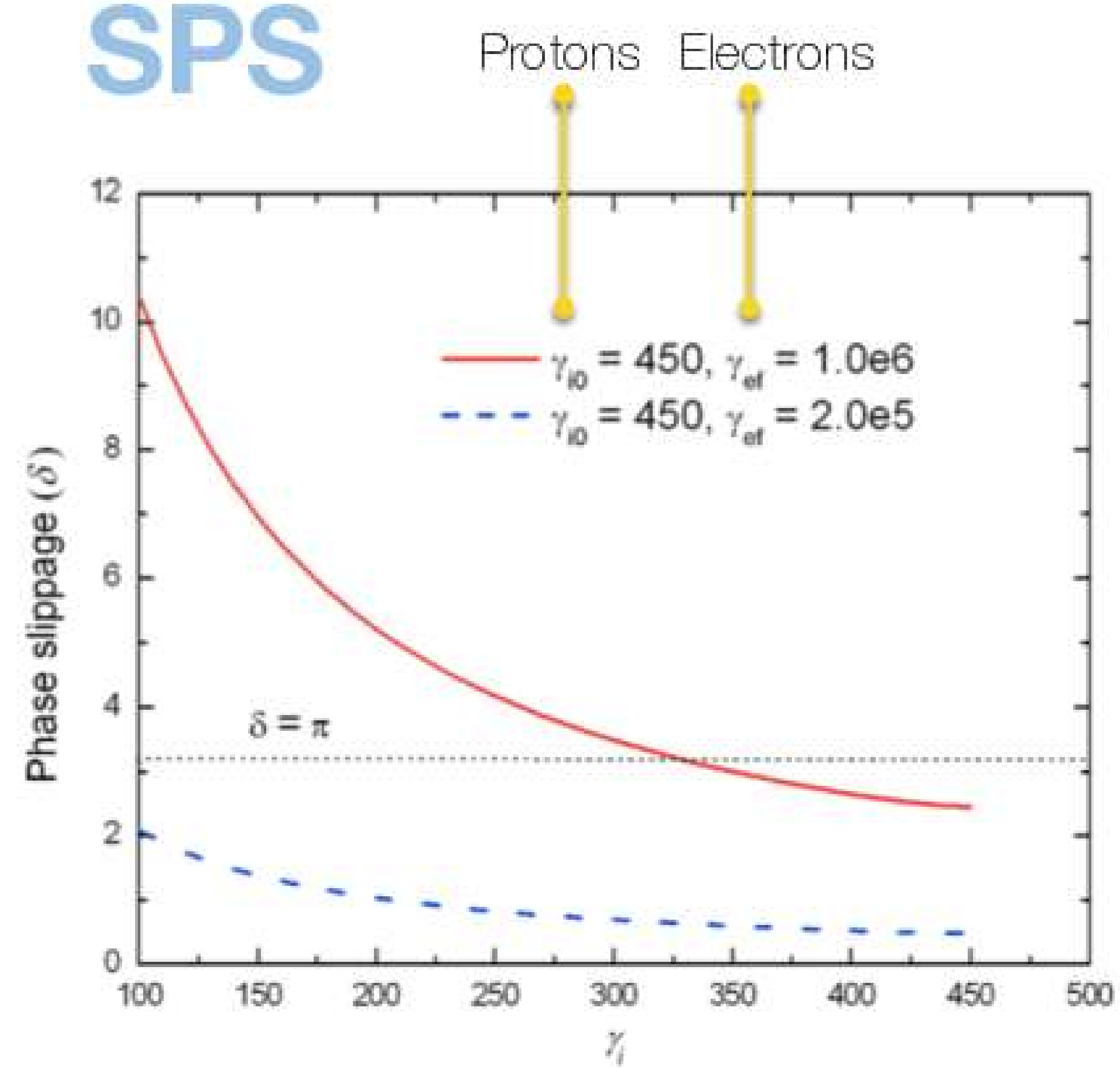


Fig. 2. Phase slippage between the SPS proton beam and the electron beam as a function of γ_i of the proton driven beam for a single 500 GeV stage and 100 GeV stage electron beam production.

G. Xia, O. Mete et al.,
NIMA Volume 740, 11 March 2014, 173–179

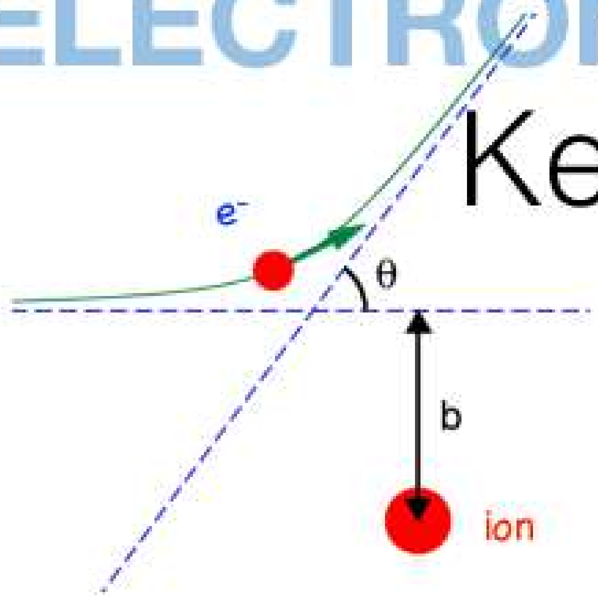
Key Issues in Collider Design

Assume a gradient of 1 GeV/m: e^+/e^- acceleration ➡ several hundred - few thousand meters,

- **Issue I:** guiding of the drive beam over such long distances,
  - Focusing: external by quads, transverse plasma wakefields.
- **Issue II:** Moreover, drive bunch lengthening due to finite momentum spread,
  - 7 TeV LHC beam, $\Delta p/p = 10^{-4}$ spread leads to 0.01 μm/m,
  - Initial LHC bunch length 7.55 cm >> 20 μm after 2 km of travel in plasma - negligible!
  - Lengthening should be carefully considered for the self modulation regime.

$$\Delta d \approx \frac{L}{2\Delta\gamma^2} \approx \frac{\Delta p}{p}\frac{m_p^2 c^4}{p^2 c^2} L$$

Key Issues in Collider Design



$$\frac{d\sigma}{d\Omega} \approx \left(\frac{2Zr_0}{\gamma}\right)^2 \frac{1}{(\theta^2 + \theta_{min}^2)^2}$$

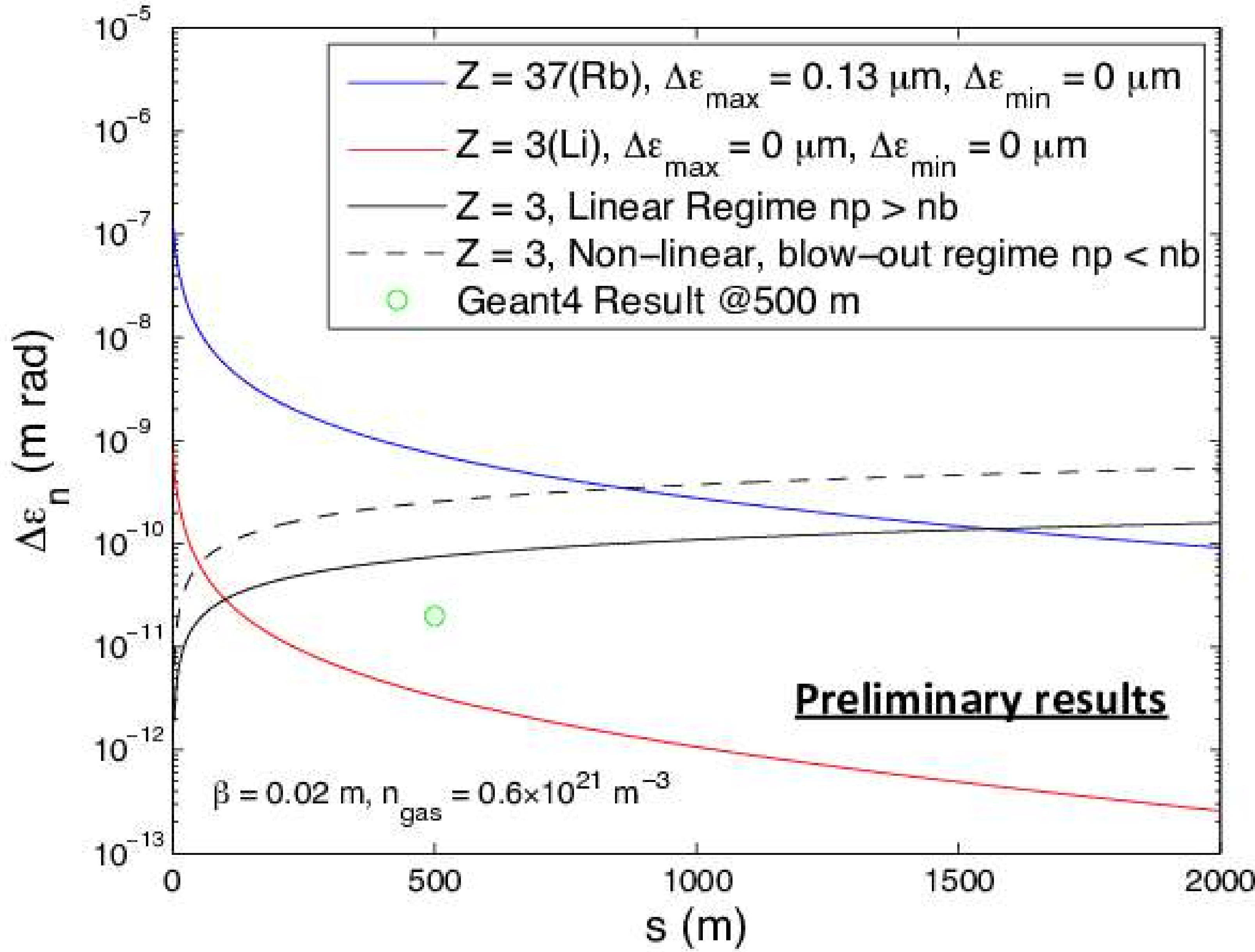
Coulomb scattering cross section.

$$\Delta\epsilon_{n,x,y} = \frac{\gamma\beta_{x,y}}{2}\overline{\mathcal{N}\langle\theta_{x,y}^2\rangle}$$

Diffusion equation representing the emittance growth.

- Elastic/inelastic scattering of the witness particles,
  - by plasma ions -- assumed stationary,
  - by plasma electrons (insignificant in the blow-out regime?) -- mobile.

- Black ➟ estimations modified from the model[1] for beam-gas scattering in a damping ring,
- Blue, red ➟ preliminary model,
- Green ➟ Geant4 result[2],
- ***Realistic model development and GEANT4 simulations in progress.***



[1]T.O. Raubenheimer, (Ph.D. thesis), SLAC-387, 1991. [2]A. Caldwell et al, Nature Physics 5, 363 (2009).

Key Issues in Collider Design

Tracking Scenario

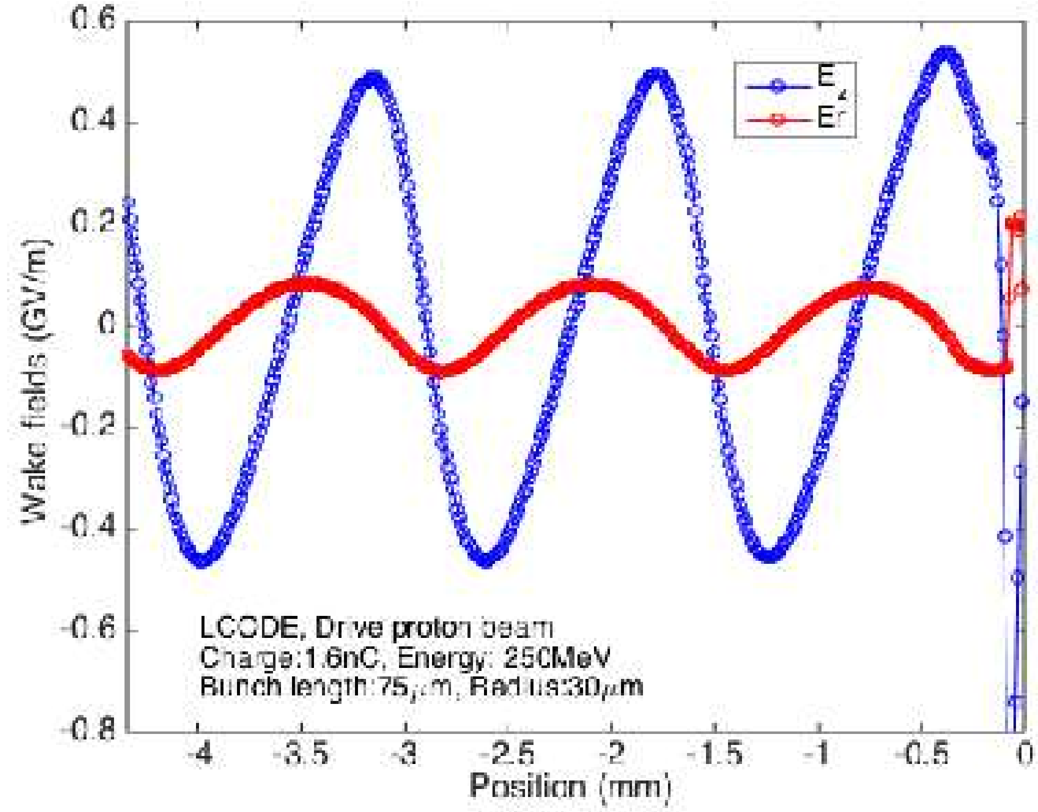
Pre-formed wakefields by LCODE

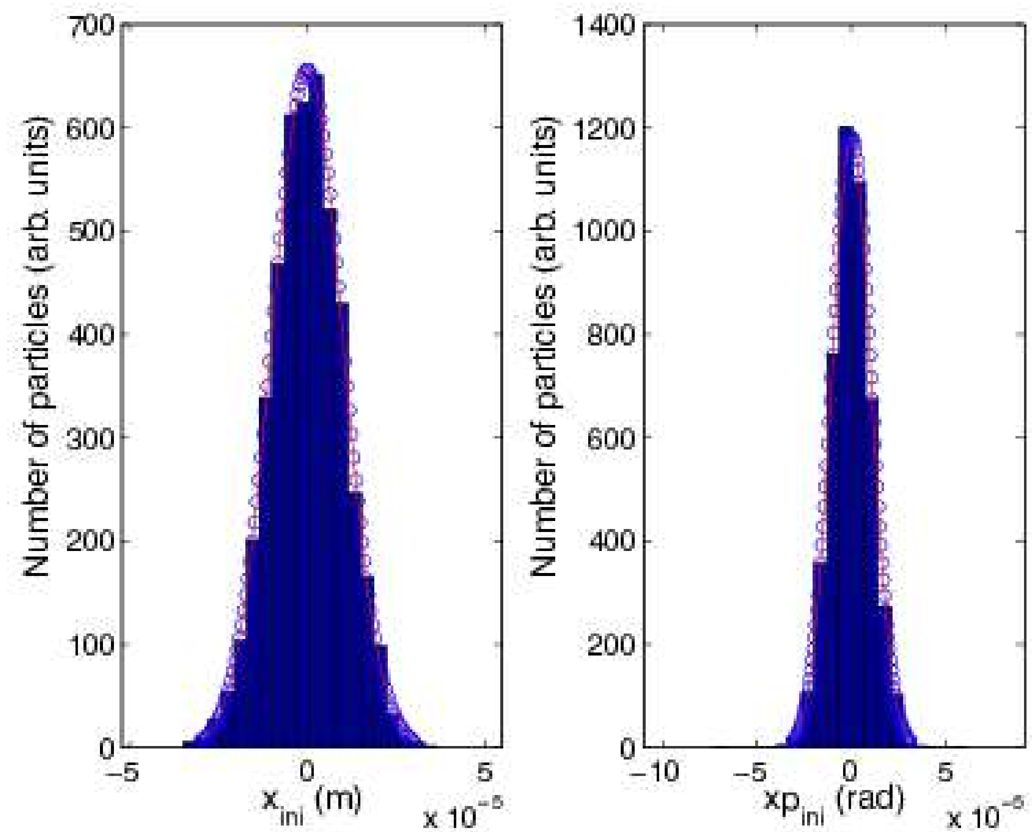
- Longitudinal (0.5 GV/m) and transverse (0.1 GV/m) fields defined in Geant4,
- Li (Z = 3, a = 6.941 g/mol)
- and Rb ((Z = 37, a = 85.468 g/mol)) gasses were considered,
- Uniform medium: 500m long, 100mm radial extent.

Initial beam

- 10k particles at 10 GeV
- Gaussian distribution for beam size and divergence, with standard deviation of 10μm and 10μrad.

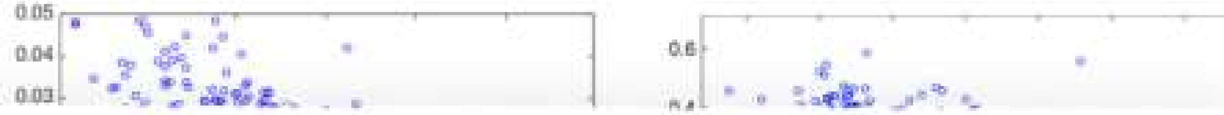
O. Mete et al.,
Physics of Plasmas 22, 083101 (2015).





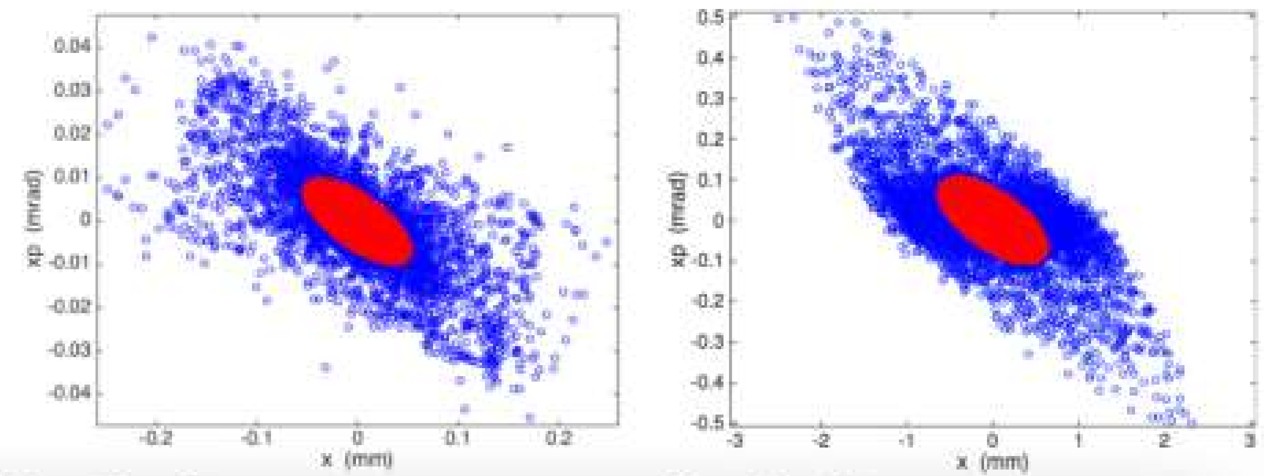
ELECTRON-PLASMA INTERACTIONS

Key Issues in Collider Design



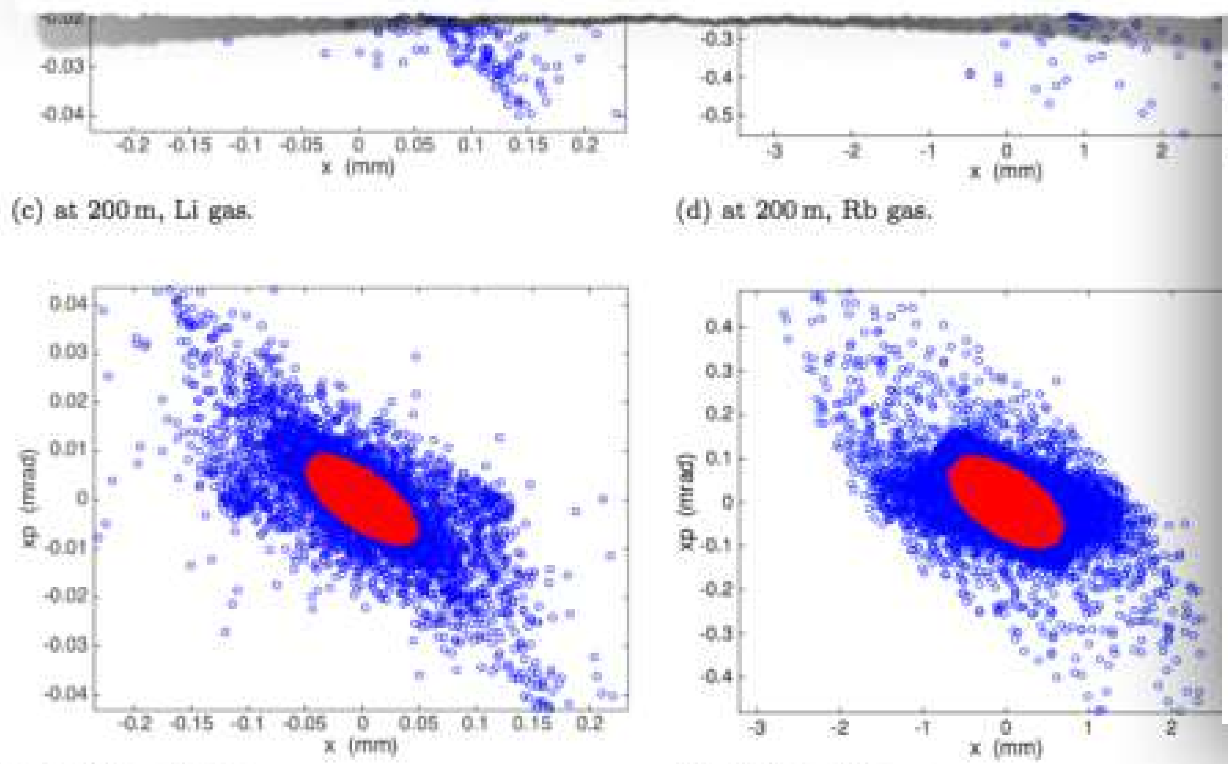
According to the simulations, the largest growth is induced by the multiple scattering of the beam particles by plasma particles. Rb gas yields two orders of magnitude larger emittance growth (41 mm mrad/m) than Li gas (0.5 mm mrad/m) in average over 500 m, as expected, since the scattering cross section is proportional to the square of the atomic number. Both cases are compared to the vacuum case where beam travels through vacuum under the effect of the transverse and longitudinal wakefields, and an average emittance growth of 6 nm/m was calculated due to effects other than scattering such as plasma-beam mismatch.

O. Mete et al.,
Physics of Plasmas 22, 083101 (2015).



(g) at 400 m, Li gas.

(h) at 400 m, Rb gas.

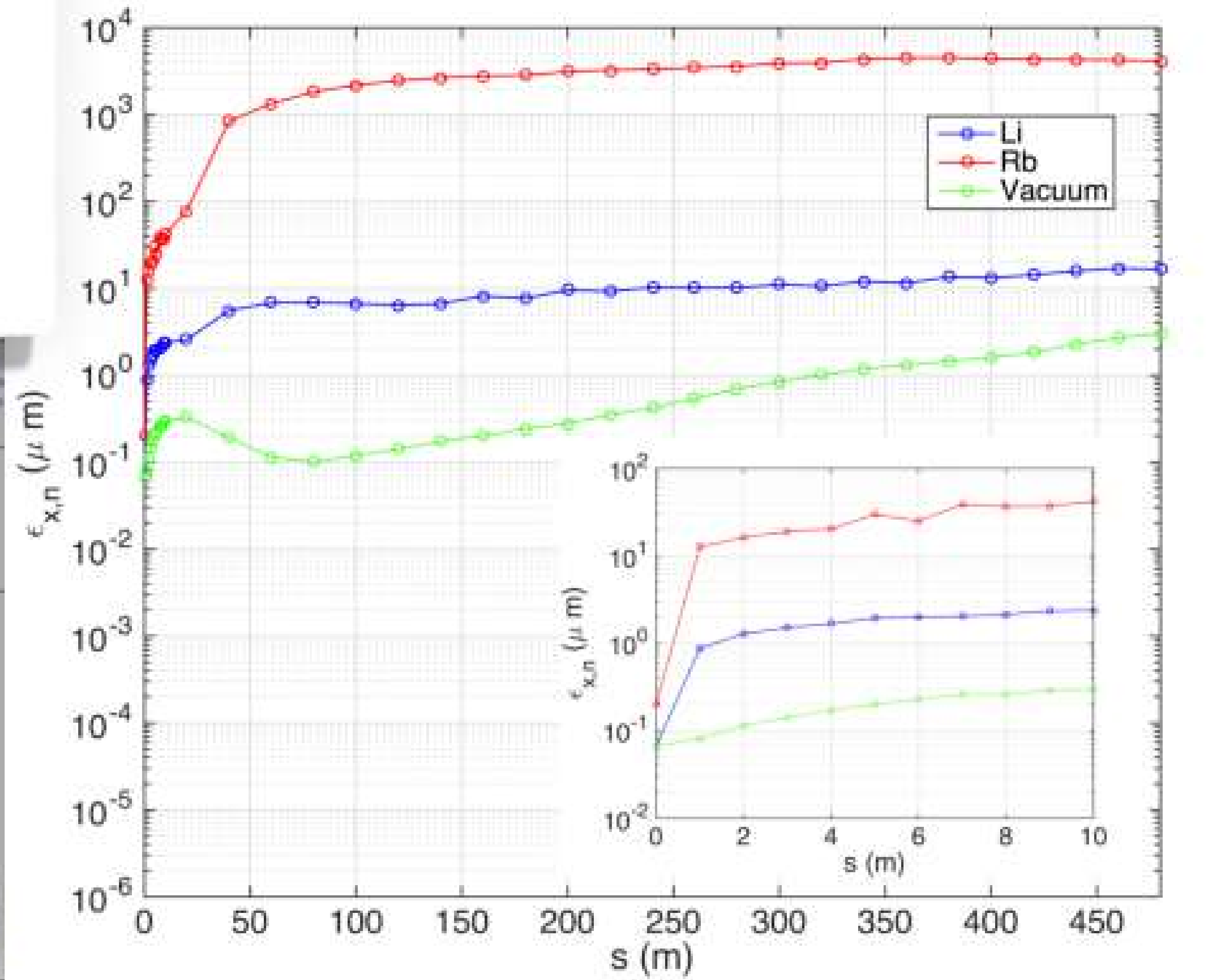


(c) at 200 m, Li gas.

(d) at 200 m, Rb gas.

(e) at 300 m, Li gas.

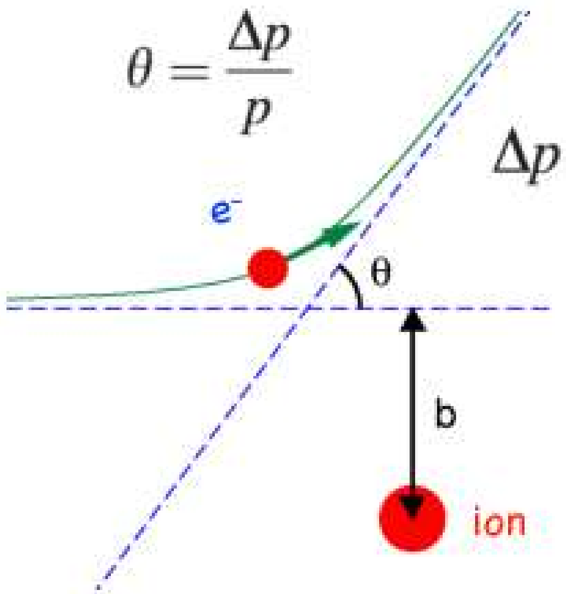
(f) at 300 m, Rb gas.



Key Issues in Collider Design

$$\theta = \frac{\Delta p}{p}$$

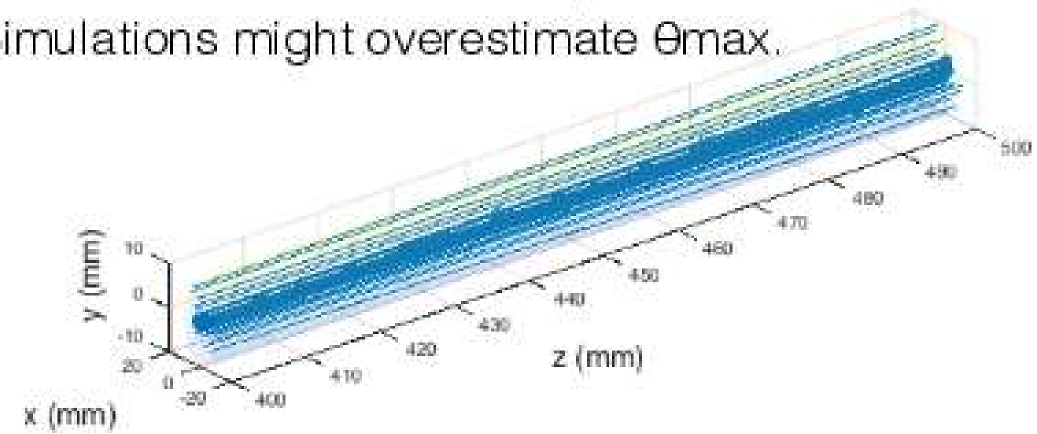
$$\Delta p \, b \geq \hbar$$

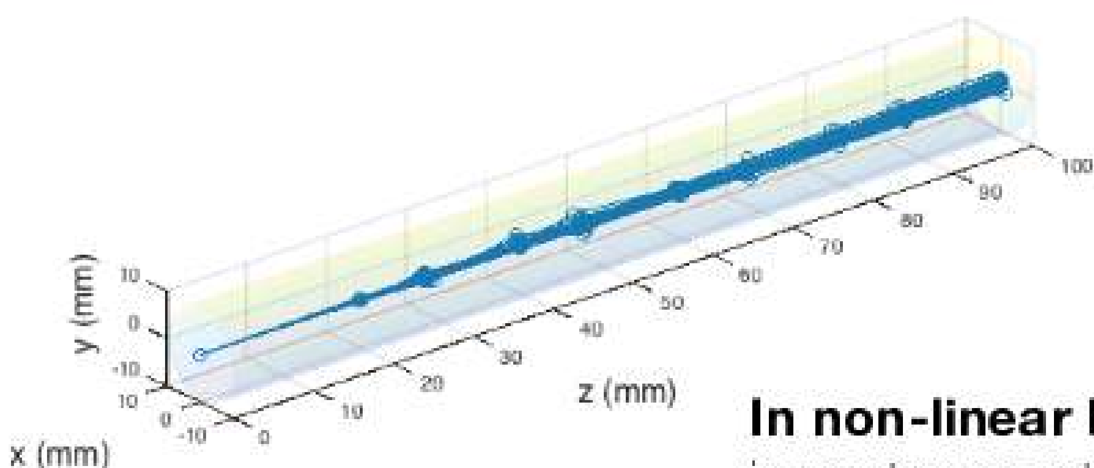


$$\theta_{min,\, max} = \frac{\hbar}{p \, b_{max,min}}$$

Minimum impact factor, can be related to the effective Coulomb radius of the nucleus, R (ion impact is larger than neutral atom case - due to the potential including the electronic structure of the ion).

Simulations might overestimate θmax.





$$\epsilon = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

$$\langle x^2\rangle = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)^2$$

$$\langle x'^2\rangle = \frac{1}{N}\sum_{i=1}^{N}(x'_i - \langle x'\rangle)^2$$

$$\langle xx'\rangle = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)(x'_i - \langle x'\rangle)$$

In non-linear bubble regime, maximum impact parameter will be defined by the bubble radius yielding much smaller scattering angles.

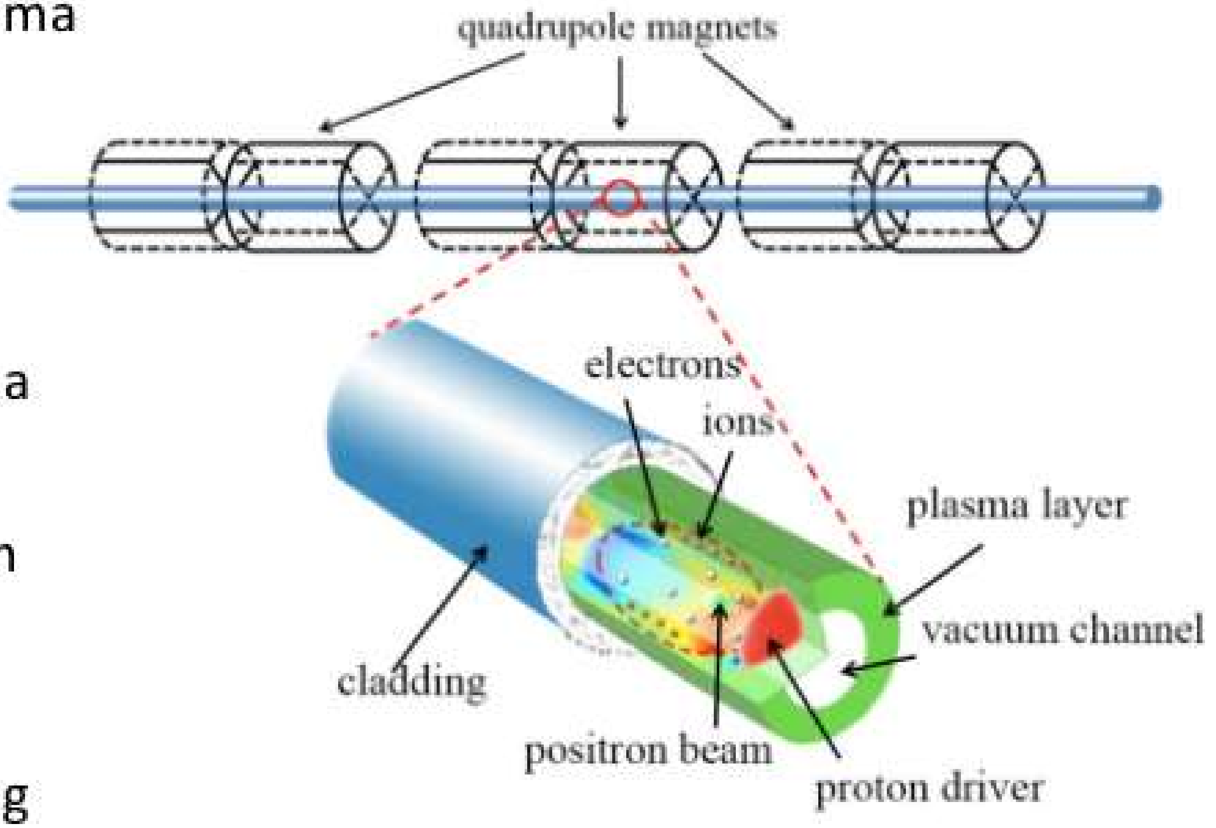
In a fully ionised plasma, maximum impact parameter corresponds to the plasma Debye length.

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}}$$

POSITRON ACCELERATION

Key Issues in Collider Design

- Electron acceleration can be done by proton-driven plasma wakefield acceleration,
- What about the positrons of a e^+e^- collider?[1,2,3]
- Hollow plasma beam:
  - **Focusing of witness:** Charge separation on the plasma layer wall due to driver space charge force,
  - **Acceleration:** Buckets (hollow plasma) are larger than uniform plasma case → Stable acc. over long plasma distance,
  - **Witness - Wave Phasing:** Possible to tune by changing plasma channel radius,



Driver: LHC type beam	Witness proton beam	Plasma
Energy, 2 TeV	Energy, 2 TeV	Hollow
Bunch length, 100 μm	Bunch charge, 1 nC	Density, 6 x 10^{14} cm^{-3}
Intensity, 10^{11}	Injected after 0.75 mm after driver	Length, 1 km
Energy spread, 10%		

- 2D simulation result:
  - Energy gain **1.3 TeV.**
- Feasible **for positrons**[4]**.**

[1] L. Yi et al., arXiv:1309.5691 [physics.plasm-ph] [2] L. Yi et al., arXiv:1306.1613 [physics.plasm-ph]
[3] W. D. Kimura et al., Phys. Rev. ST Accel. Beams 14, 041301
[4] New results from FACET for positrons —> Nature 524, 442–445 (27 August 2015)

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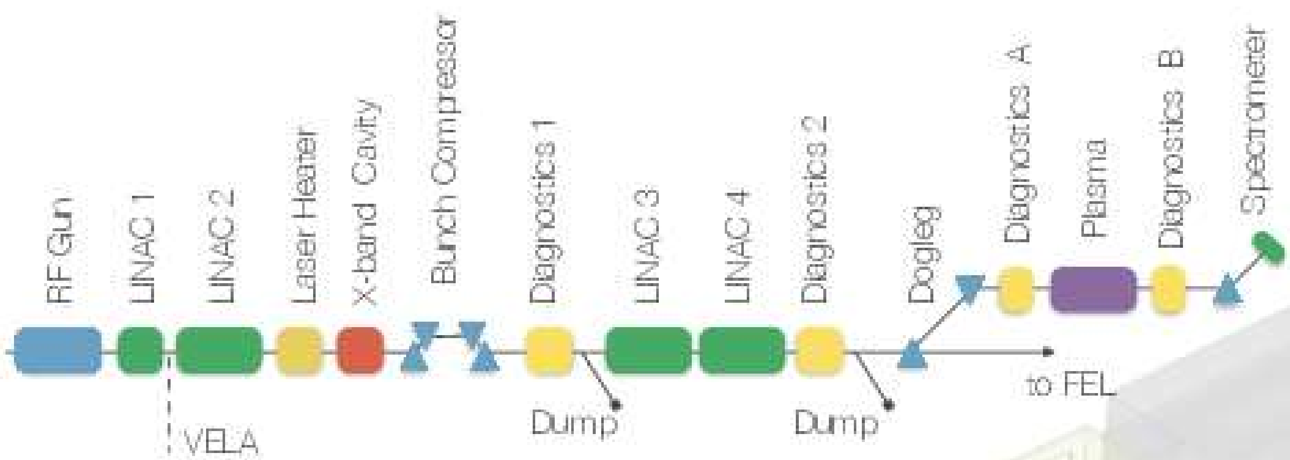
  - Plasma lens

PARS Project



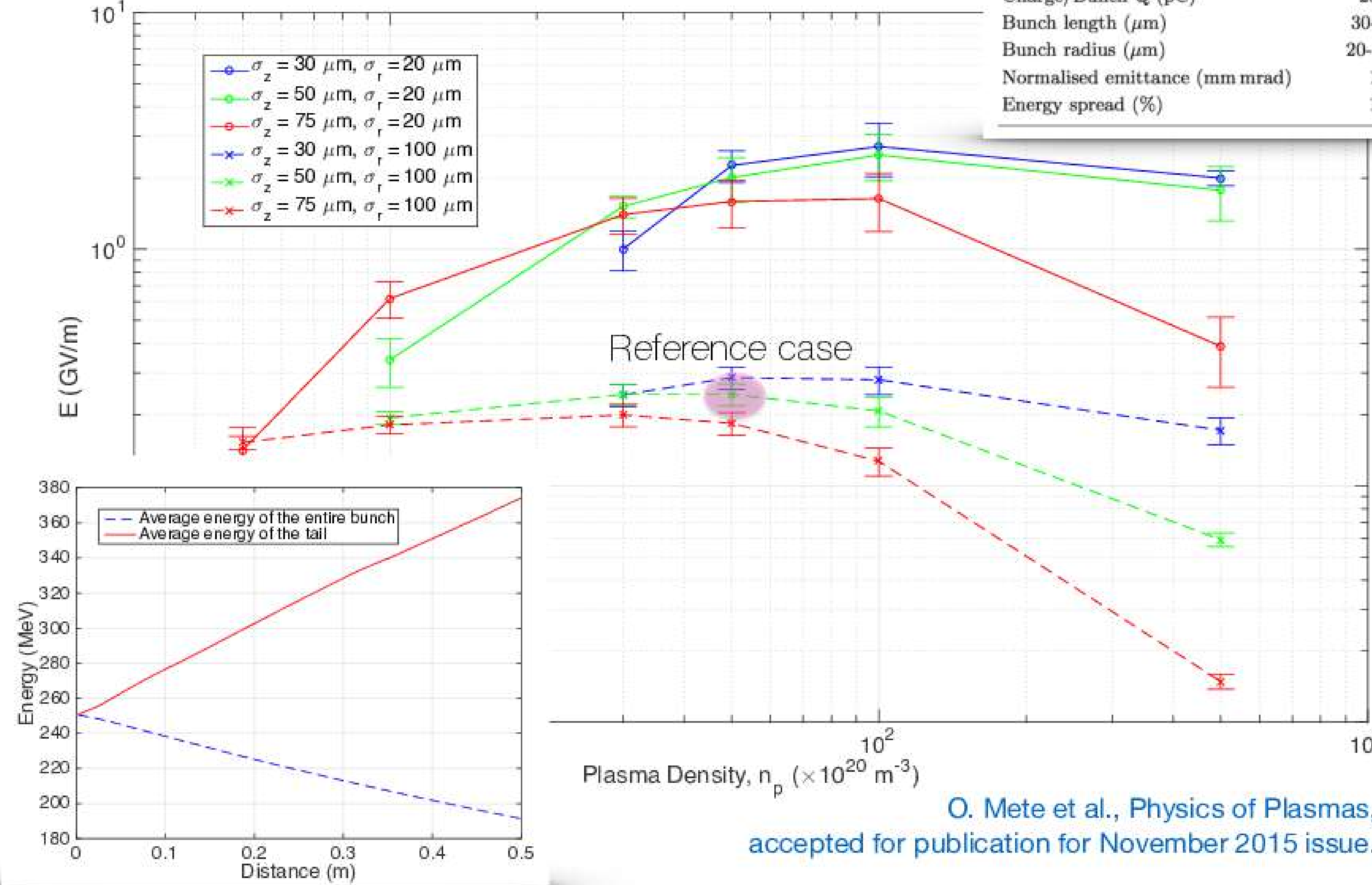
Operating modes	Long Pulse	Short Pulse	Ultra-Short Pulse
Beam energy (MeV)	250	250	250
Charge/Bunch Q (pC)	250	250	20-100
Electron/Bunch N_b ($\times 10^9$)	1.56	1.56	0.125-0625
Bunch length rms (fs)	250-800 (flat top)	100-250	≤ 30
Bunch length (μm)	75-240	30-75	9
Bunch radius (μm)	20-100	20-100	20-100
Normalised emittance (mm mrad)	≤ 1	≤ 1	≤ 1
Energy spread (%)	1	1	1

…in collaboration with Deepa Angal-Kalinin and other ASTeC and CI colleagues.

Single Bunch

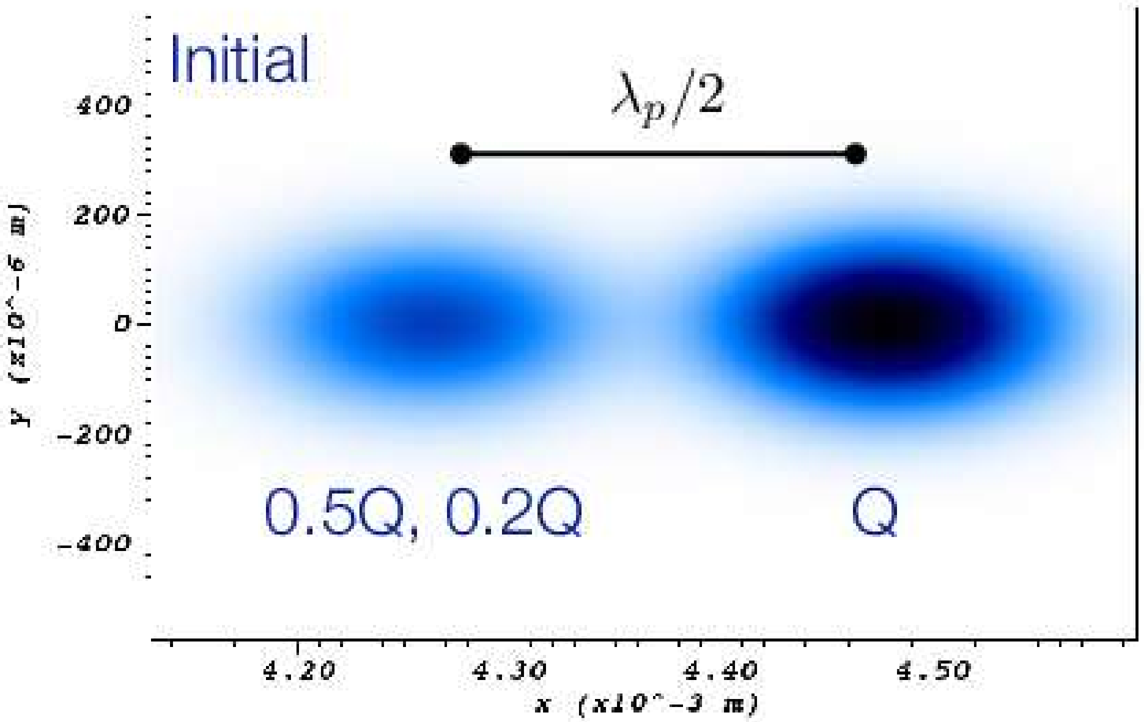
PARS Project

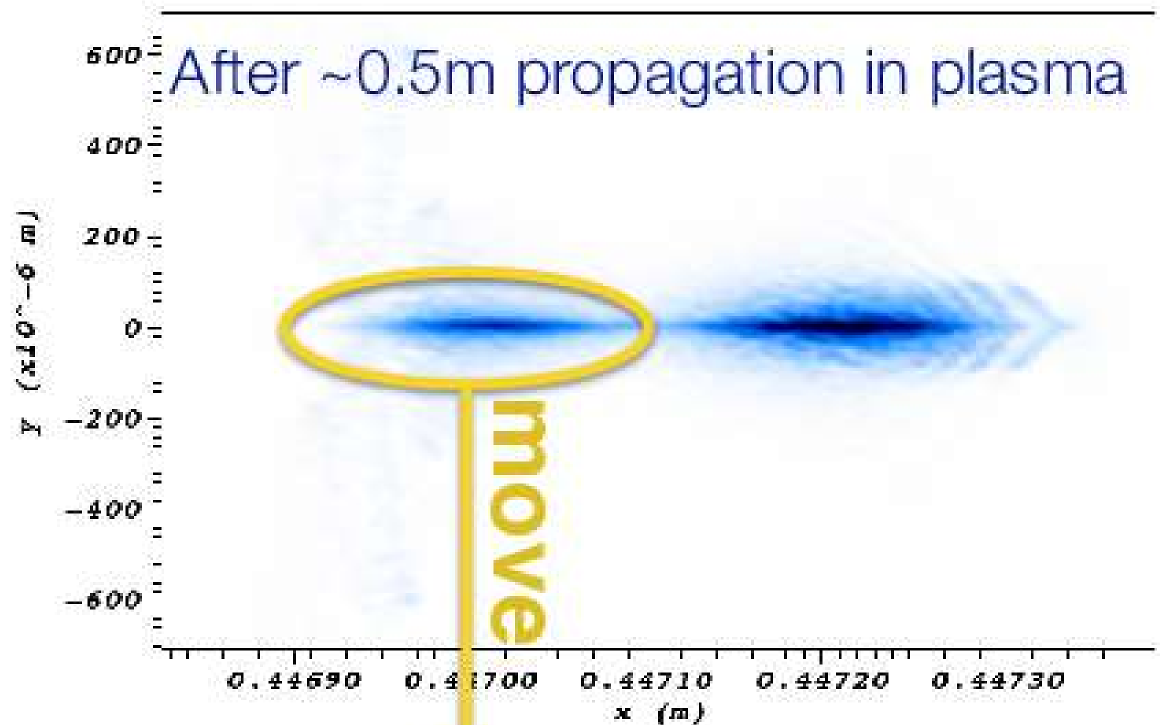
Plasma	
Density (m^3)	1×10^{20}-5×10^{22}
Length (cm)	10-50
Gas type	Ar, H_2
Electron Beam	
Beam energy (MeV)	250
Charge/Bunch Q (pC)	250
Bunch length (μm)	30-75
Bunch radius (μm)	20-100
Normalised emittance (mm mrad)	1
Energy spread (%)	1

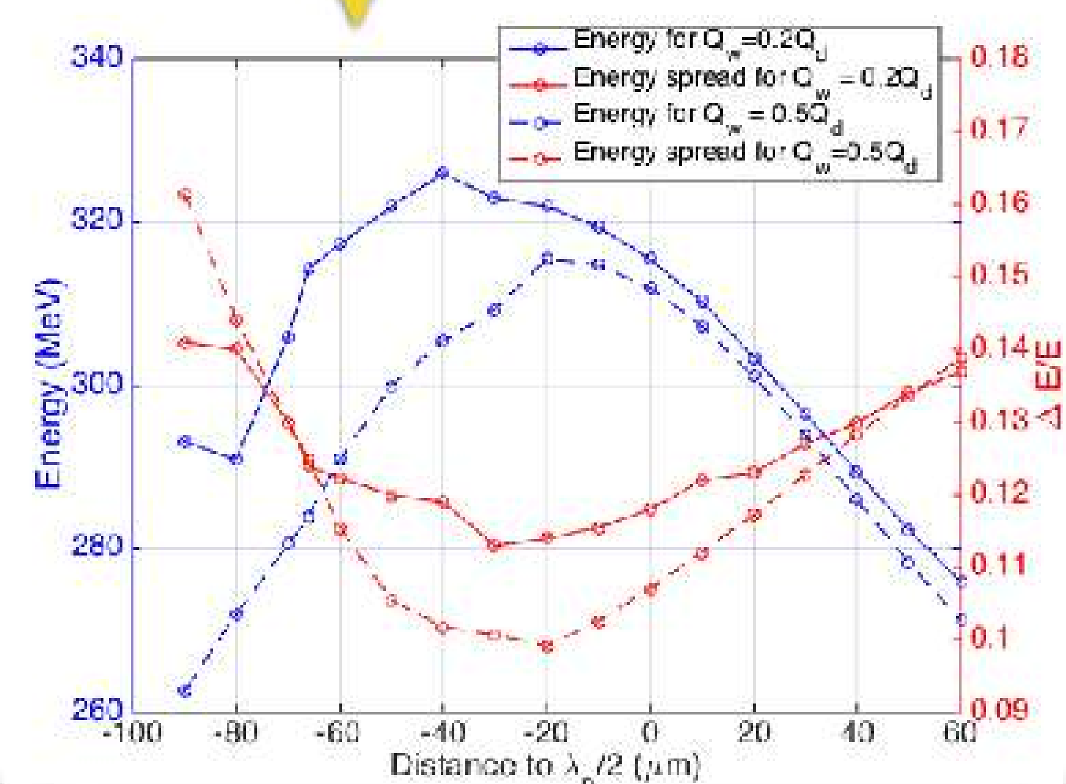


O. Mete et al., Physics of Plasmas, accepted for publication for November 2015 issue.

PARS Project







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Energy spread (%)	1

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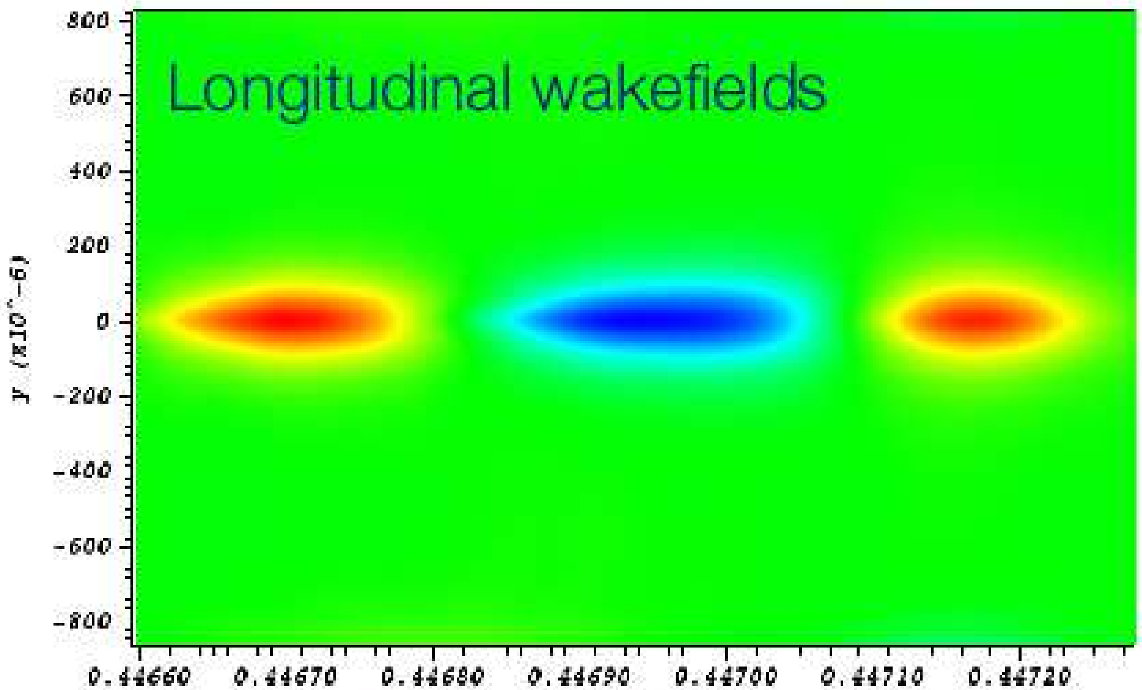
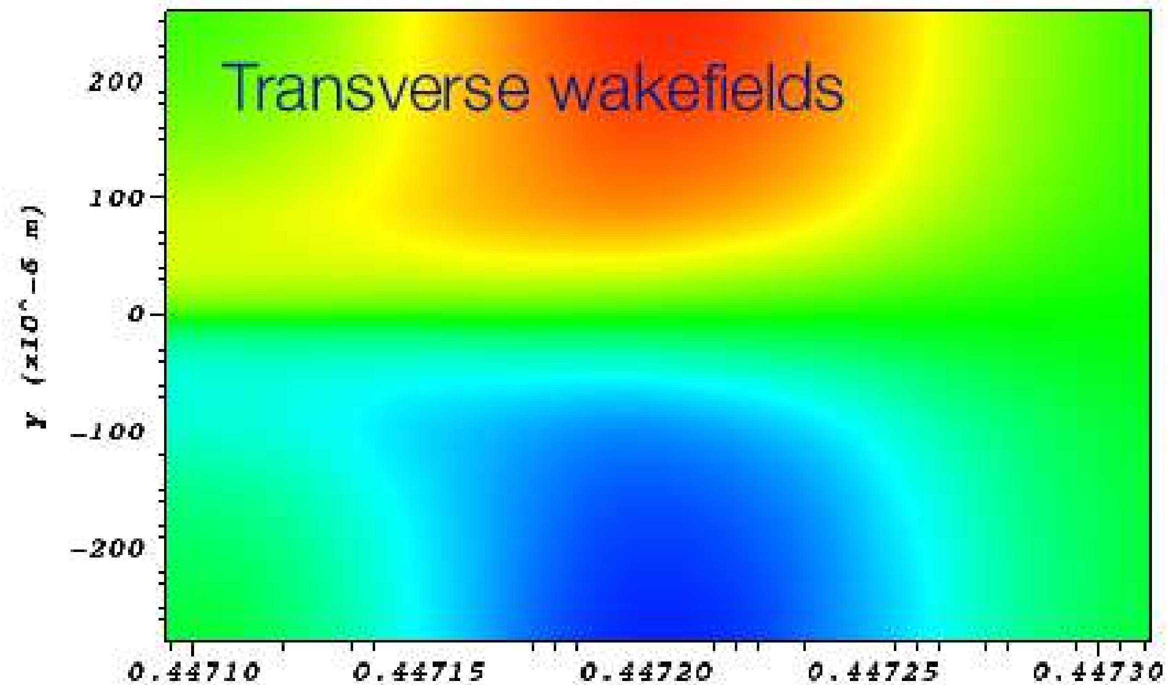
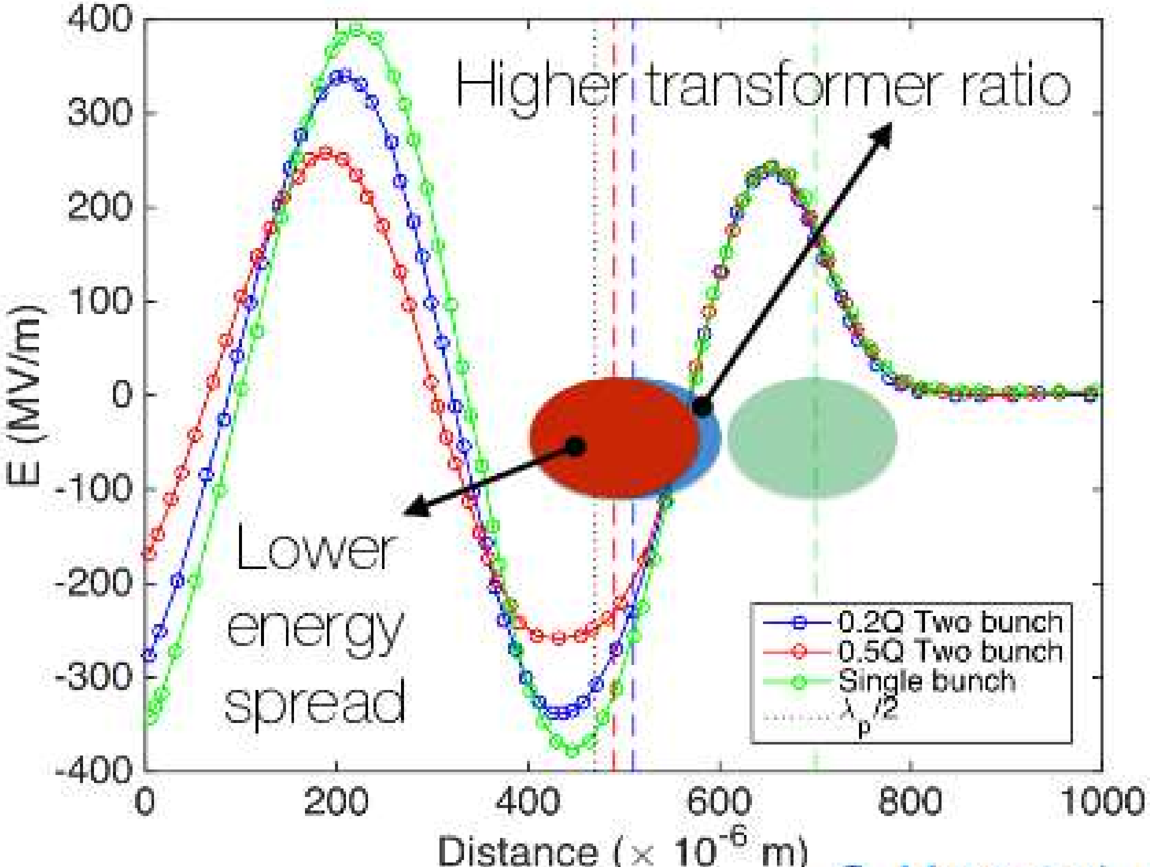
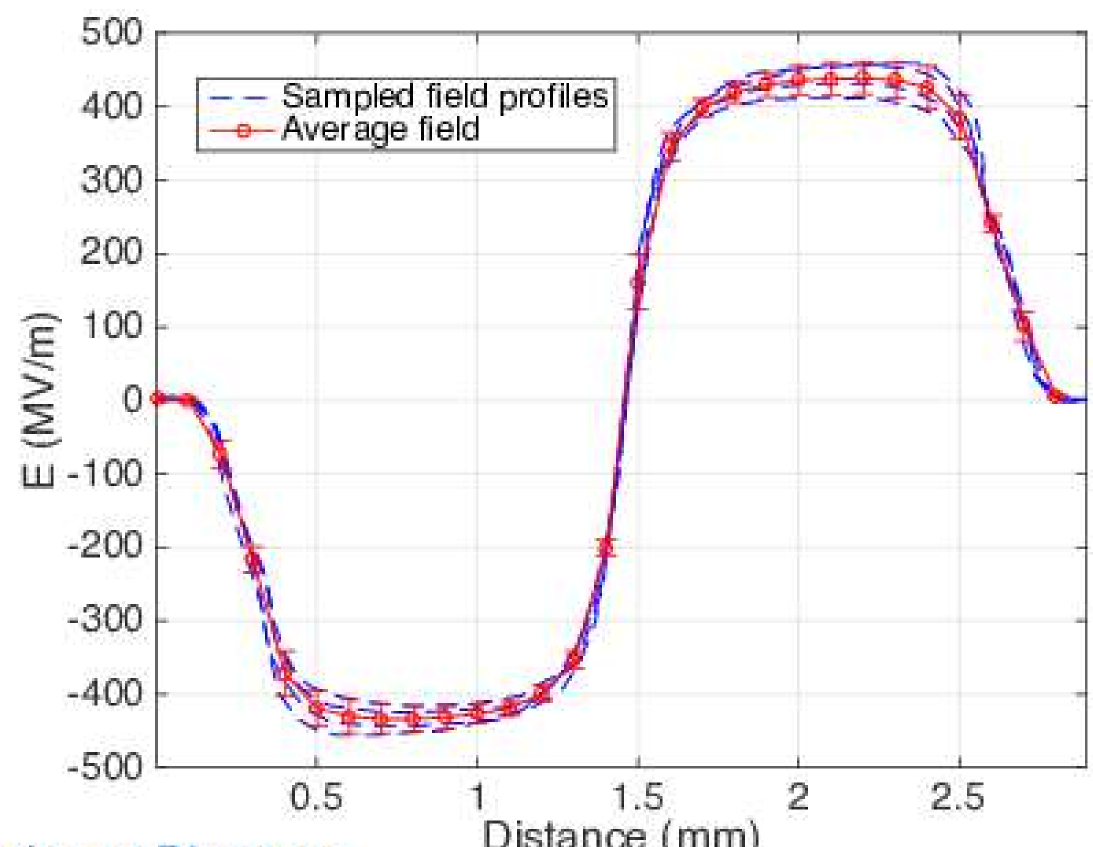
PARS Project







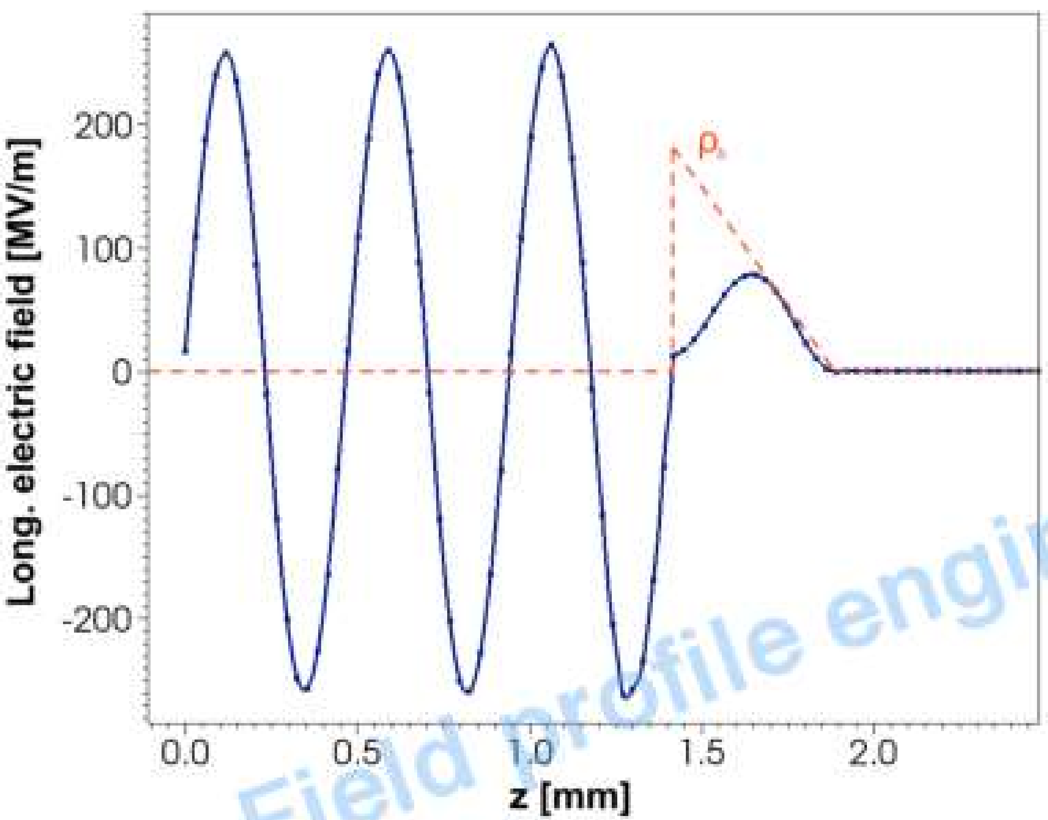


O. Mete et al., Physics of Plasmas, accepted for publication for November 2015 issue.

Beam quality studies

PARS Project

Energy Spread Energy Transfer Efficiency

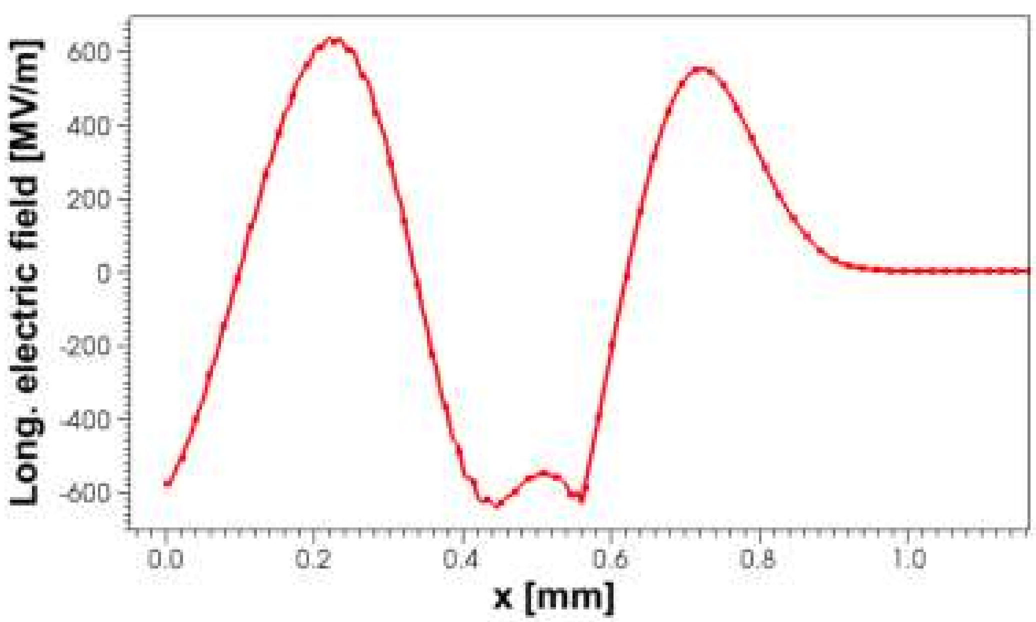


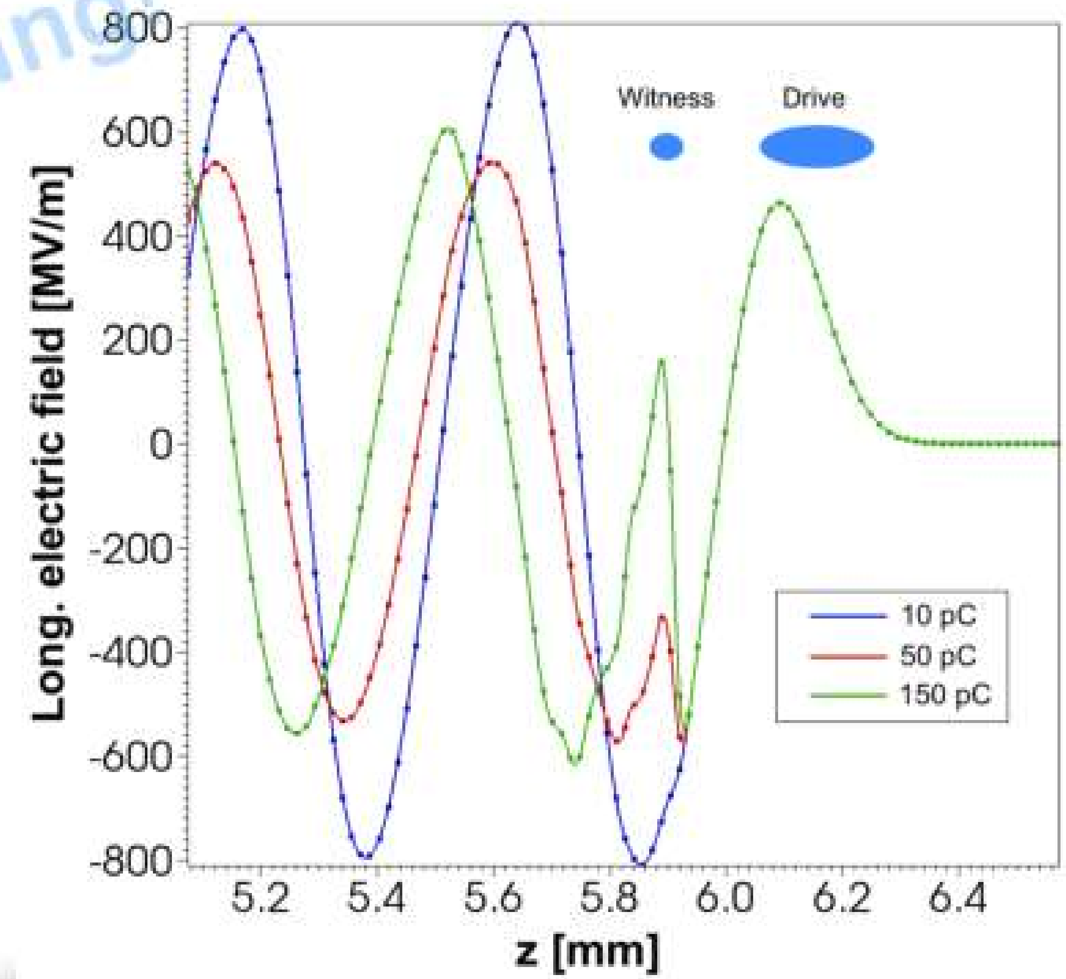
$$R = \frac{E_+}{E_-}$$

$$E = RE_0$$

Results from Kieran Hanahoe (PhD Student) - to be submitted for publication soon.

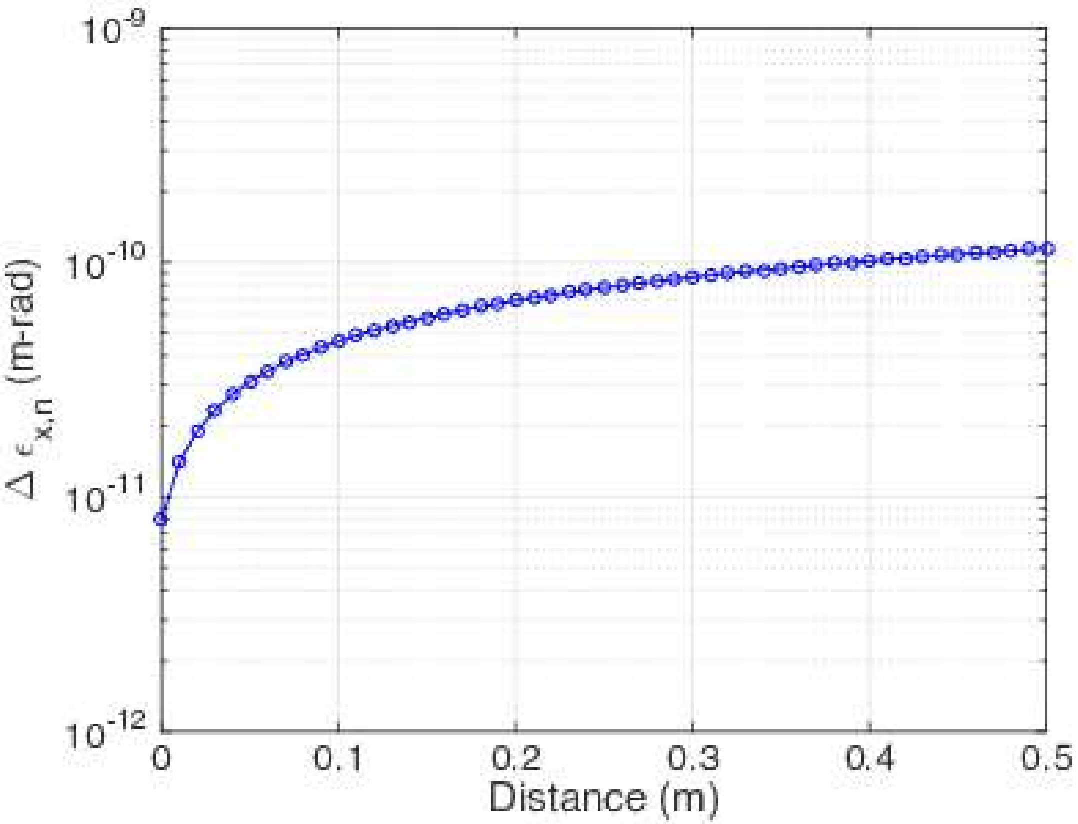
Field profile engineering!

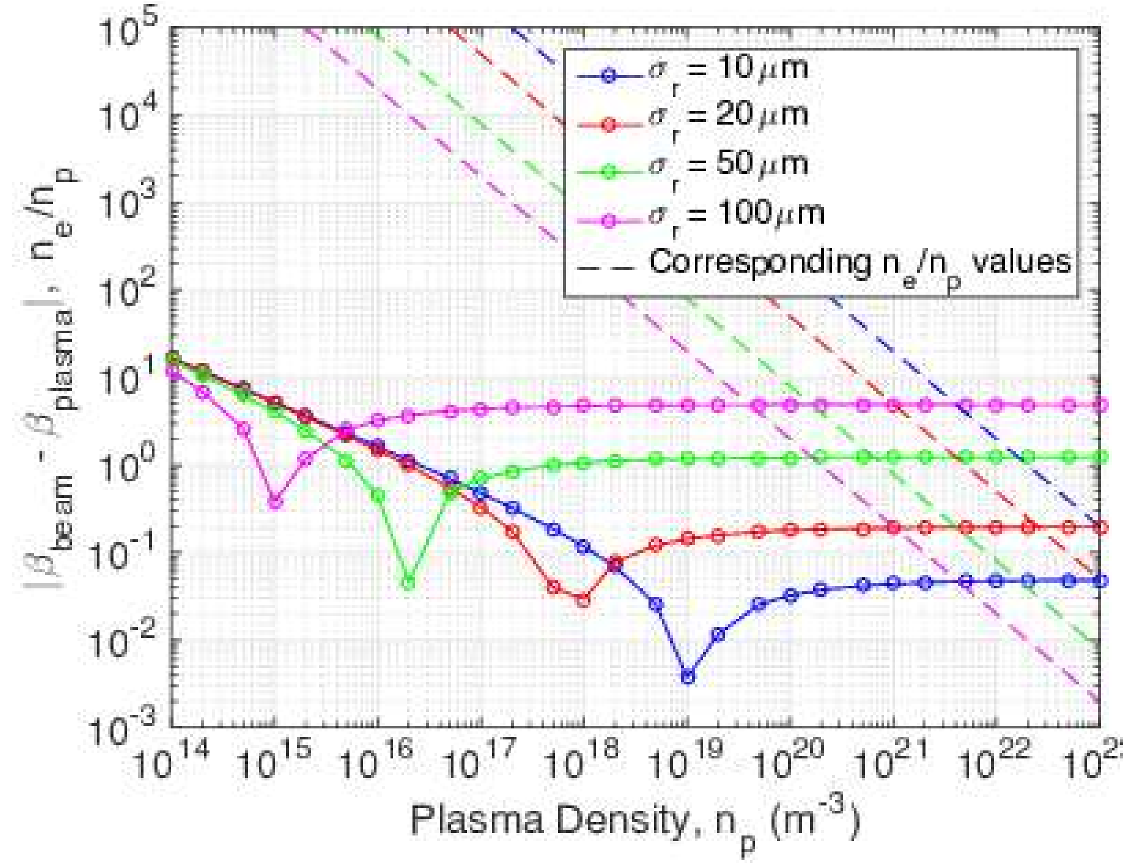




Beam quality studies Emittance Growth

PARS Project





Emittance growth due to scattering for the reference case.

- Theory (based on gas-scattering in damping rings) suggested negligible growth.
- Model is being updated considering ion case where the effective potential is modified including the electronic structure of ions.

Beam-plasma matching.

- Beta functions of the beam and plasma should match.

non-linear bubble focusing

$$K = (eE_r/rm_e\gamma c^2)^{1/2} \qquad K = \omega_p^2/(2\gamma c^2)$$

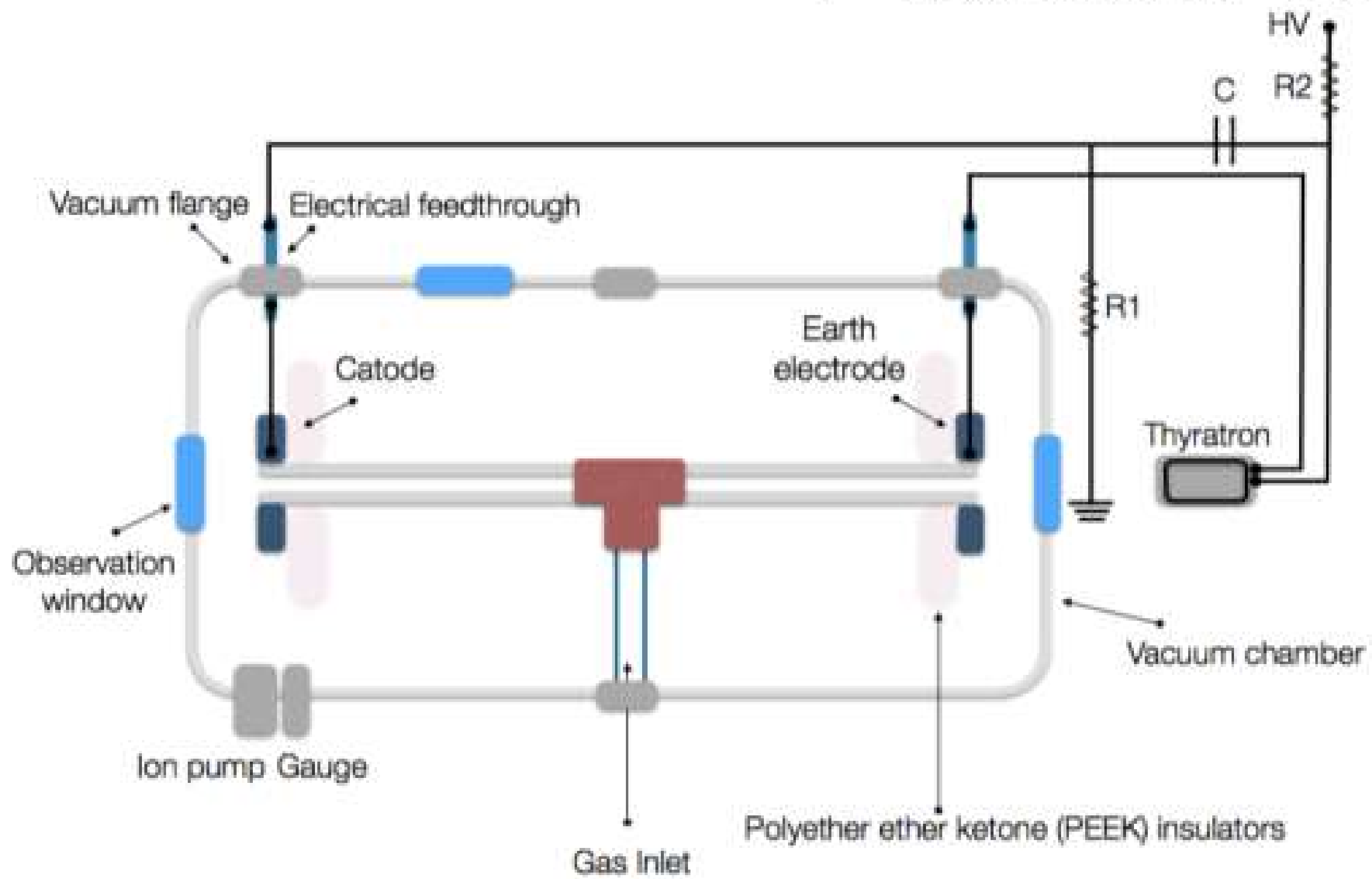
$$\sigma_r''(z) + \left[K^2 - \frac{\varepsilon_N^2}{\gamma^2\sigma_r^4(z)}\right]\sigma_r(z) = 0$$ envelope eq.

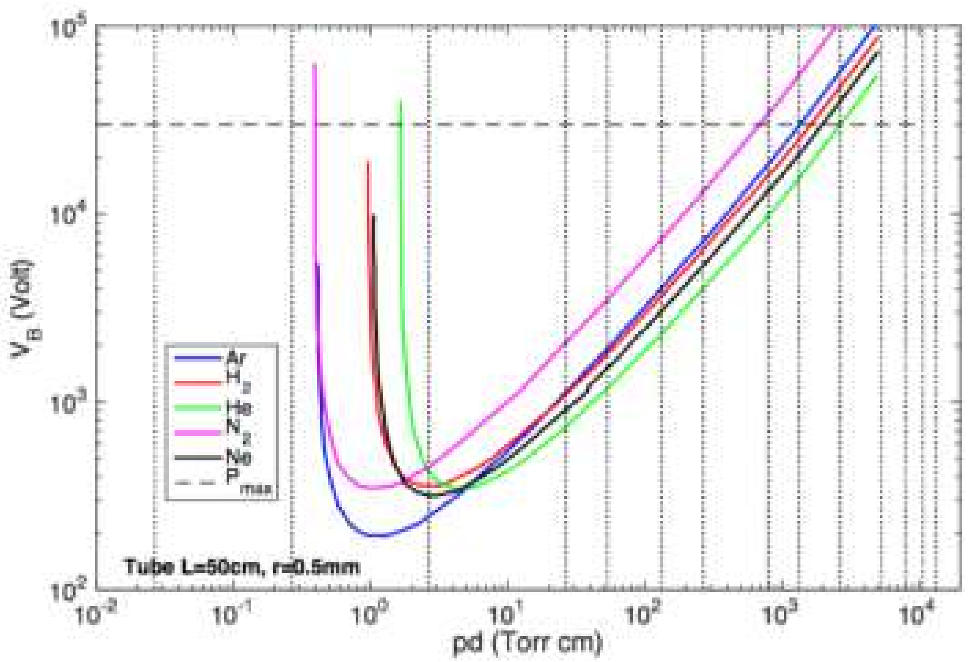
$$\beta_{beam} = \gamma\sigma_r^2/\varepsilon_N \approx \beta_{plasma} = 1/K$$ matching condition

$$\omega_p = \sqrt{n_p e^2/\epsilon_0 m_e}$$

Gas filled capillary based discharge

Plasma Source





…in collaboration with Anthony Dyson, Simon Hooker (JAI); Bernhard Hidding (The Univ. of Strathclyde), Ali Alacakir, TAEO.

np (m^-3)	Pressure (mbar)	Pd (5cm) (mbar cm)	Pd (10cm) (mbar cm)	Pd (30cm) (mbar cm)	Pd (50cm) (mbar cm)
1E+17	0.000533	0.002665	0.00533	0.01599	0.02665
1E+18	**0.00533**	0.02665	0.0533	0.1599	0.2665
1E+19	0.0533	0.2665	0.533	1.599	2.665
1E+20	0.533	2.665	5.33	15.99	26.65
2E+20	1.067	5.335	10.67	32.01	53.35
5E+20	2.7	13.5	27	81	135
1E+21	5.33	26.65	53.3	159.9	266.5
3E+21	**16**	80	160	480	800
5E+21	26.7	133.5	267	801	1335
1E+22	53.33	266.65	533.3	1599.9	2666.5
2E+22	106.67	533.35	1066.7	3200.1	5333.5
3E+22	160	800	1600	4800	8000
4E+22	213	1065	2130	6390	10650
5E+22	266.7	1333.5	2667	8001	13335

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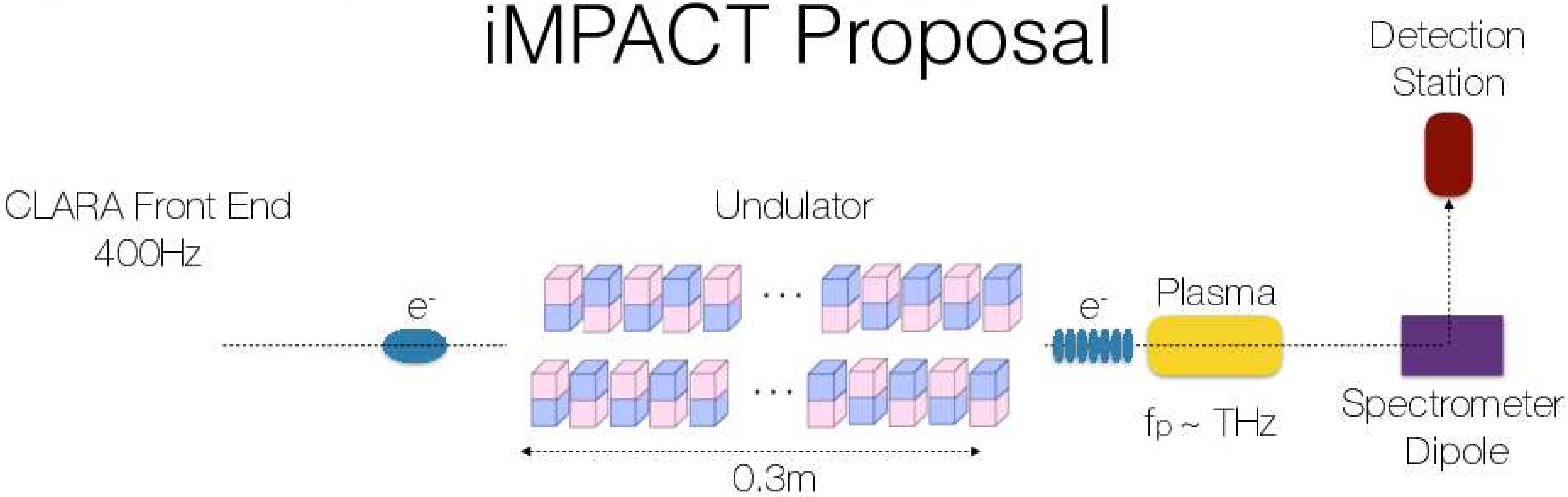
Multi-Bunch Plasma Acceleration

iMPACT Proposal



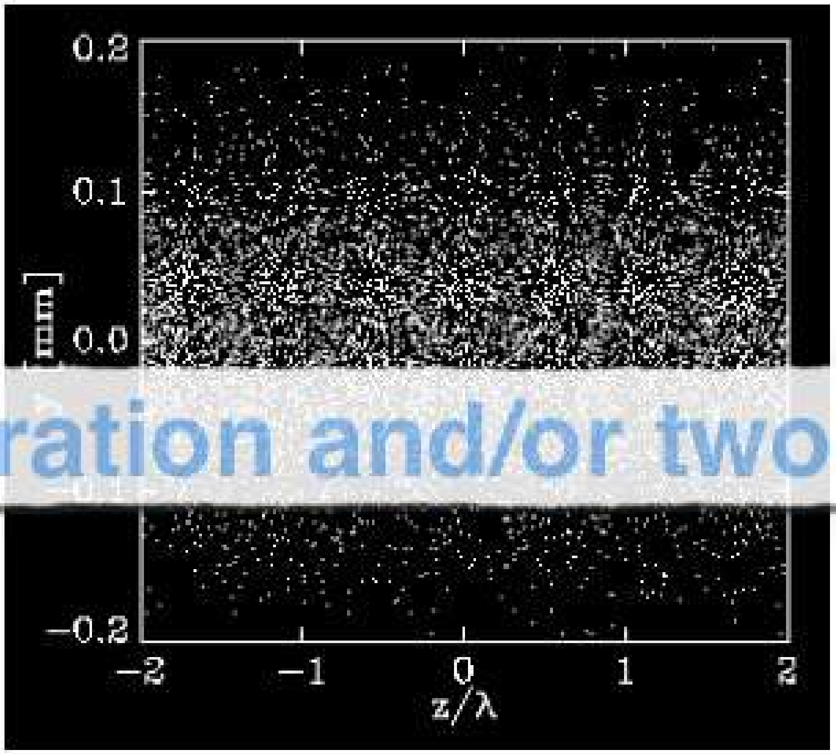
Gain length, where radiation energy saturates:
Total microbunching occurs.

$$L_g = (1+\eta)L_{g0}$$

$$L_{g0} = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$ ← Pierce parameter

$$\rho = \left(\frac{1}{16}\frac{I_{pk}}{I_A}\frac{K^2[JJ]^2\lambda_u^2}{4\pi^2\gamma^3\sigma_x^2}\right)^{1/3}$$

$$L_{sat} = 10L_g$$



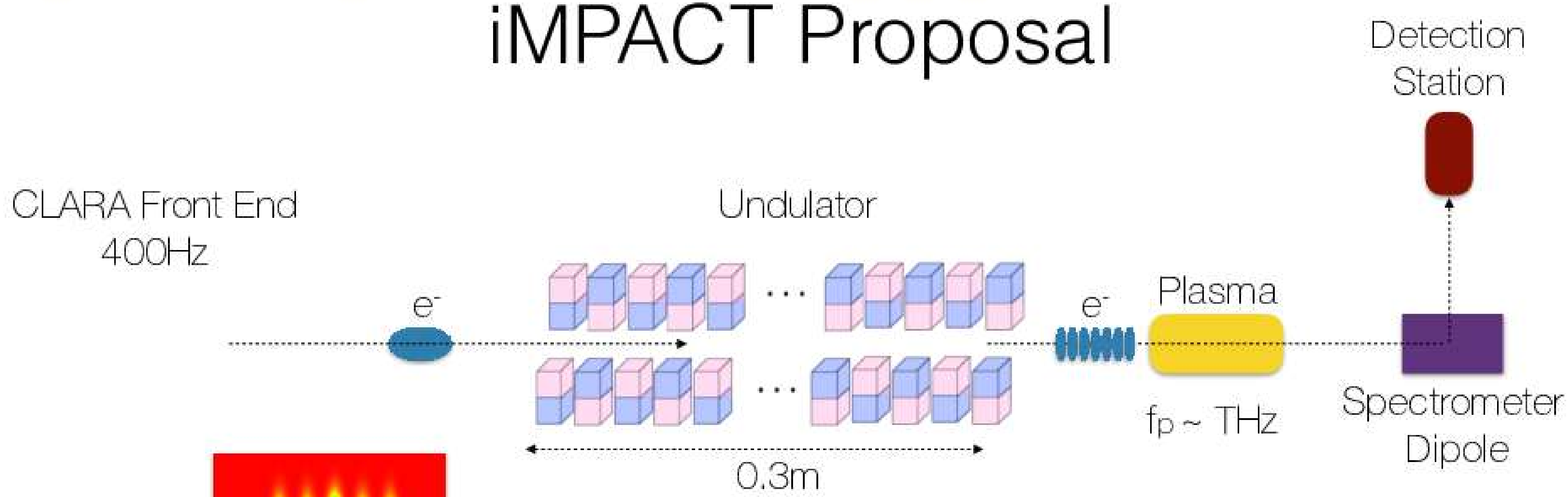
http://genesis.web.psi.ch/gallery.html

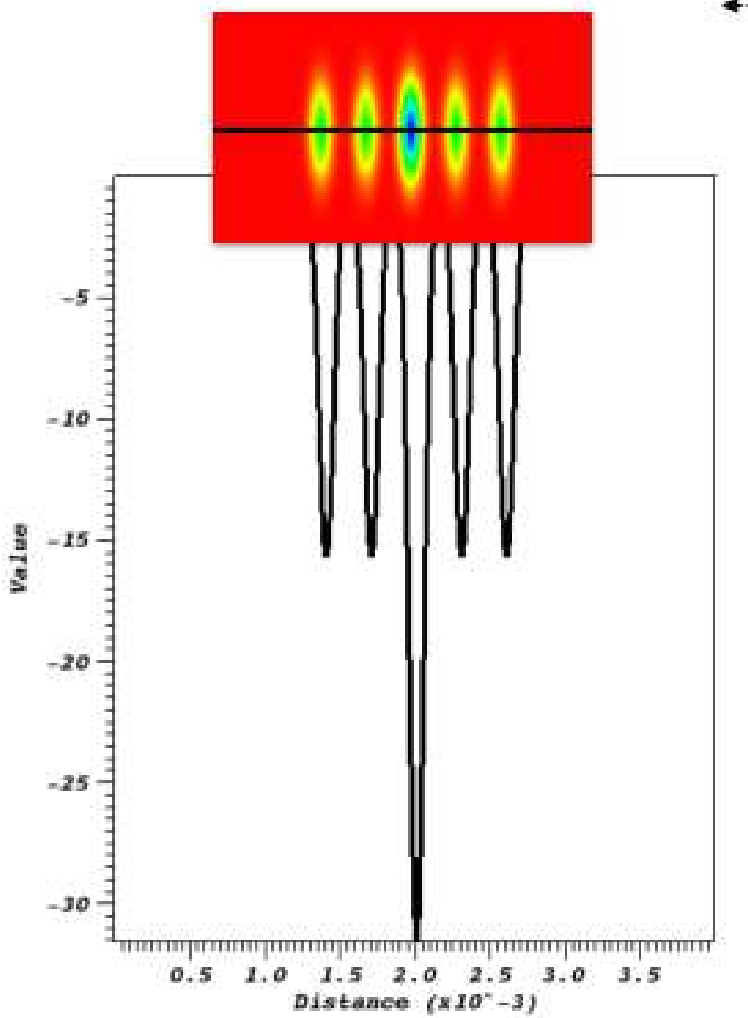
$$Q = 250\,pC$$
$$\sigma_x = 100\,\mu m$$
$$\sigma_z = 75\,\mu m$$
$$E = 50\,MeV$$
$\lambda_u =$ [illegible]
$$B = 1\,T$$
$$L_{sat} \approx 0.3\,m$$
$$f_m = 1\,THz$$

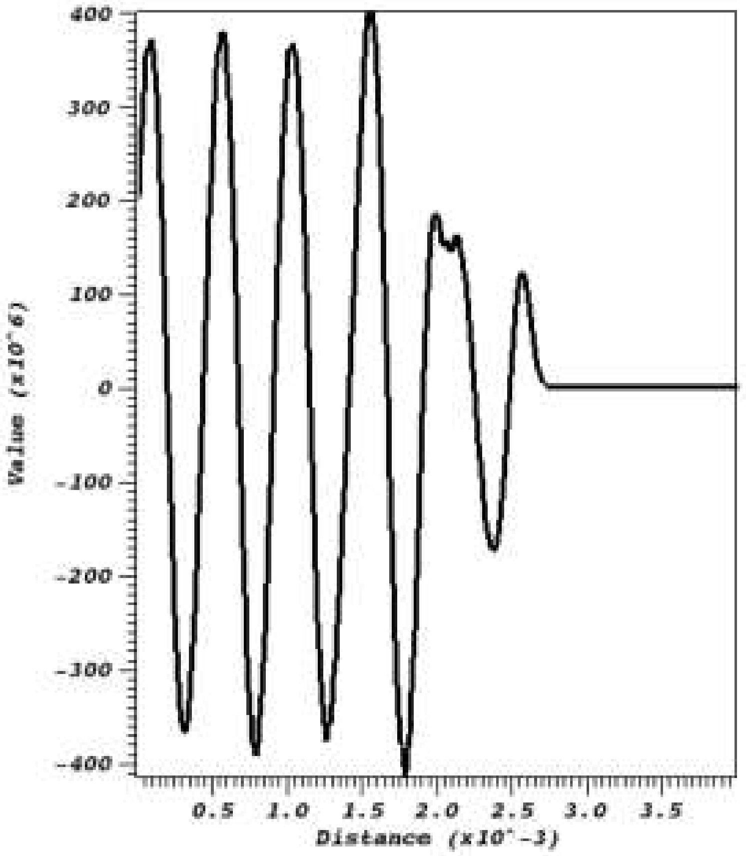
Multi-bunch operation and/or two beam scheme…

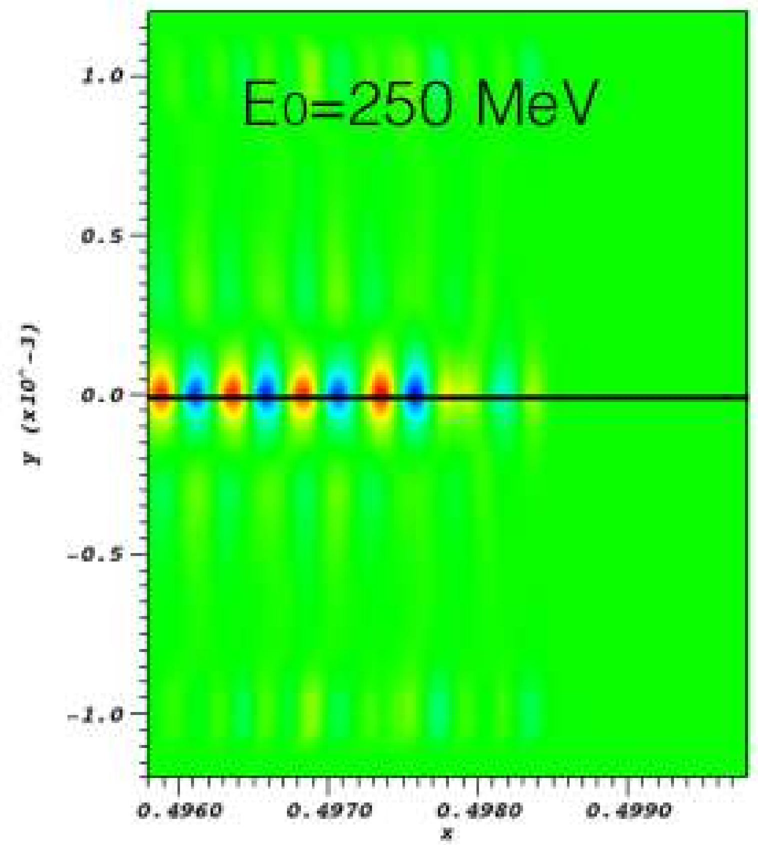
Multi-Bunch Plasma Acceleration

iMPACT Proposal



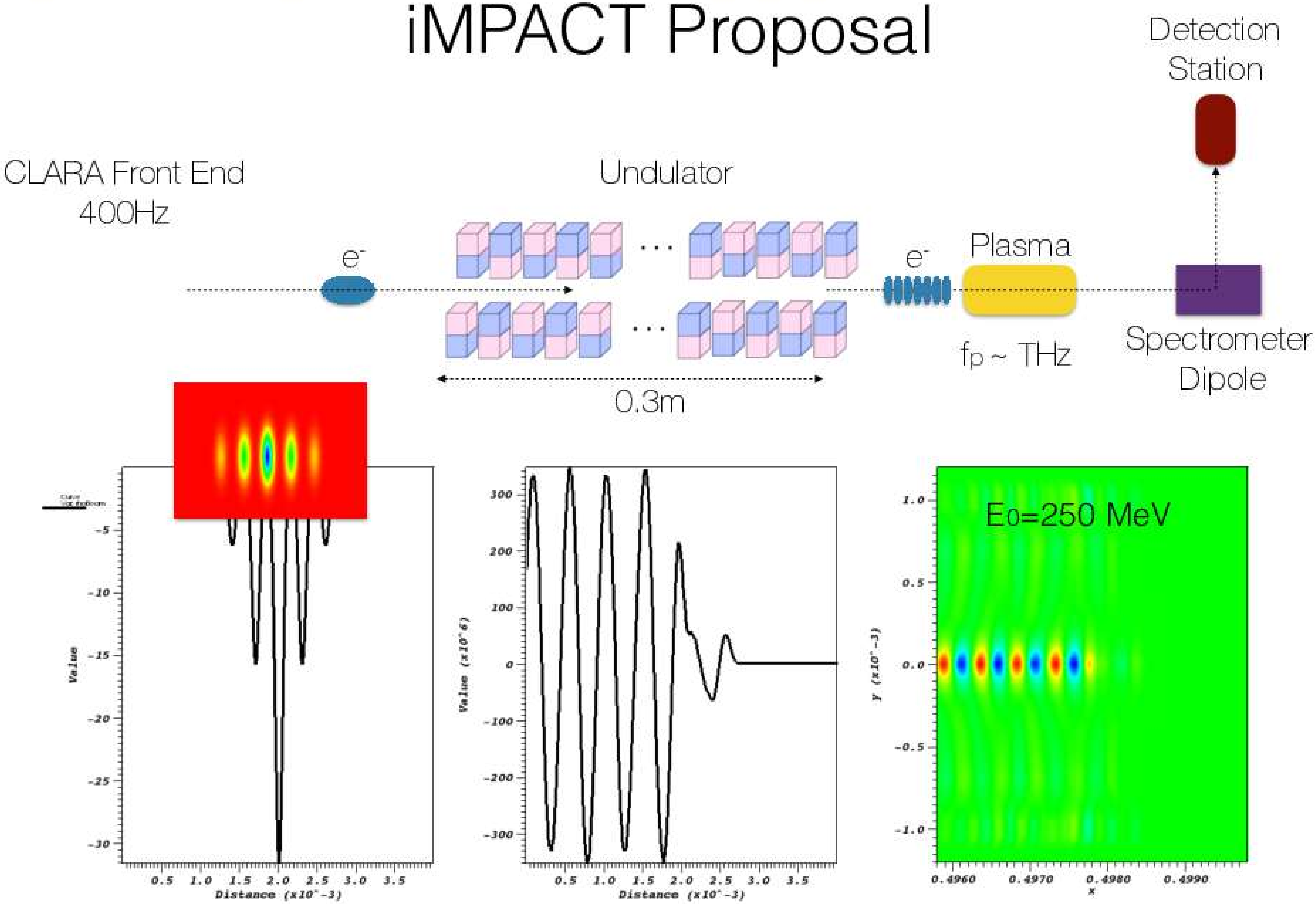






Multi-Bunch Plasma Acceleration

iMPACT Proposal



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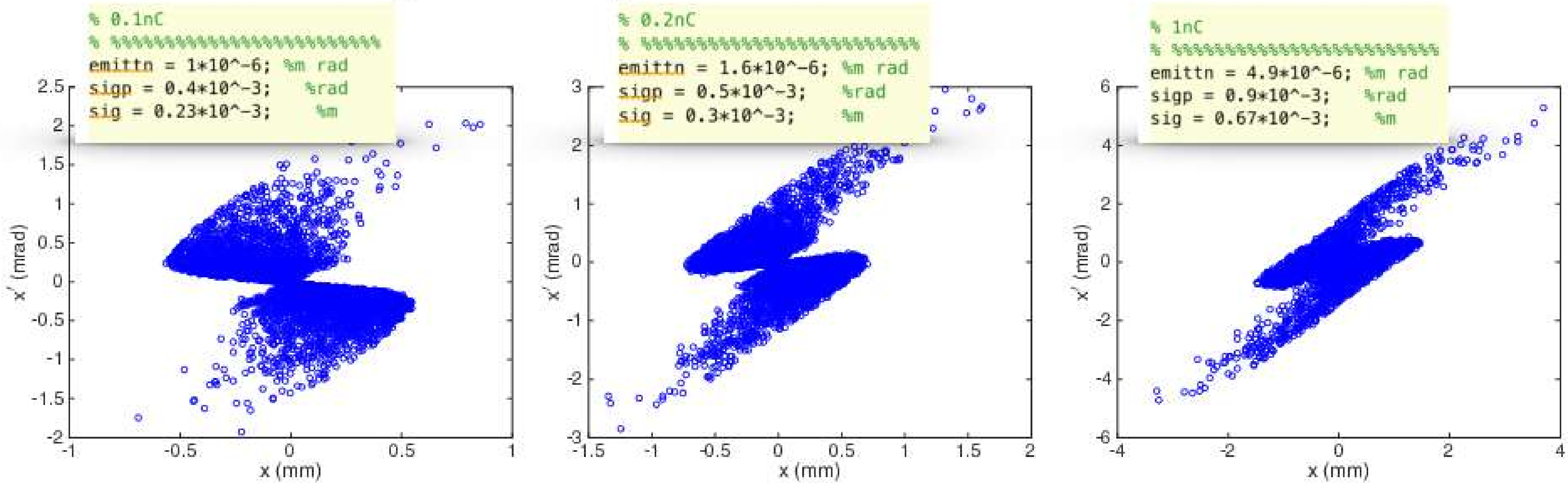
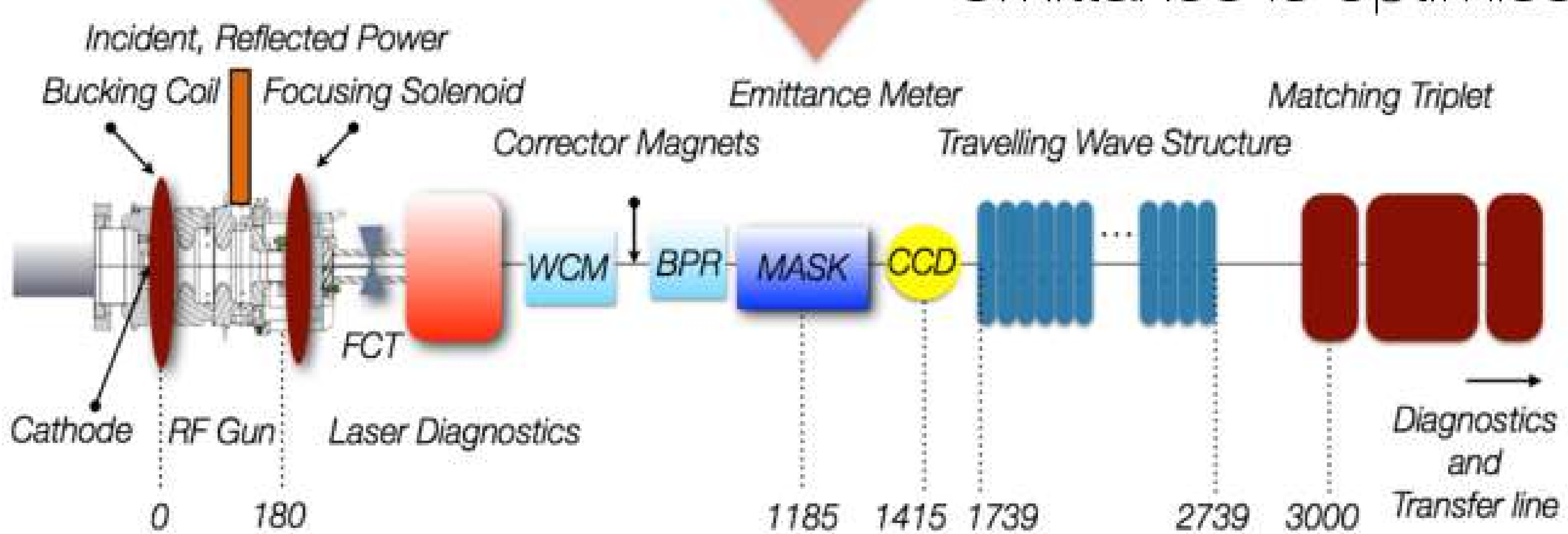
What is the range to be measured?

Range of divergence to measure at the mask.



Phase spaces at the mask when emittance is optimised at ATS exit.

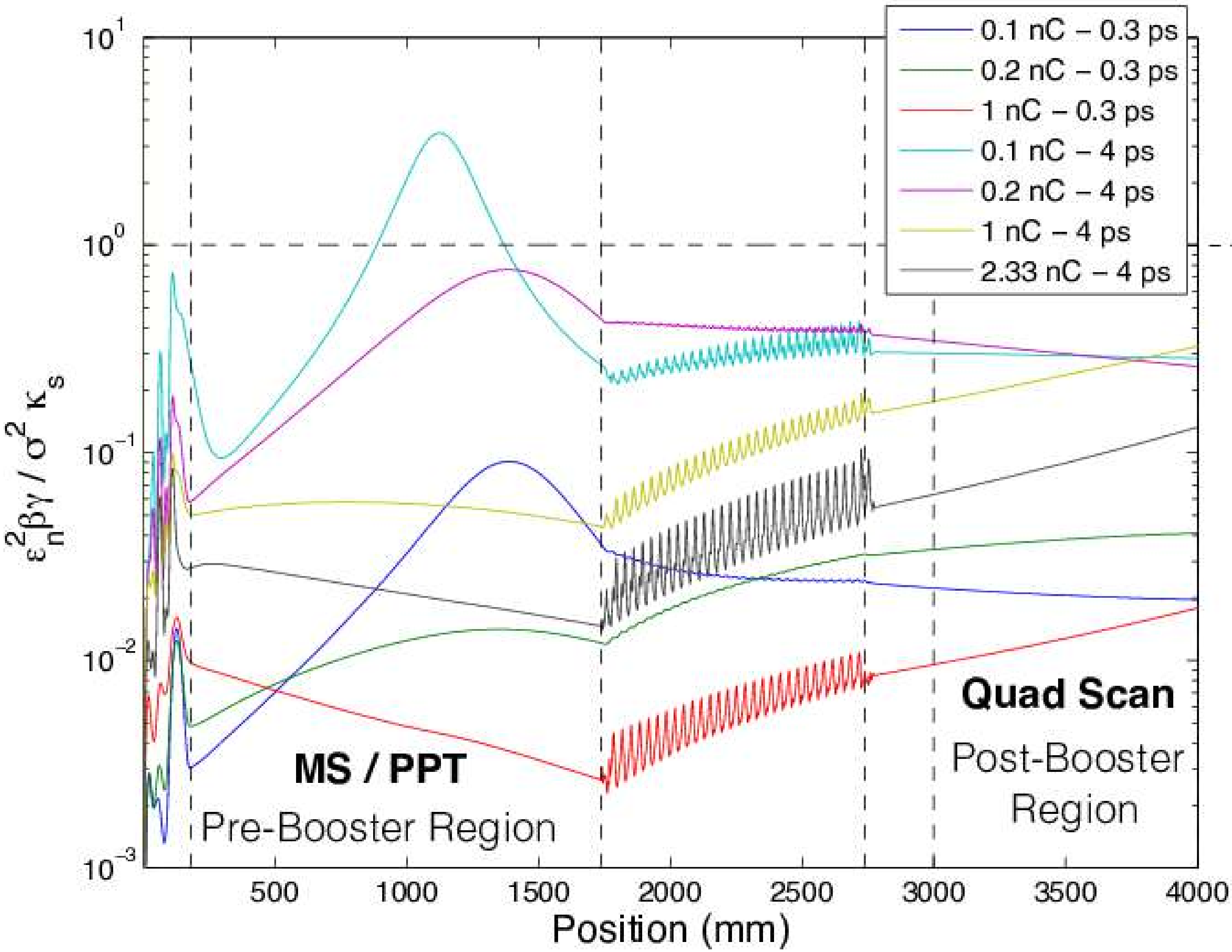


Emittance Diagnostics and Space Charge Limits

Defocusing space charge term

Outward pressure due to rms emittance.

$$\sigma'' + \sigma' \frac{\gamma'}{\beta^2\gamma} + K_r\sigma - \frac{\kappa_s}{\sigma\beta^3\gamma^3} - \frac{\epsilon_n^2}{\sigma^3\beta^2\gamma^2} = 0$$



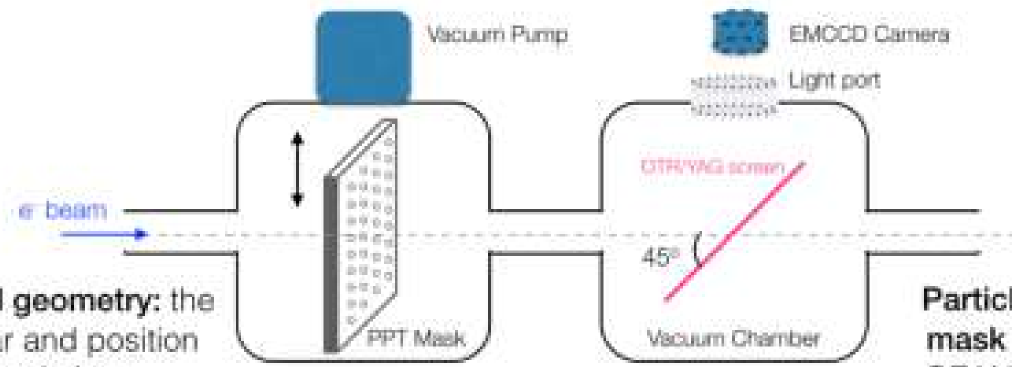
Emittance Dominated

$$\epsilon_n^2\beta\gamma >> \sigma^2\kappa_s$$

Space Charge Dominated

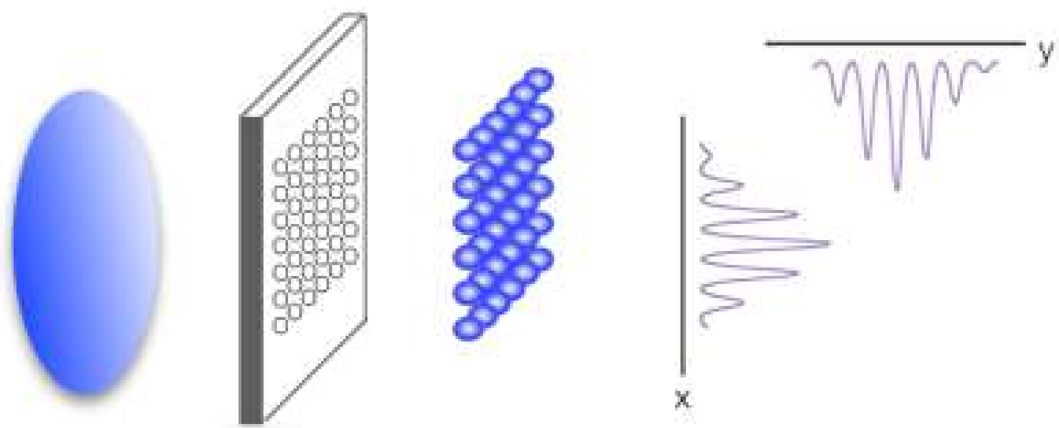
$$\epsilon_n^2\beta\gamma << \sigma^2\kappa_s$$

2D Emittance Measurement System



General geometry: the angular and position resolution.

Particles through the mask on the screen: GEANT4 simulations.



$$R' = \frac{2I}{\gamma^2 I_0} \frac{\omega L}{d\epsilon_n}$$

Beam-lets should be emittance dominated after the mask (ratio of emittance to space charge term should be smaller than unity.)

$$L_s = \frac{E}{dE/dx} \approx \frac{E(MeV)}{1.5(MeV\ cm^2\ g^{-1})\rho(g\ cm^{-3})}$$

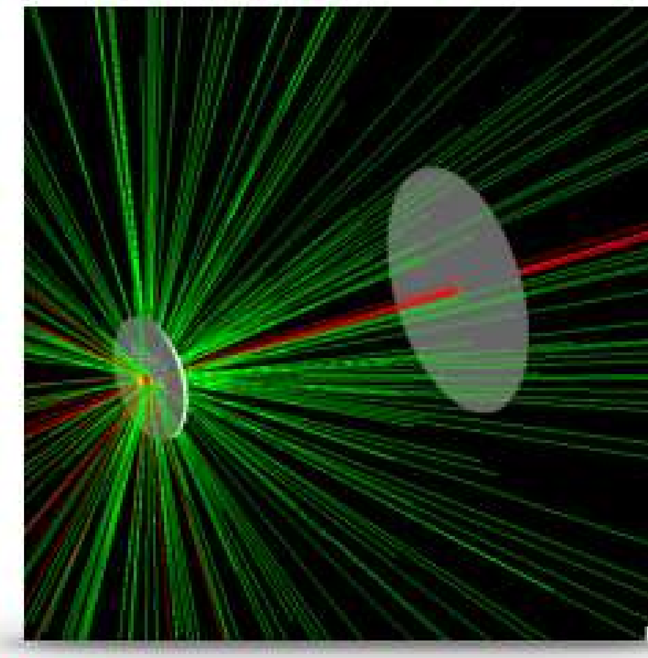
Stopping distance of mask, "Bethe-Bloch" formula.

$$4\sigma' L < d$$

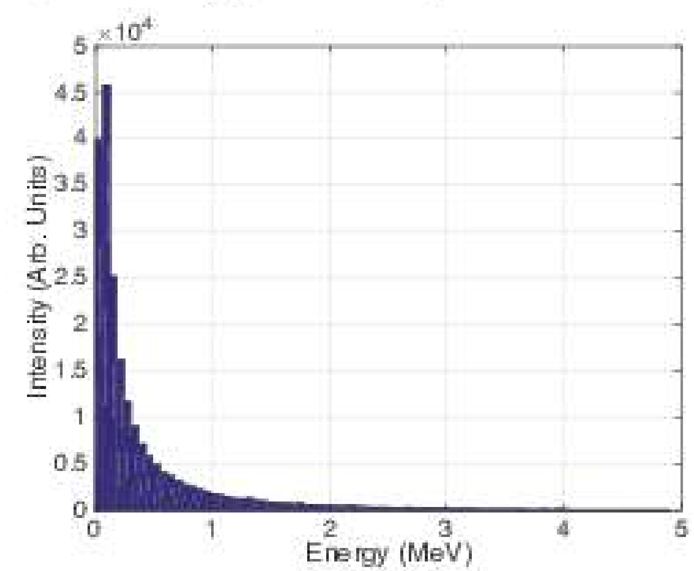
Prevent beam-let profiles from overlapping on the screen.

$$\frac{\sigma}{d} = \frac{L\sigma'}{r_d}$$

Position and divergence resolutions should be comparable.



Red: 5 MeV, 100 electrons (for visibility).
Green: γ particles,



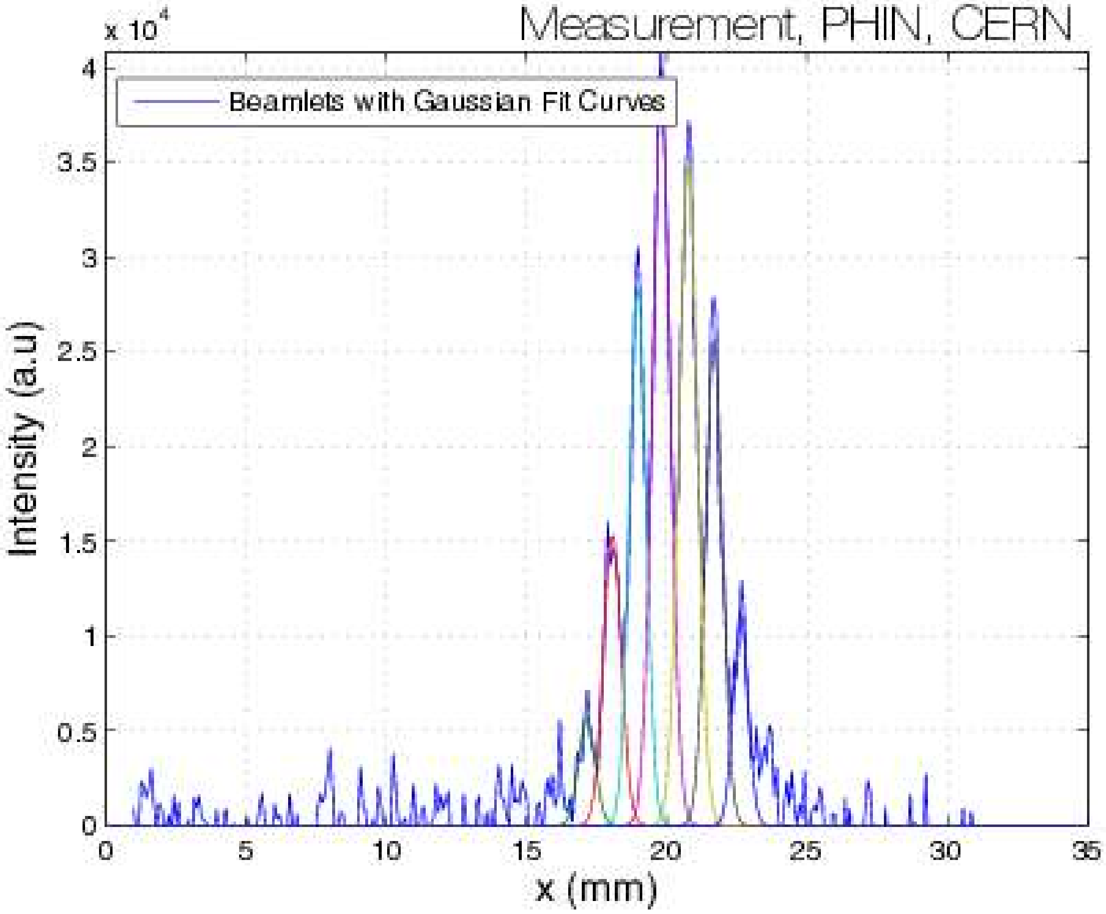
Gamma particles' energy spectrum for 5MeV 100k electrons.

...in collaboration with Carsten Welsch, Ralph Fiorito (Liverpool University)

2D Emittance Measurement System

Intensity of individual beamlets: ρ_i

Mean positions of the beamlets: $x_{i,c}$



Divergences of the beamlets:

$$x'_{i,c} = < x_i - iw > /L$$

Spread on the divergences: σ'_i

The definition of the transverse rms emittance:

$$\epsilon_x \equiv \sqrt{< x^2 >< x'^2 > - < xx' >^2}$$

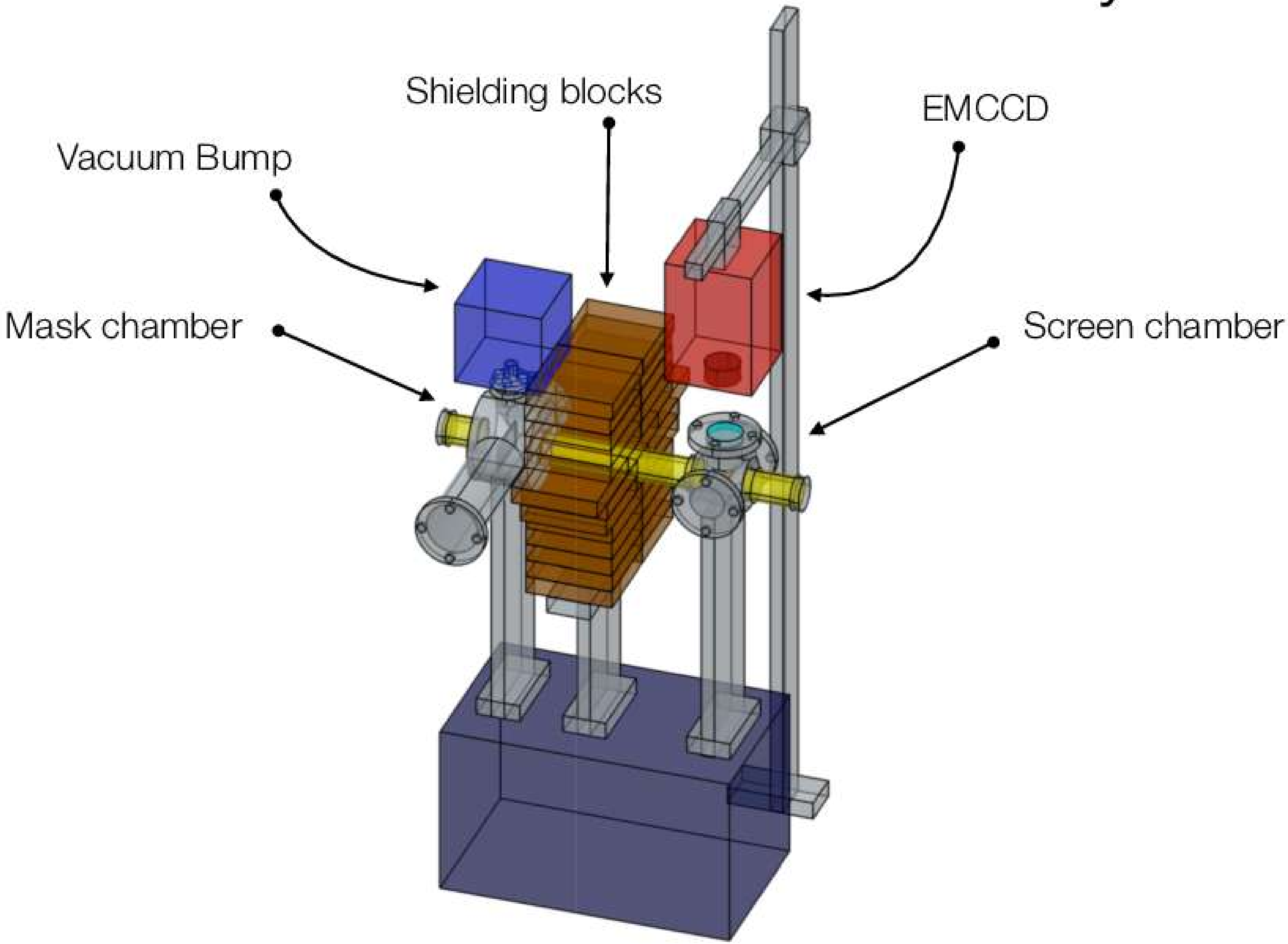
$$< x^2 > = \frac{\sum_{i=1}^{N} \rho_i x_{i,c}^2}{\sum_{i=1}^{N} \rho_i}$$

$$< x'^2 > = \frac{\sum_{i=1}^{N} \rho_i (x'^2_{i,c} - \sigma'^2_i)}{\sum_{i=1}^{N} \rho_i}$$

$$< xx' > = \frac{\sum_{i=1}^{N} \rho_i x_{i,c} x'_{i,c}}{\sum_{i=1}^{N} \rho_i}$$

Analysis is repeated in both axes.

2D Emittance Measurement System

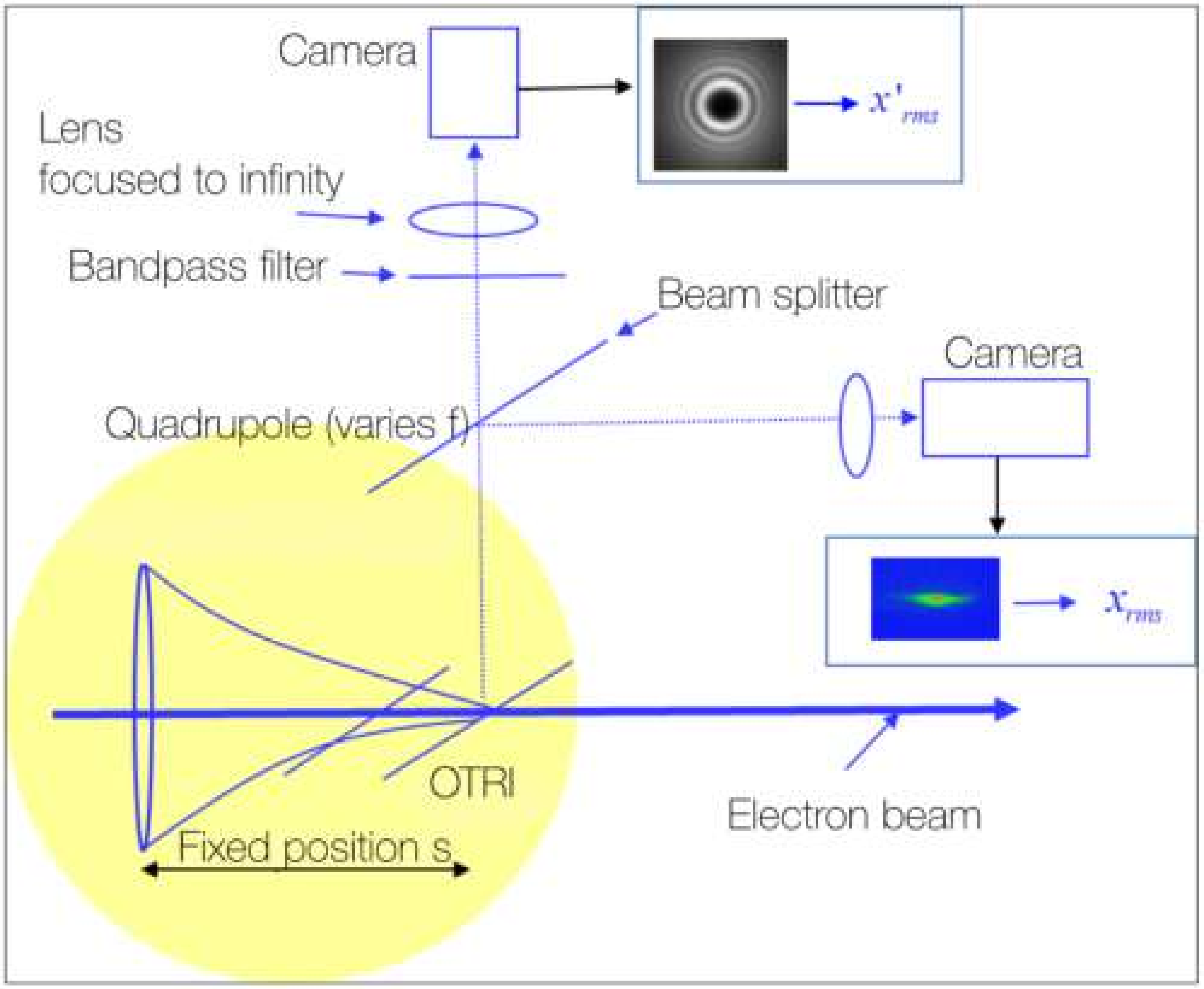


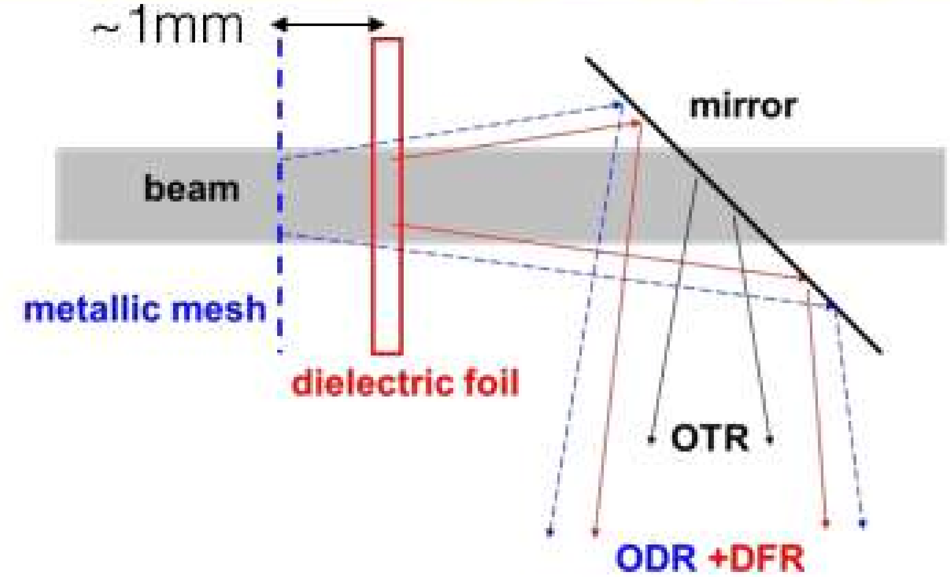
... numerical characterisation completed, tests in Argonne (AWA) 2016/Q1.

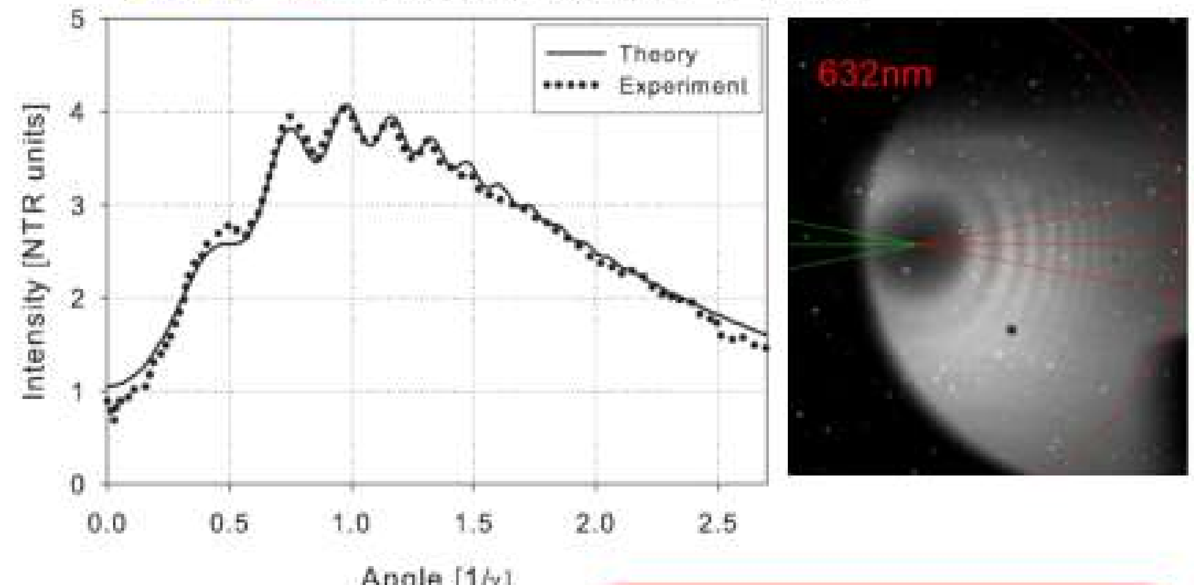
Optical Transition Radiation Interferometry (OTRI)

Beam Size and Divergence Measurements **using OTRI**

Modified technique for beams with low energy using **ODR-DFRI**







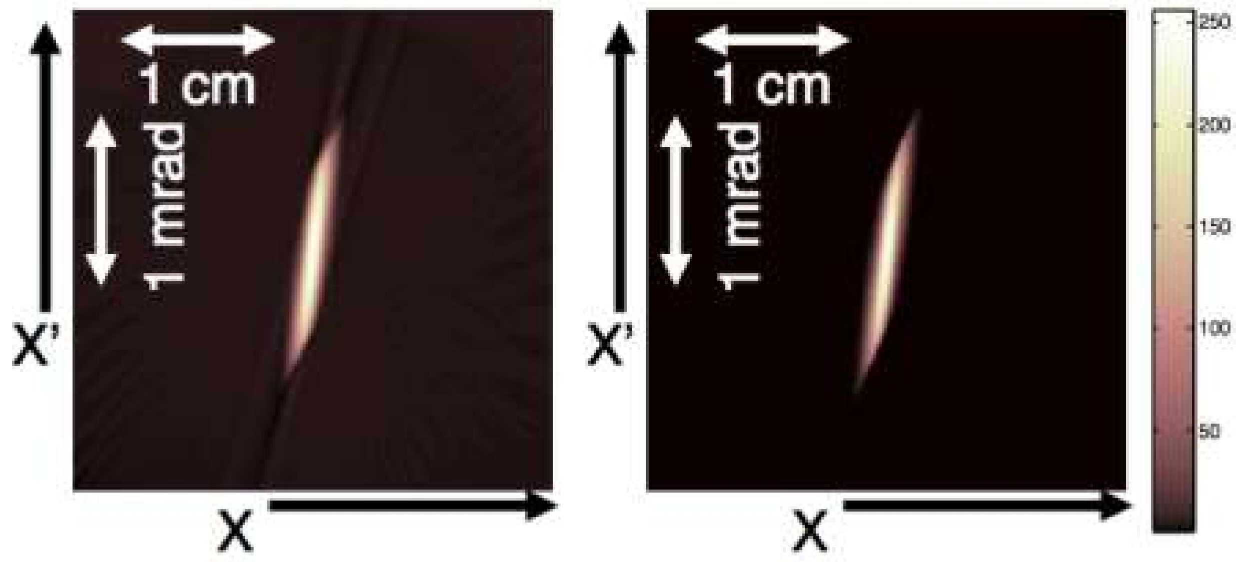
- **Both techniques:** Fringe visibility provides divergence,
- **OTRI:** foils well separated for high E,
- **ODR-DFRI:** foils close together - low E.

from Ralph Fiorito

Phase Space Tomography

Phase Space Tomography with existing Quad Scan Setup

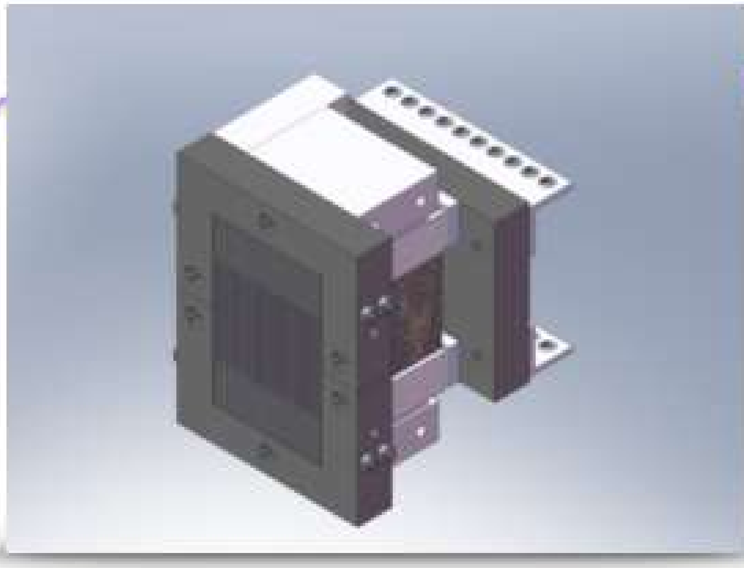
- **Phase space tomography:** reconstruction of the phase space distribution by using one dimensional measured projections as a function of focusing.
- **Experimentally:** Beam size measurements from the "existing" quad scan setup can be analysed with tomographic algorithms to reveal more detailed information.
- **Analysis:** Preparation of an analysis code using "Filtered-Backprojection Algorithm (FBA)" is **in progress**. *D. Stratakis et al., PRSTAB 9, 112801 (2006) (Maryland)*
- **Compared to quad scan:** a larger angular scan (more projections) required to cover the entire phase space. This can be achieved either one or two quads - simulations **in progress**.



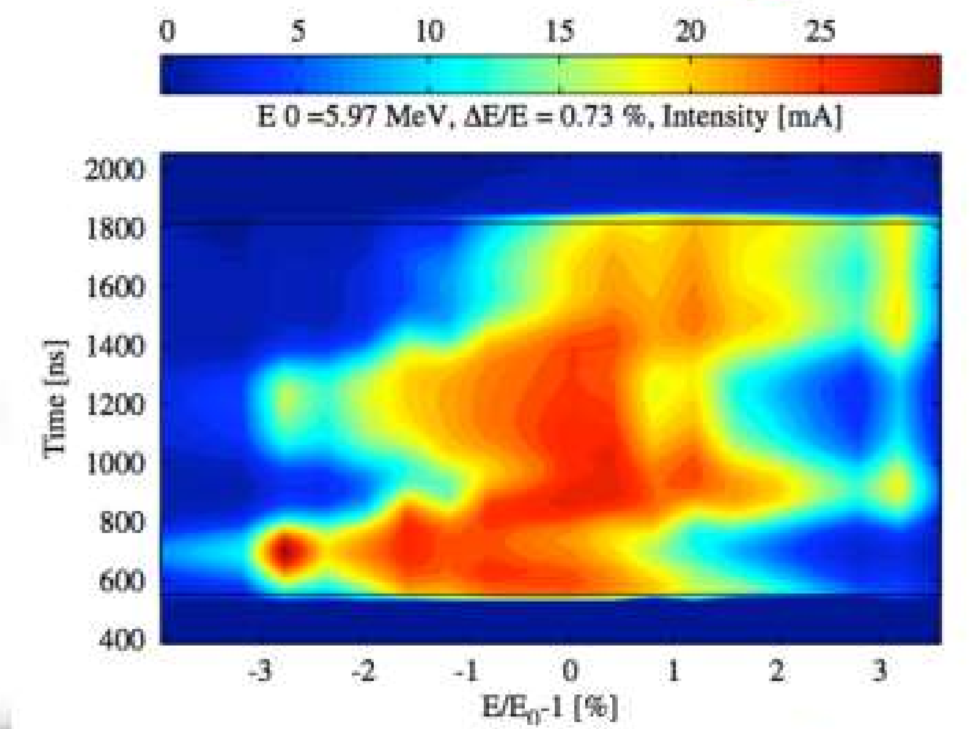
(a) *PRSTAB 9, 112801* (b)

FIG. 3. (Color) $X'X$ phase space for the 0.6 mA electron beam: (a) using tomography; (b) direct WARP.

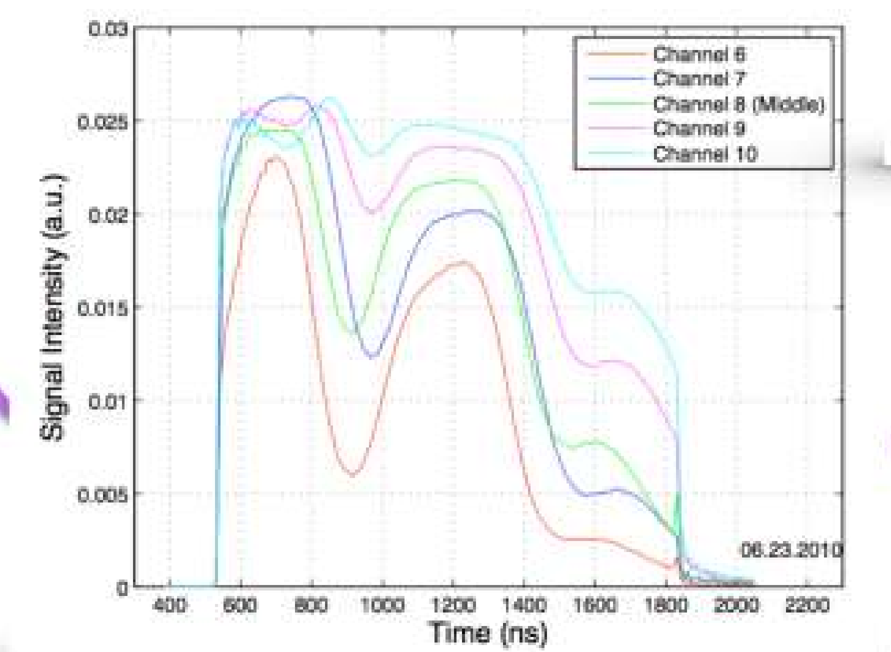
Energy Spectrometer for PWA Experiments



D. Egger, et al., CTF-NOTE-099

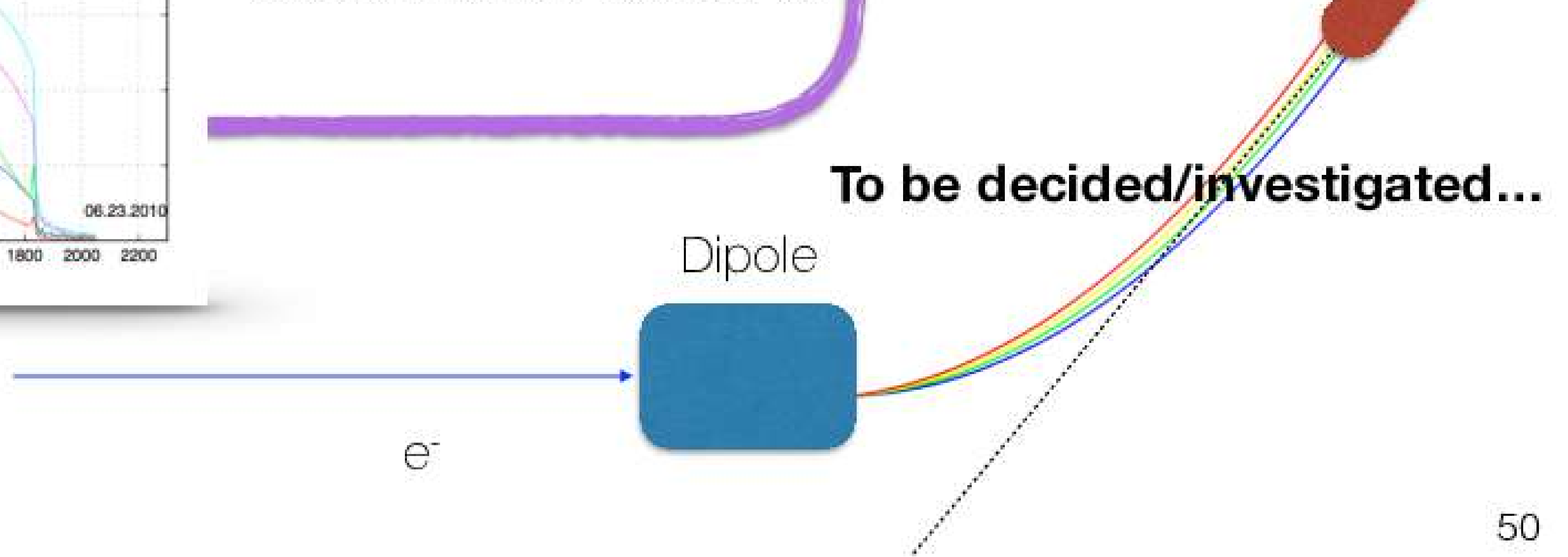


Measurements, PHIN, CERN



Challenge: Measure from MeVs to GeVs

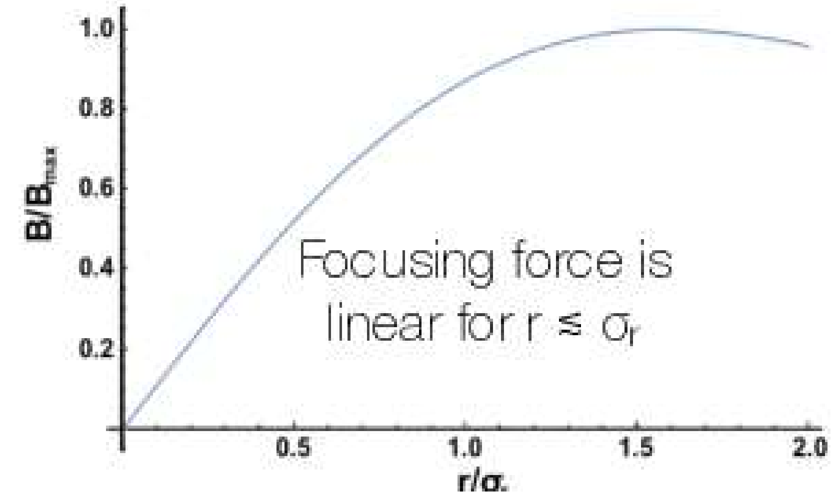
Possible solutions: Large aperture magnet, double magnet…

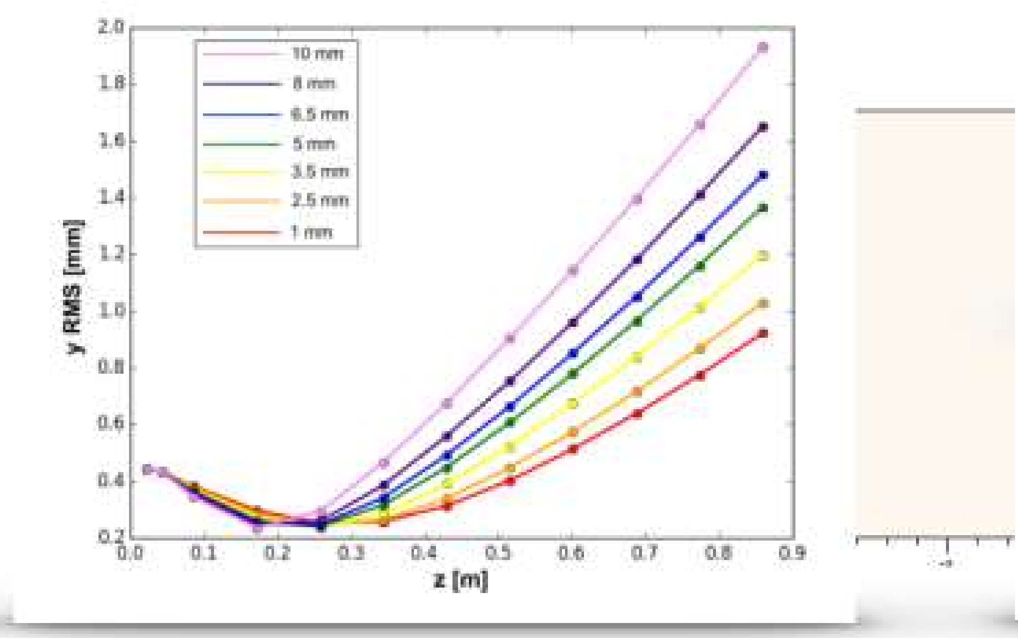


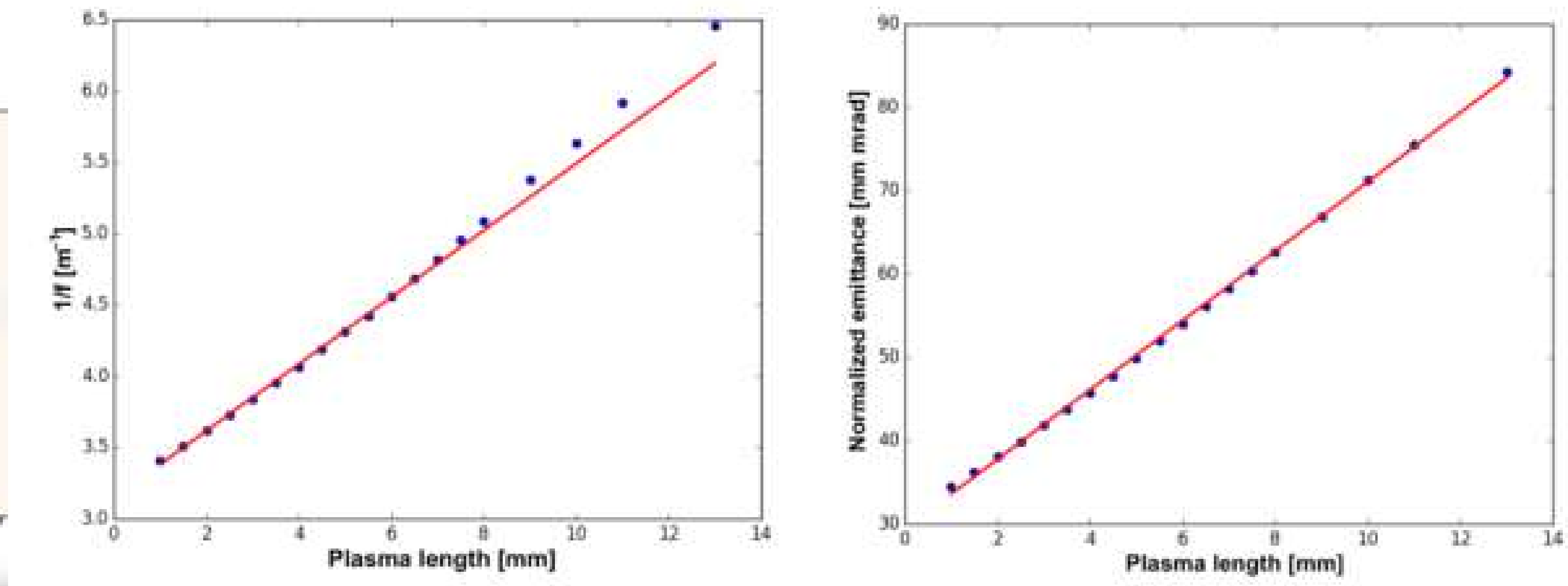
To be decided/investigated…

Plasma Lens

- Plasma responds to cancel the space charge of a relativistic bunch.
- Plasma ions cancel the electric field of the bunch.
- Magnetic field of the bunch focuses the beam.







Focusing force differs from that of an ideal lens, leading to emittance growth.

- **Spherical aberration,** Focusing force not linear with radius.
- **Longitudinal aberration,** Focusing force varies with longitudinal position in bunch.

K. Hanahoe, et al., Simulation Studies of Plasma Lens Experiments at Daresbury Laboratory, under review by PPCF.

Conclusions

- We contribute to the search for advanced accelerating techniques through following activities:
    - designing and characterising of electron sources and injectors with flexible-wide range specifications,
    - numerical and analytical plasma-beam interaction; wakefield generation, high quality beam production,
    - future uses of the technology; e^-p, e^-e^+ colliders,
    - implementation in the local facilities; PARS at CLARA, iMPACT at CLARA Front End,
    - low energy high brightness beam diagnostics with large dynamic range.


ZZZzzzzzzzz...
Thank you for your attention...