Radiation production from the LWFA and its relevance to high field physics

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Laser-plasma accelerators

Parameters

Undulator radiation

Betatron radiation

Radiation reaction

SCAPA

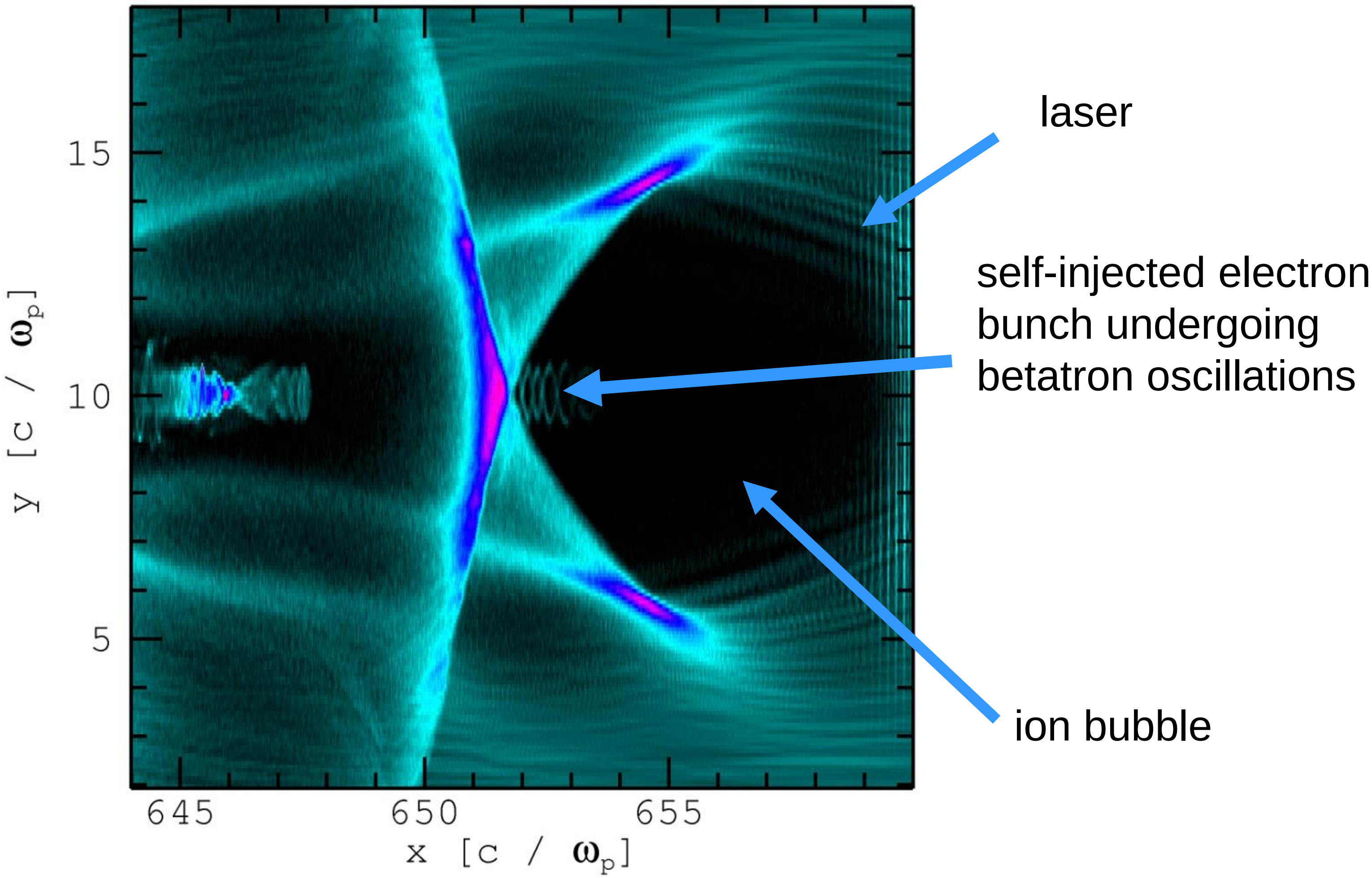
Bubble structure – relativistic regime

ion bubble radius $R \approx \dfrac{\sqrt{a_0}\lambda_p}{2}$

University of Strathclyde Science

First experiments on controlled acceleration:
2004

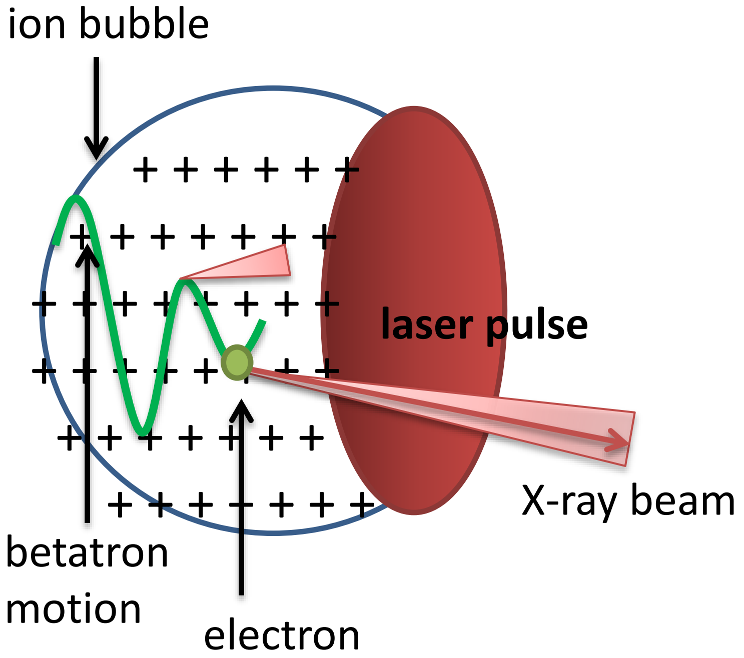
- ALPHA-X (UK: IC, Strathclyde, RAL)
- LBNL (US)
- LOA (France)

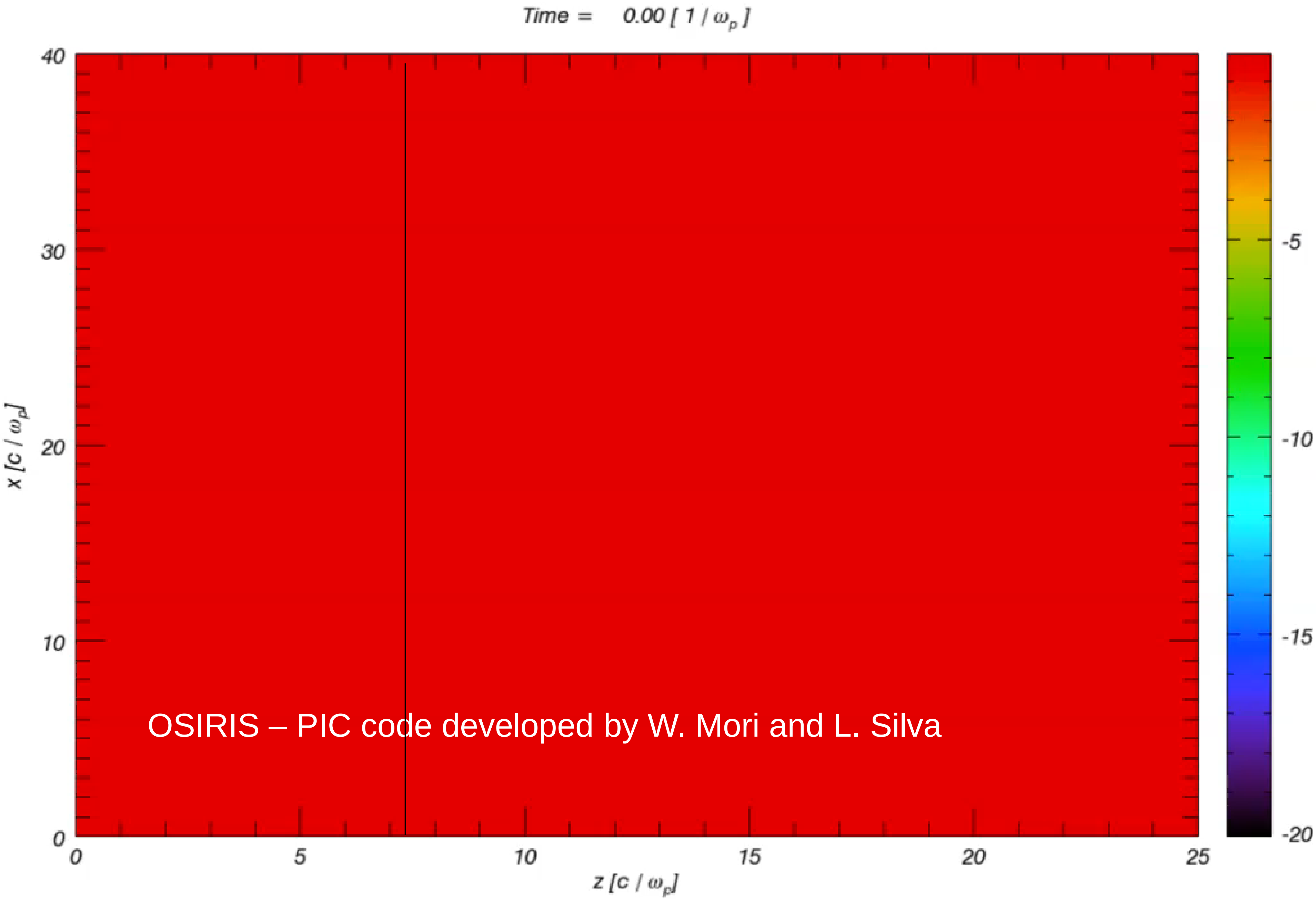


LWFA

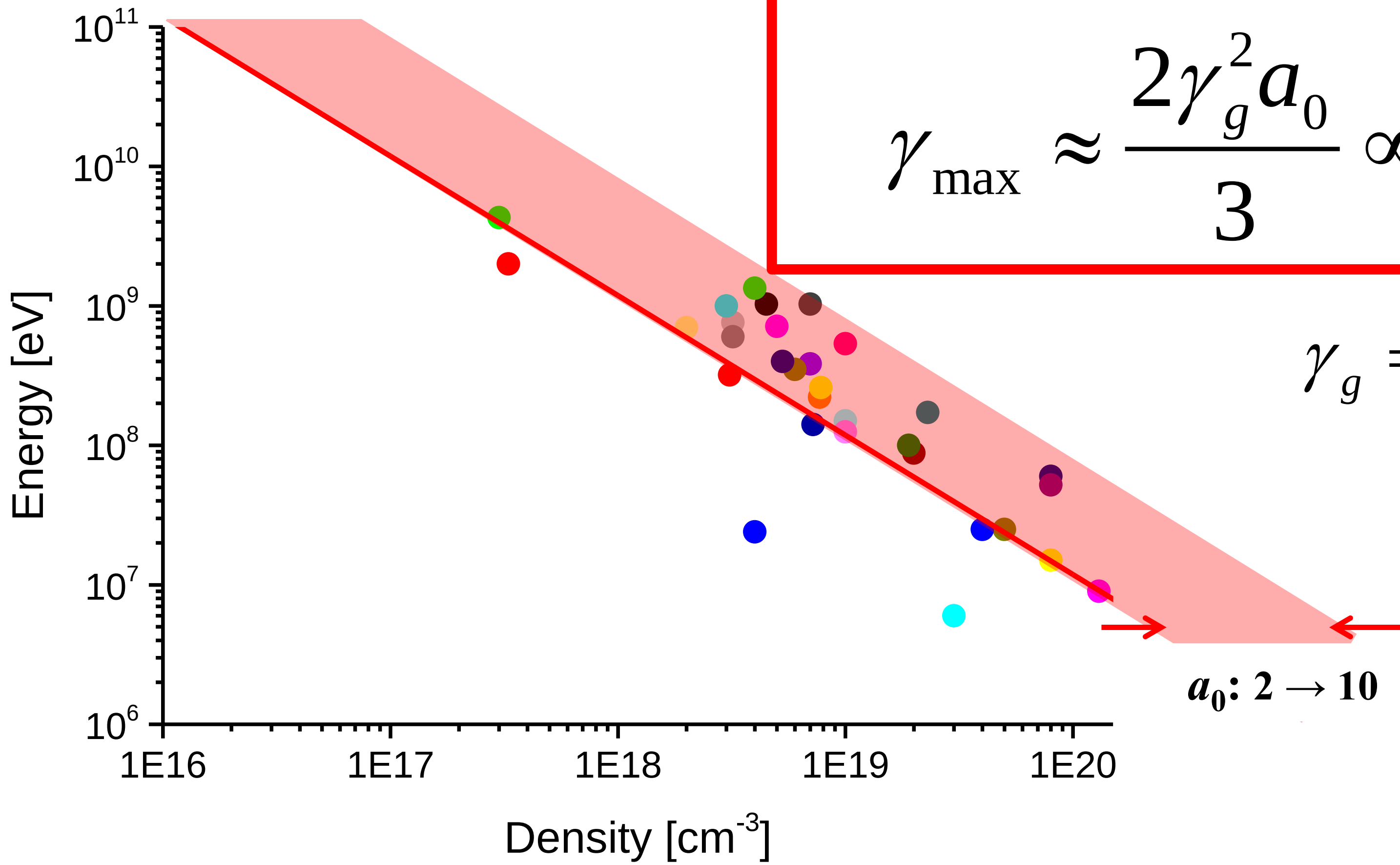
BUBBLE REGIME

- Laser ponderomotive force creates stable evacuated spherical structures trailing the laser pulse
- Trapped electrons undergo transverse oscillations while accelerating
- Synchrotron like radiation is emitted in a narrow cone




Time = 0.00 [1 / ω_p]
40
30
20
10
0
x [c / ω_p]
0
5
10
15
20
25
z [c / ω_p]
-5
-10
-15
-20
OSIRIS – PIC code developed by W. Mori and L. Silva

Energy Scaling



$$\gamma_{\max} \approx \frac{2\gamma_g^2 a_0}{3} \propto \frac{1}{n}$$

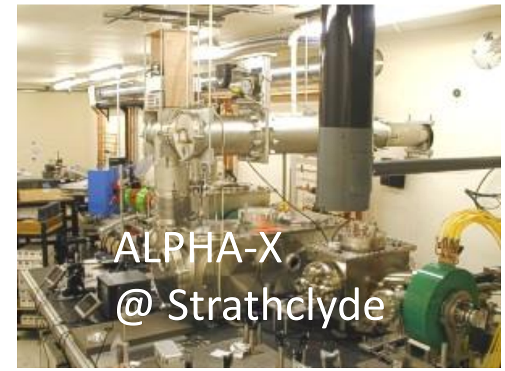
$$\gamma_g = \frac{\omega_0}{\omega_p}$$

Need a combination of bubble regime (must be above critical power for relativistic self-focussing) and linear regime to get to very high energies

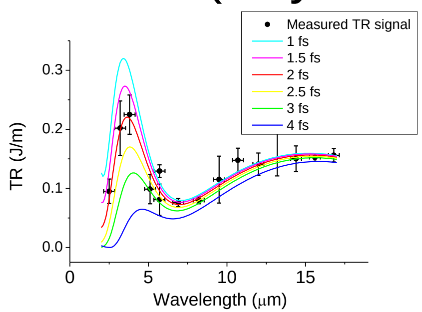
ALPHA-X: Advanced Laser Plasma High-energy Accelerators towards X-rays – Template for SCAPA

Compact R&D facility to develop and apply femtosecond duration particle, synchrotron, free-electron laser and gamma ray sources

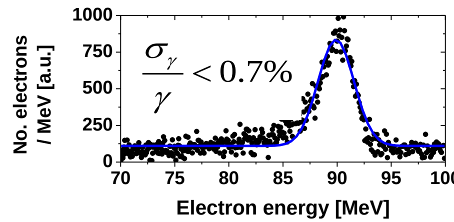
Jaroszynski et al., (Royal Society Transactions, 2006)



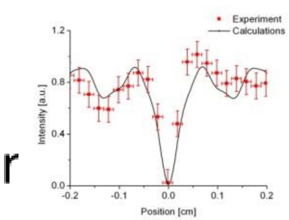
CTR: electron bunch duration: 1-3 fs

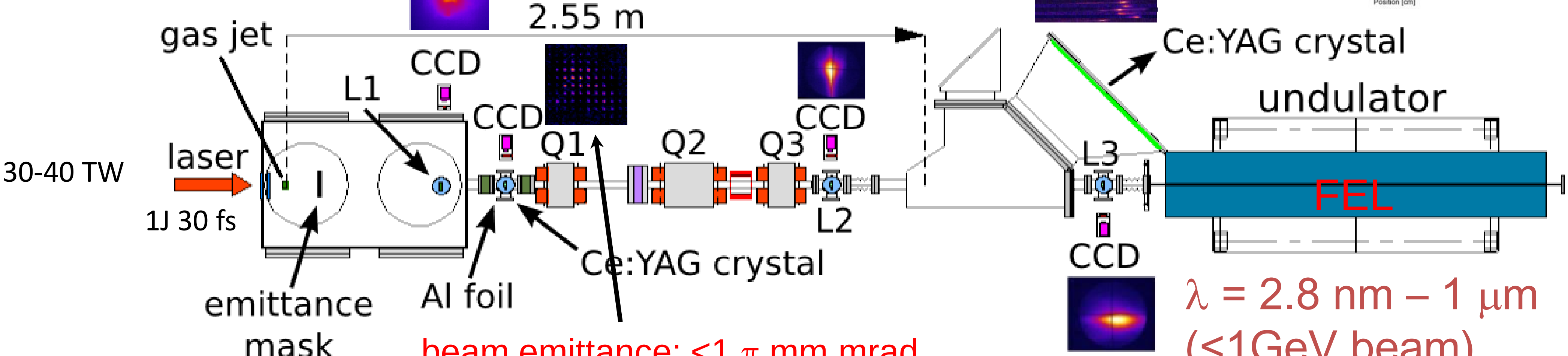


electron beam spectrum



phase contrast imaging with 50 keV photons





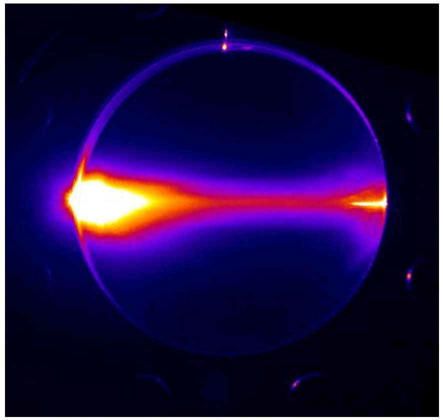
beam emittance: <1 π mm mrad

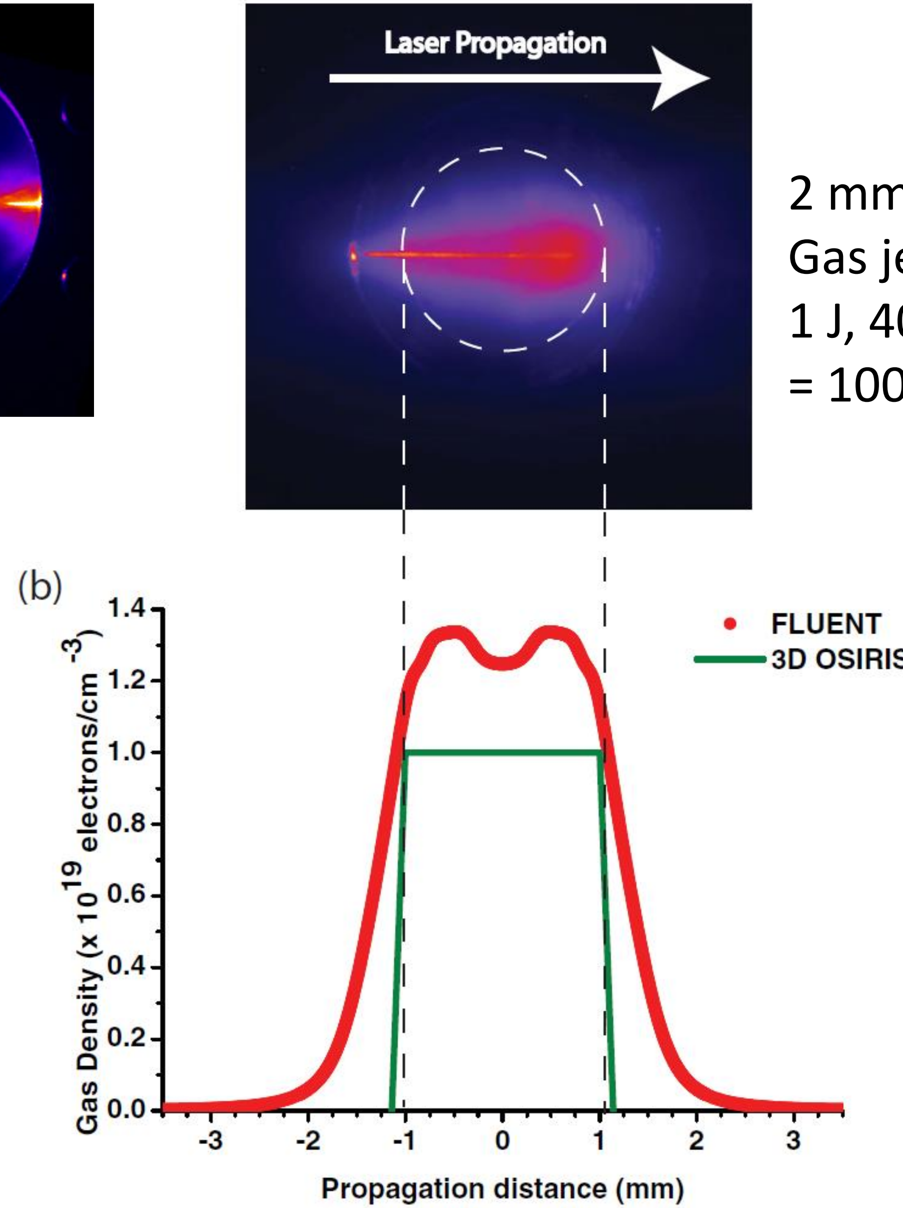
λ = 2.8 nm – 1 μm (<1GeV beam)

Brilliant particle source: 10 MeV → GeV, kA peak current, fs duration

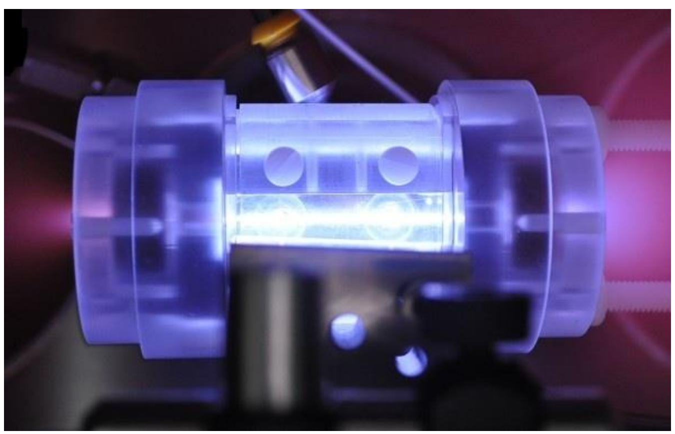
Plasma media: capillary, gas jet and plasma cells

4 cm long gas
Cell
10 J, 50 fs
= 850 MeV
(RAL)



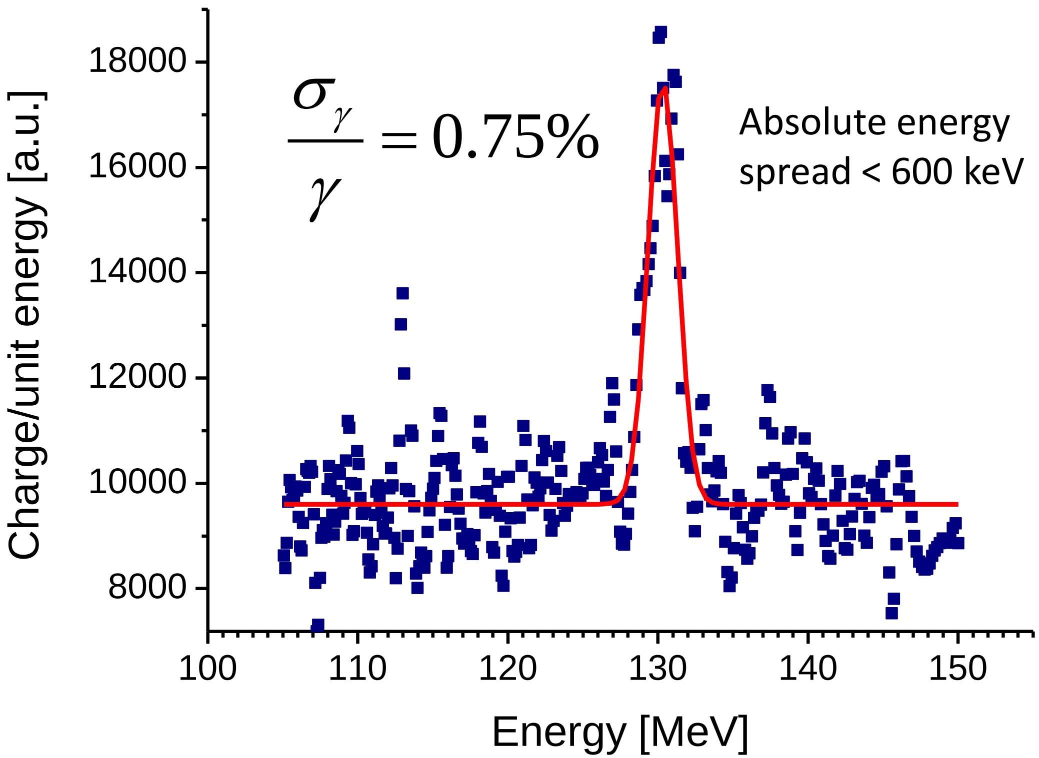


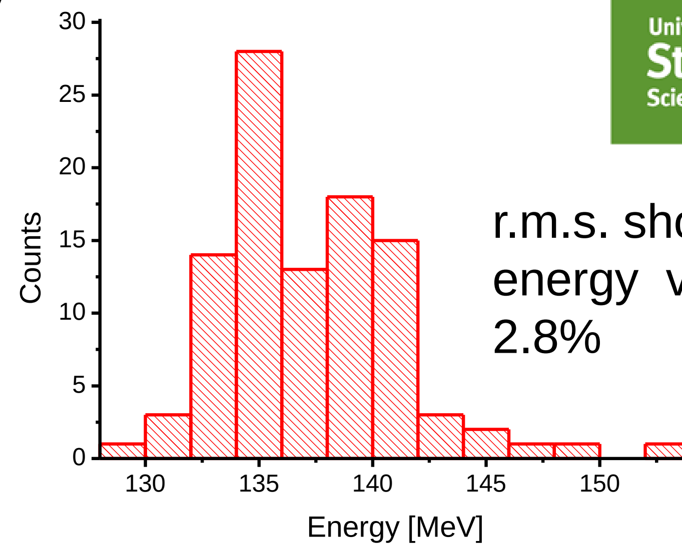
2 mm
Gas jet
1 J, 40 fs
= 100 – 300 MeV



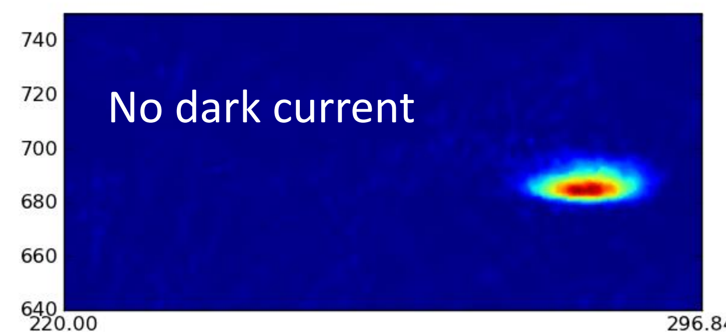
4 cm
Plasma capillary
10 J, 50 fs
~ 1 GeV (RAL)

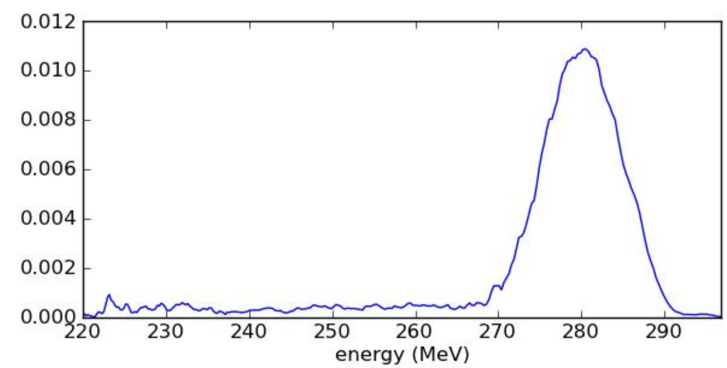
Energy spread, beam loading and stability





r.m.s. shot to shot energy variation 2.8%

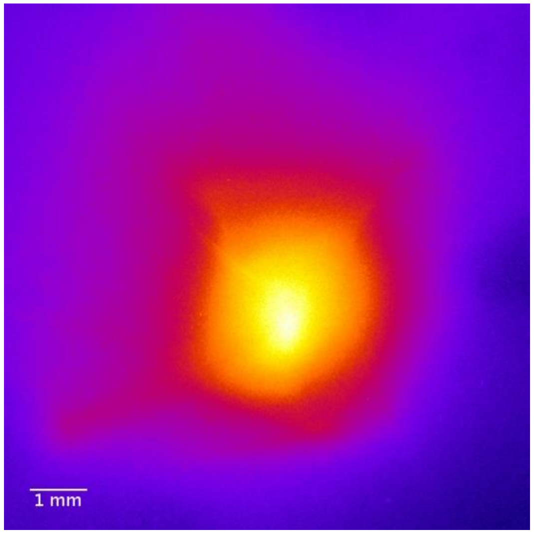




Maximum energy obtained in 2 mm ≈ 300 MeV

With stable laser and gas jet

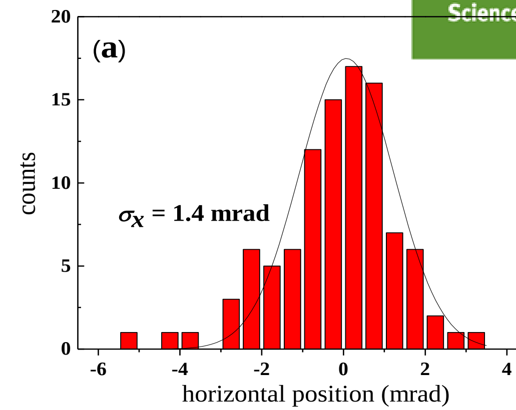
Electron Beam- Pointing Stability

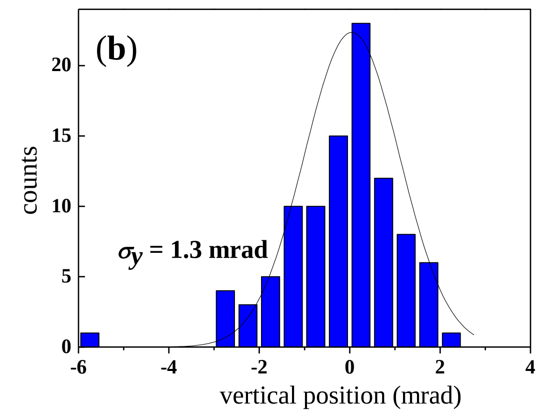


Electron beam recorded on YAG screen

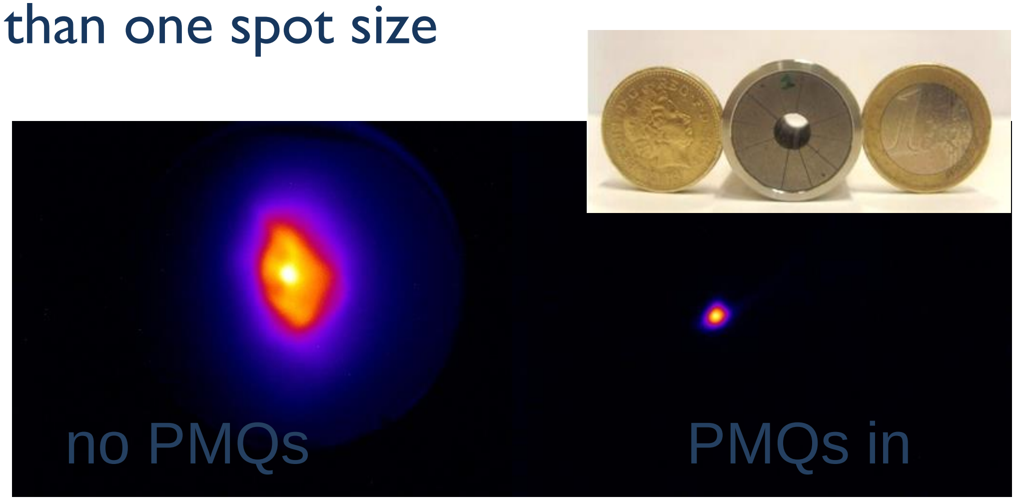
High resolution

Gas jet

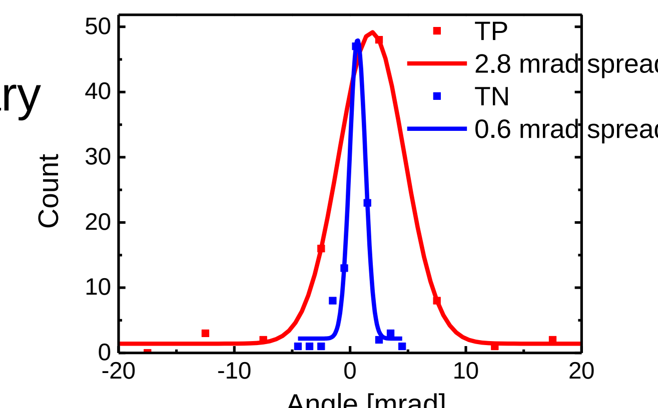




Electron beam pointing deviation is less than one spot size

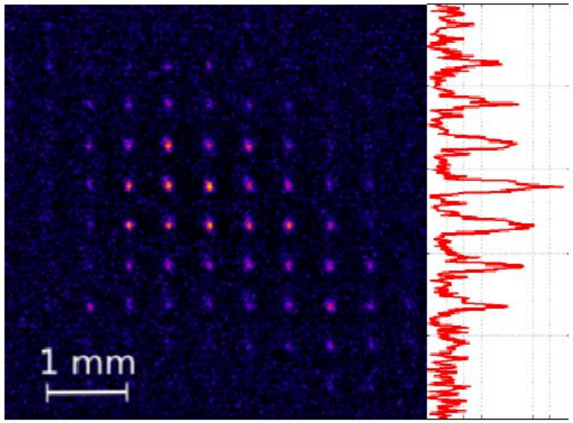


Capillary

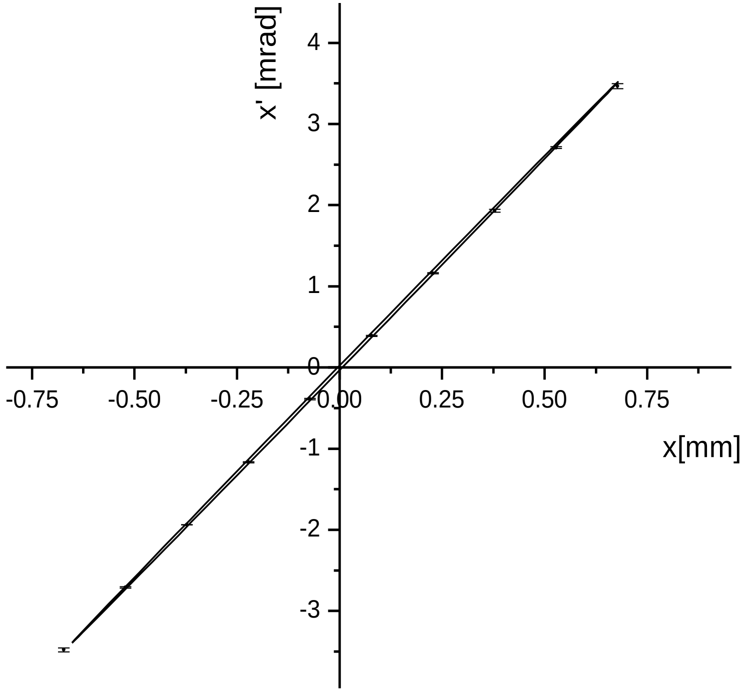


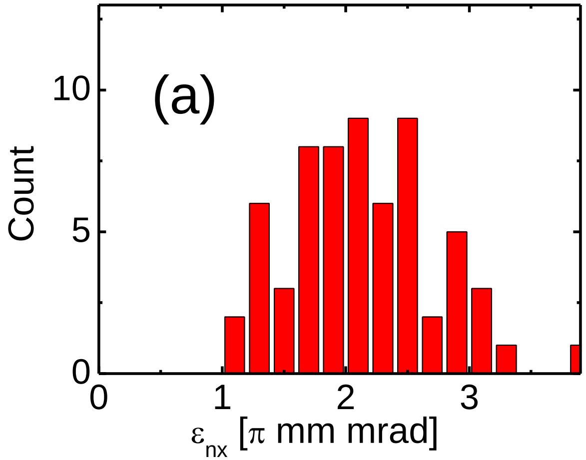
Emittance

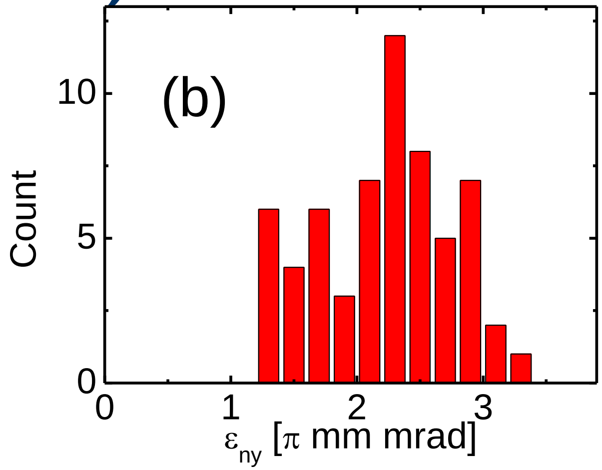
- Thin tungsten mask with holes ϕ ~ 25 μm



- divergence 1 – 2 mrad with 125 MeV electrons
- average ε_N = (2.2 ± 0.7)π mm mrad
- best ε_N = (1.0 ± 0.1)π mm mrad
- Elliptical beam: $\varepsilon_{N,X} > \varepsilon_{N,Y}$
- Upper limit because of resolution
- **With PMQs emittance grows by factor of 5 (measured)**

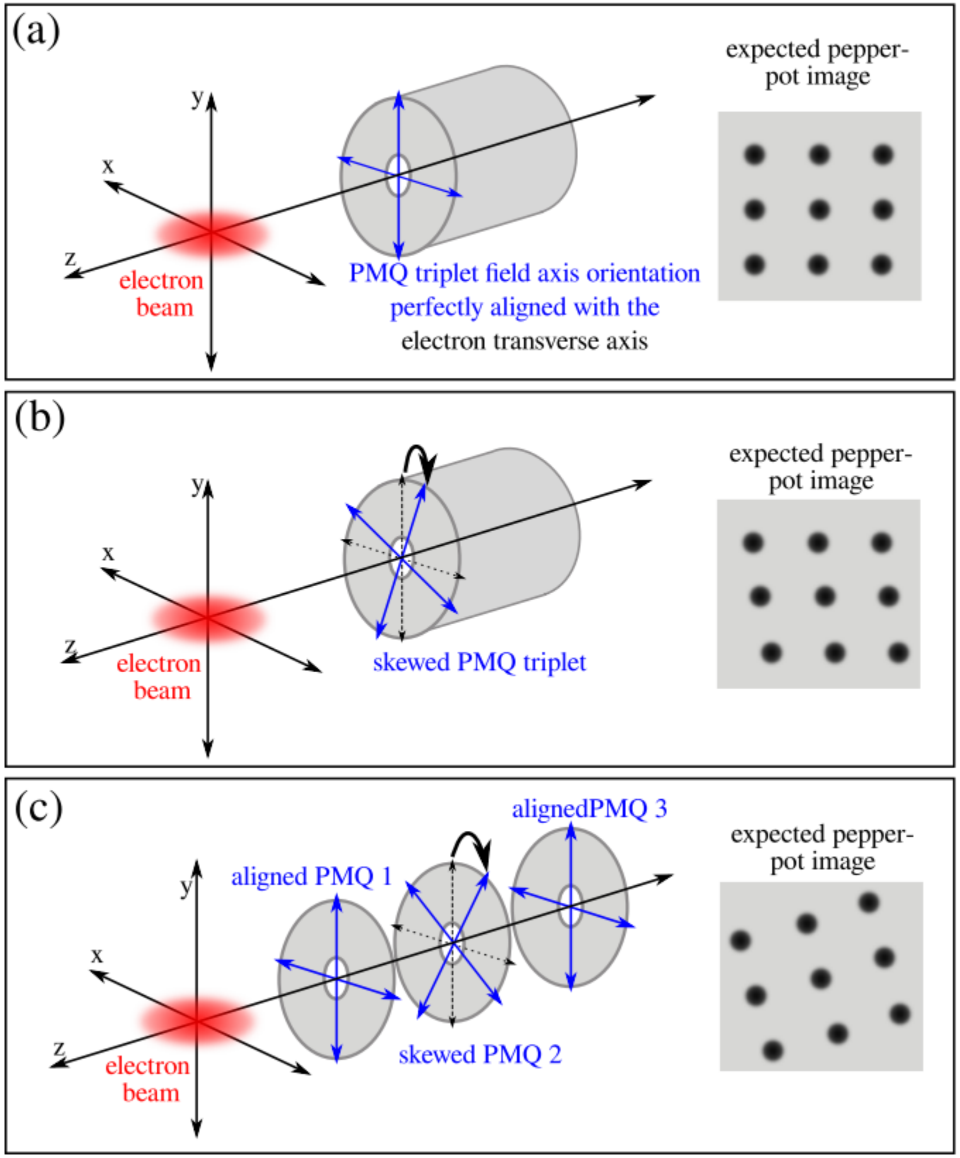


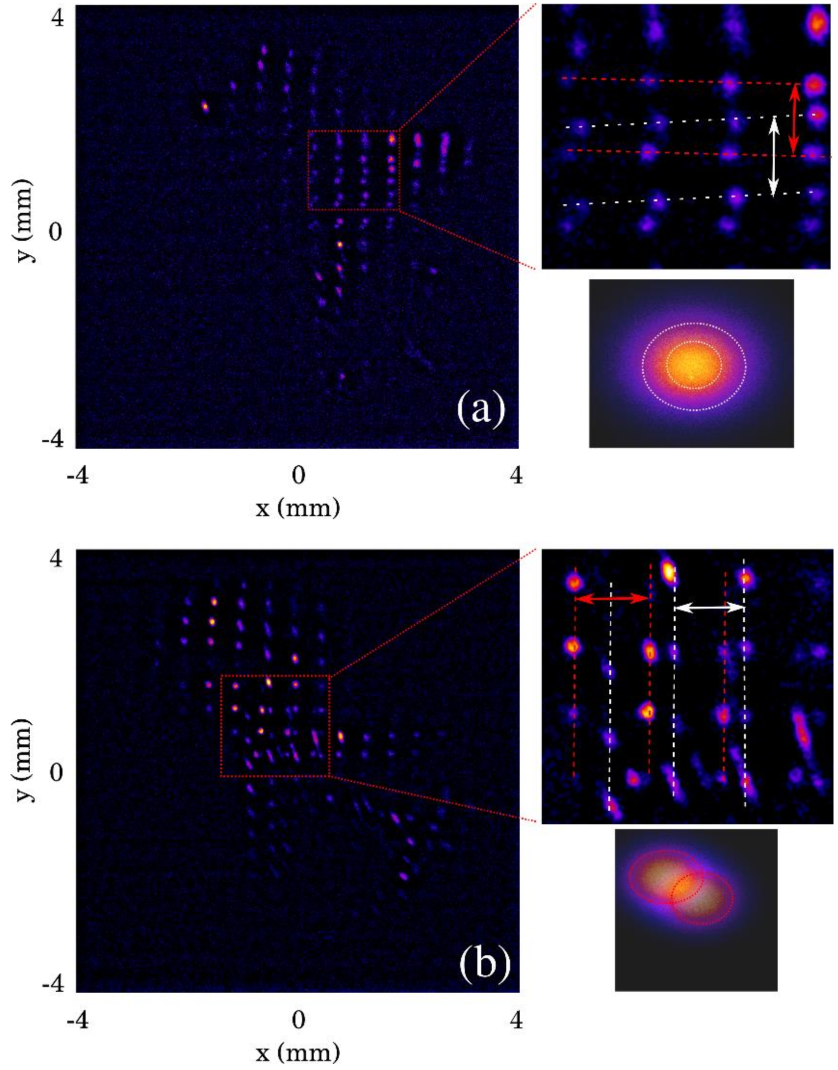




See Brunetti et al., PRL (2010)

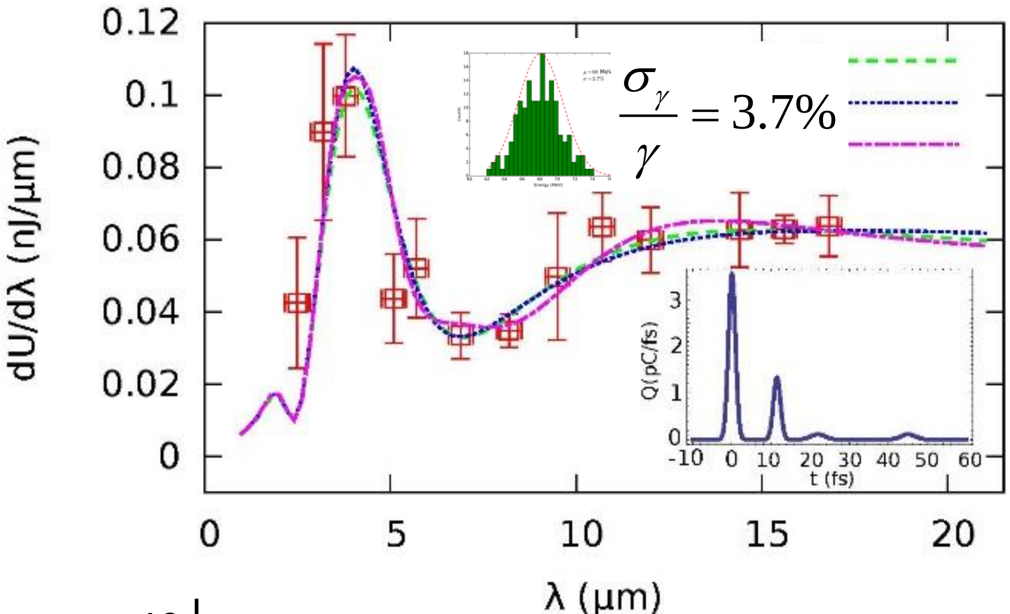
Evidence of multiple beams





Manahan et al., New J. Phys. (2014).

Bunch length measurements: Coherent Transition Radiation



Coherent transition radiation spectrum gives bunch length

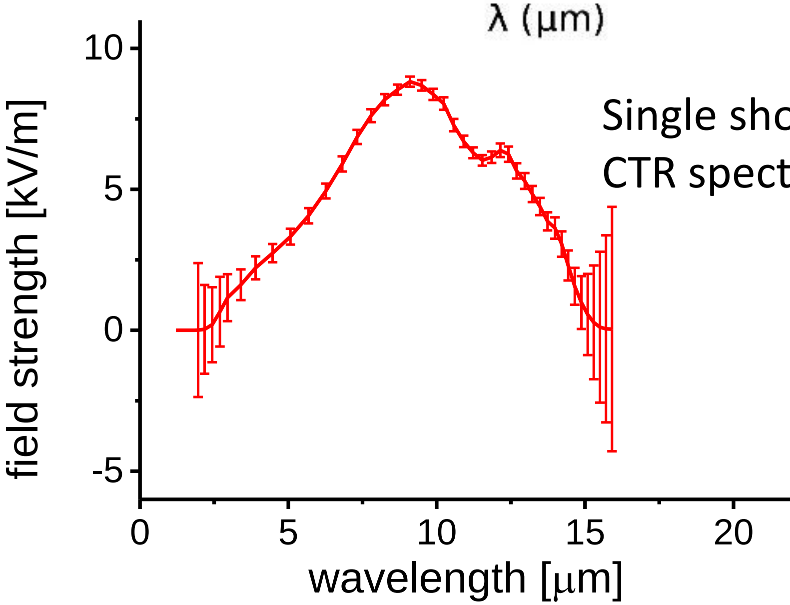
Chirp:

$$\frac{\delta\gamma}{\delta z} \approx \frac{2(z-R)\gamma_{max}}{R^2}$$

2 fs bunch measured at 1 m from source

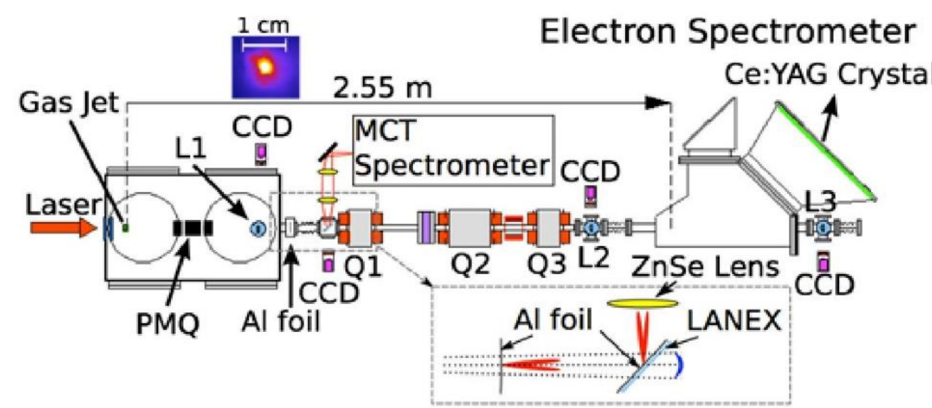
Peak current several kiloAmperes

$$\delta_{foil} = \delta_{acc} + \frac{D\delta_\gamma}{\gamma_0^3}$$



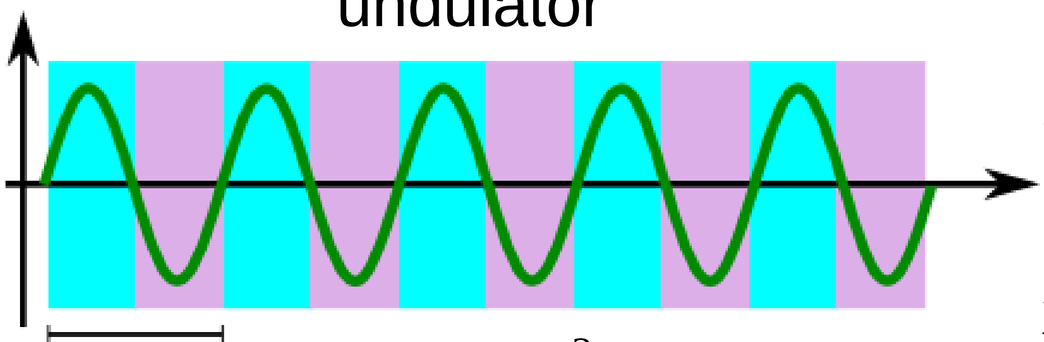
Single shot CTR spectrum

Ultra-short bunches: ~ 1 fs at source – Peak current several kA



Ex

Radiation from relativistic electrons



$$\omega = \frac{4\pi c\gamma^2}{\lambda_u\left(1 + a_u^2/2 + \gamma^2\theta^2\right)}$$

$$z(t) = \left(1 + \frac{a_u^2}{4\gamma^2}\right)vt - \frac{a_u^2}{8\gamma^2 k_u}\cos(2\omega_u t)$$

$$\mathrm{x(t)} = \frac{a_u}{k_u\gamma}\cos(\omega_u t)$$

$$\omega_u = k_u\left(1 + \frac{a_u^2}{4\gamma^2}\right)v$$

$$k_u = 2\pi/\lambda_u$$

Photons per electron
per undulator period

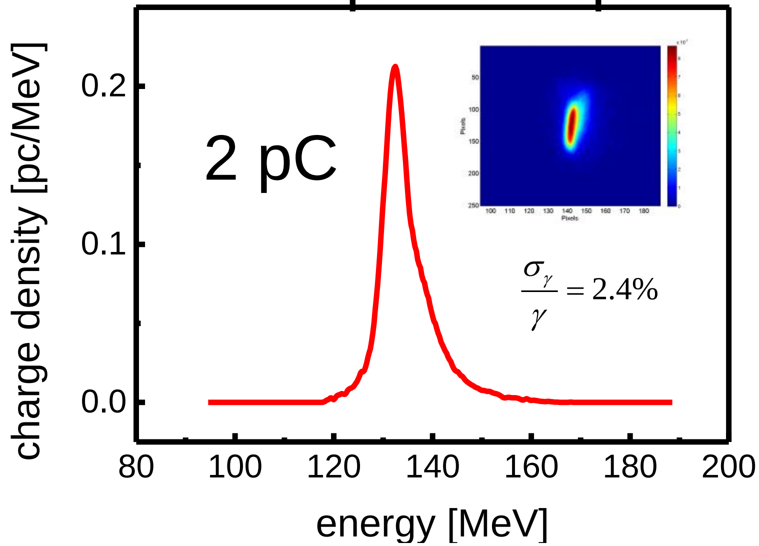
$$N_{phot} = \frac{2\pi}{3}\alpha a_u^2, \quad a_u < 1$$

$$N_{phot} = \frac{5\sqrt{3}\pi}{6}\alpha a_u, \quad a_u > 1$$

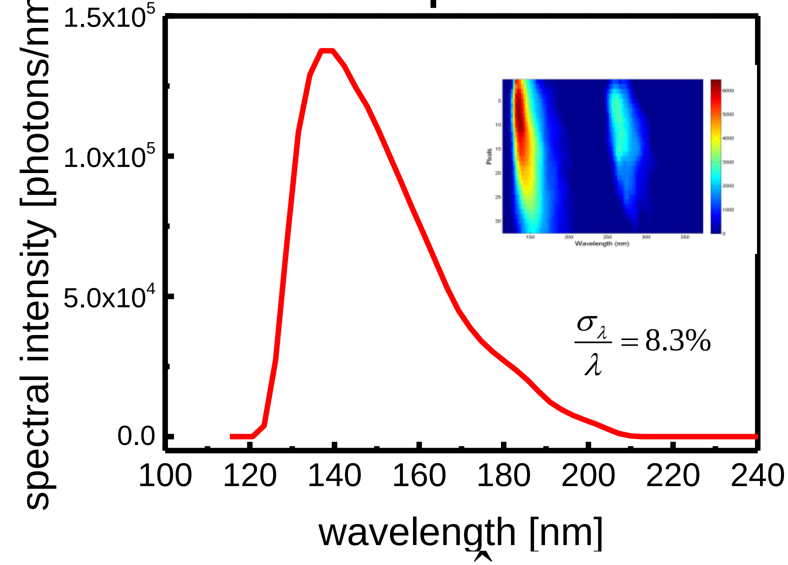
a_u <1: undulator radiation
a_u >1: wiggler radiation
α: fine structure constant

Strathclyde UV undulator measurements

10^7 photons predicted



6×10^6 photons measured

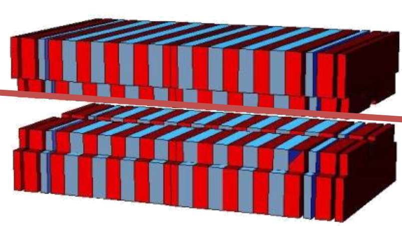


42 fs

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{a_u^2}{2} + \gamma^2\theta^2\right); \qquad \frac{\Delta\lambda}{\lambda} \approx \frac{1}{2N_u} \qquad a_u = \frac{e\hat{B}\lambda_u}{2\pi mc}$$

$$2\sigma_\gamma / \gamma \approx \left[\left(\sigma_\lambda / \lambda\right)^2_{measured} - (\vartheta^2\gamma^2)^2 - 1/N_u^2\right]^{1/2}$$

MP Anania, et al.,
Applied Physics Letters
104, 264102 (2014)

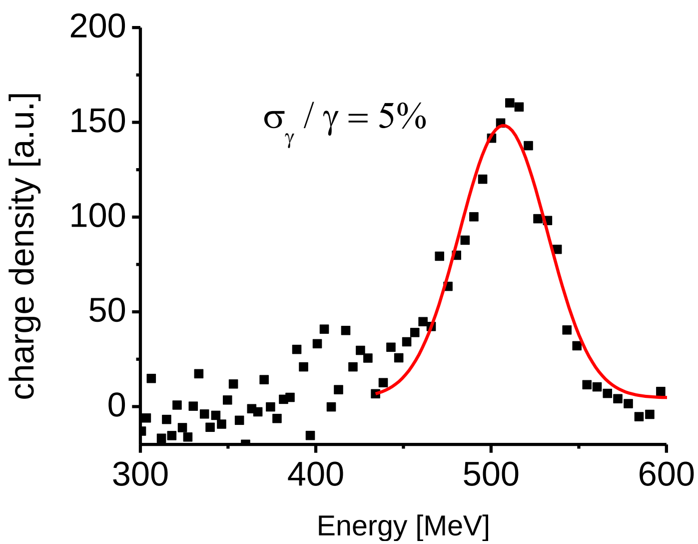


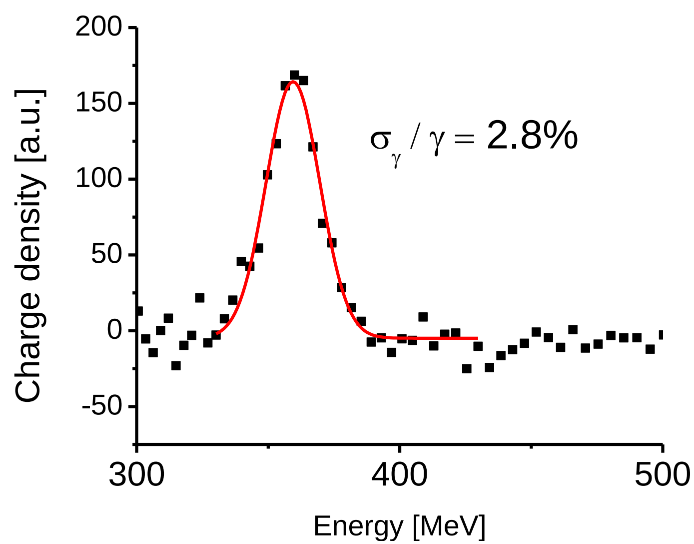
N_u=100, λ_u=1.5 cm

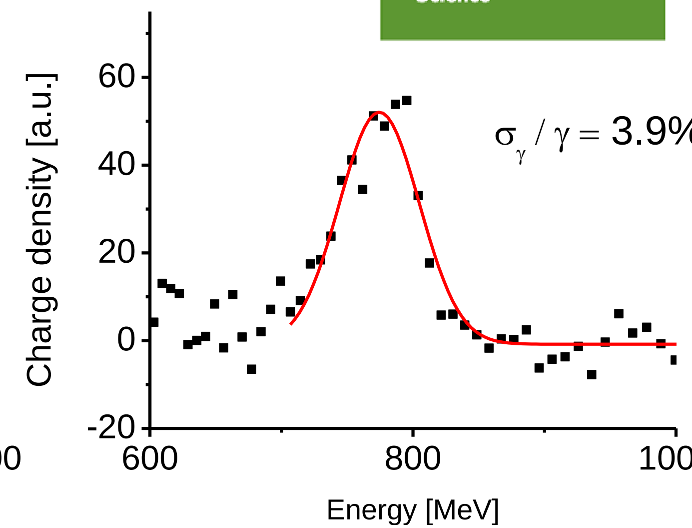
First experiments in visible:
HP Schlenvoigt, et al.,
Nature Physics 2008

$$\frac{1}{\sqrt{N_u \gamma}}$$

5 J laser at RAL: Electron Beams from Capillary

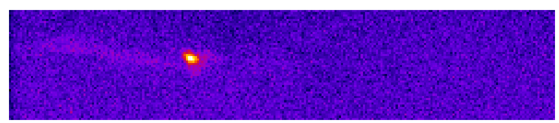




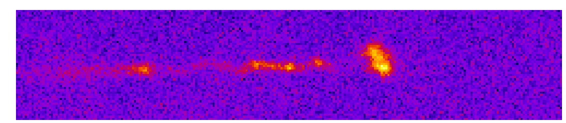


RAL GEMINI: limited by spectrometer resolution – maximum energy measured 850 MeV from 4 cm capillary.

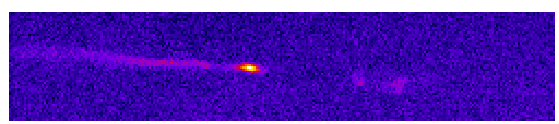
$$\gamma_d \approx 2\gamma_g^2 a_0 / 3$$



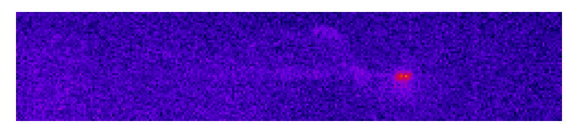
E_0 = 260 MeV, σ_γ/γ $_{MEAS}$ ~ 2.5%



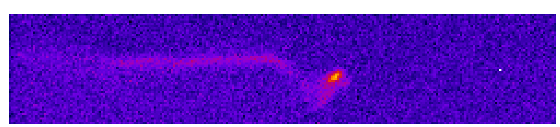
E_0 = 610 MeV, σ_γ/γ $_{MEAS}$ ~ 4.5%



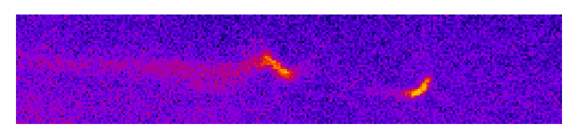
E_0 = 340 MeV, σ_γ/γ $_{MEAS}$ ~ 2.5%



E_0 = 690 MeV, σ_γ/γ $_{MEAS}$ ~ 4%

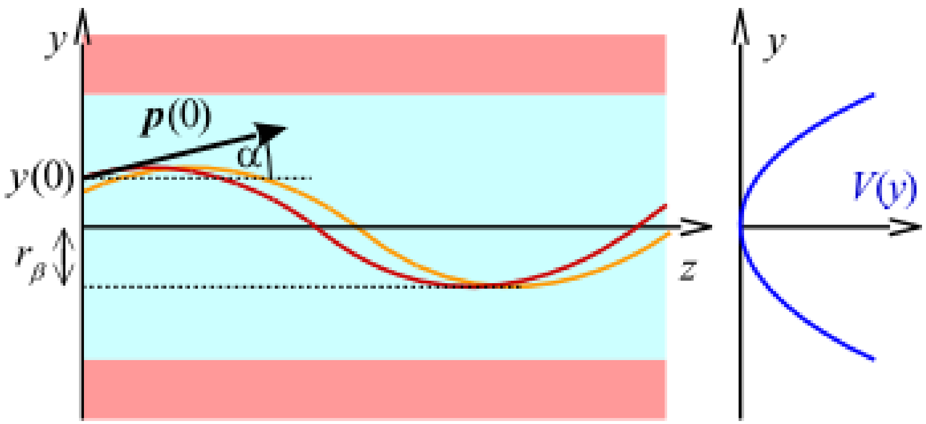


E_0 = 510 MeV, σ_γ/γ $_{MEAS}$ ~ 3%

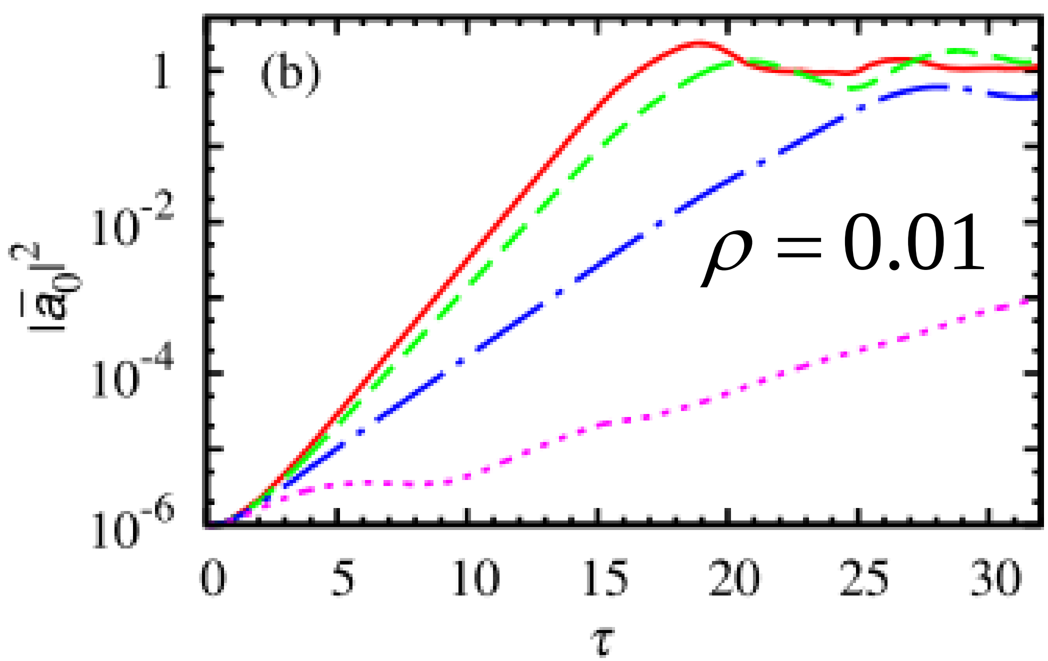


E_0 = 770 MeV, σ_γ/γ $_{MEAS}$ ~ 4%

Ion Channel Laser

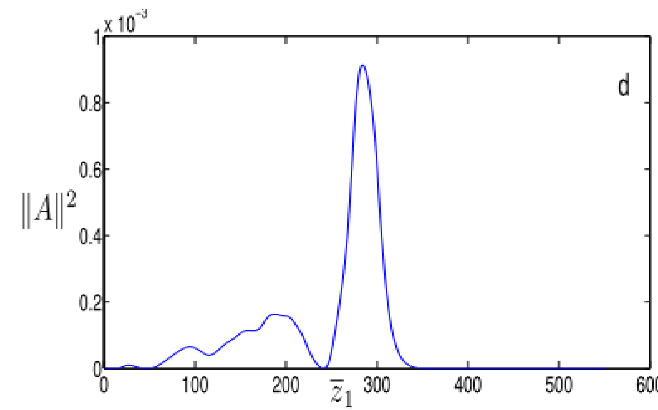


$$\rho = \left[\eta_h^2 \eta_m \bar{\eta}_f \omega_b^2 R_\beta^2 \big/ \left(8\tilde{\gamma}_0 c^2\right)\right]^{1/2} \approx 3.3 \times 10^{-3}\left[\left(n_b/10^{18}\ \mathrm{cm}^{-3}\right)\big/\tilde{\gamma}_0\right]^{1/2}\left(R_\beta/\mu\mathrm{m}\right).$$



Similar to FEL but with variable wiggler parameter for each electron

Ersfeld et al., NJP (2014)



Betatron radiation emission during LWFA

SCALING LAWS

Acceleration:

- Bubble radius: $R = 2\sqrt{a_0}/k_p$
- Dephasing Length: $L_d \simeq 2/3\omega_0^2/\omega_p^2,\ \omega_p = \sqrt{4\pi n_e e^2/m_e}$
- Max Energy: $\gamma_d \approx 2\gamma_g^2 a_0/3$

Betatron Radiation:

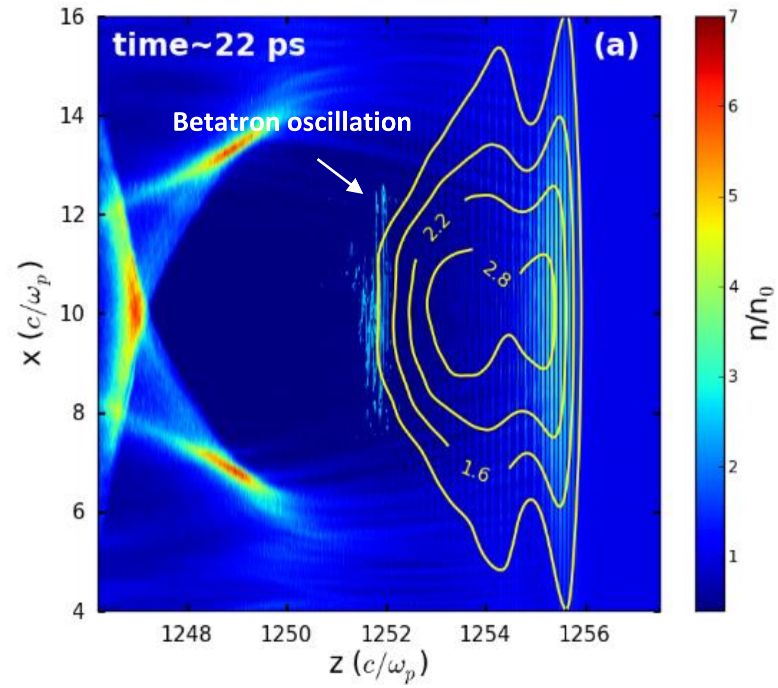
- Betatron Frequency: $\omega_\beta = \omega_p/\sqrt{2\gamma}$
- Transverse momentum: $a_\beta \propto \sqrt{\gamma n_e} r_\beta$
- Divergence: $\vartheta = a_\beta/\gamma$
- Critical photon Energy: $E_c \propto \gamma^2 n_e r_\beta$ $\quad h_c \approx 3a_\beta^3/8$
- Efficiency: $N_{phot/cycle} = \alpha a_\beta$

Betatron radiation emission during LWFA

BETATRON RESONANCE

- The bubble partially filled by laser pulse
- Electrons enter into resonance with the laser field
- Laser drives larger amplitude betatron oscillations:

Increase in r_β, a_β, E_c



Betatron radiation emission during LWFA

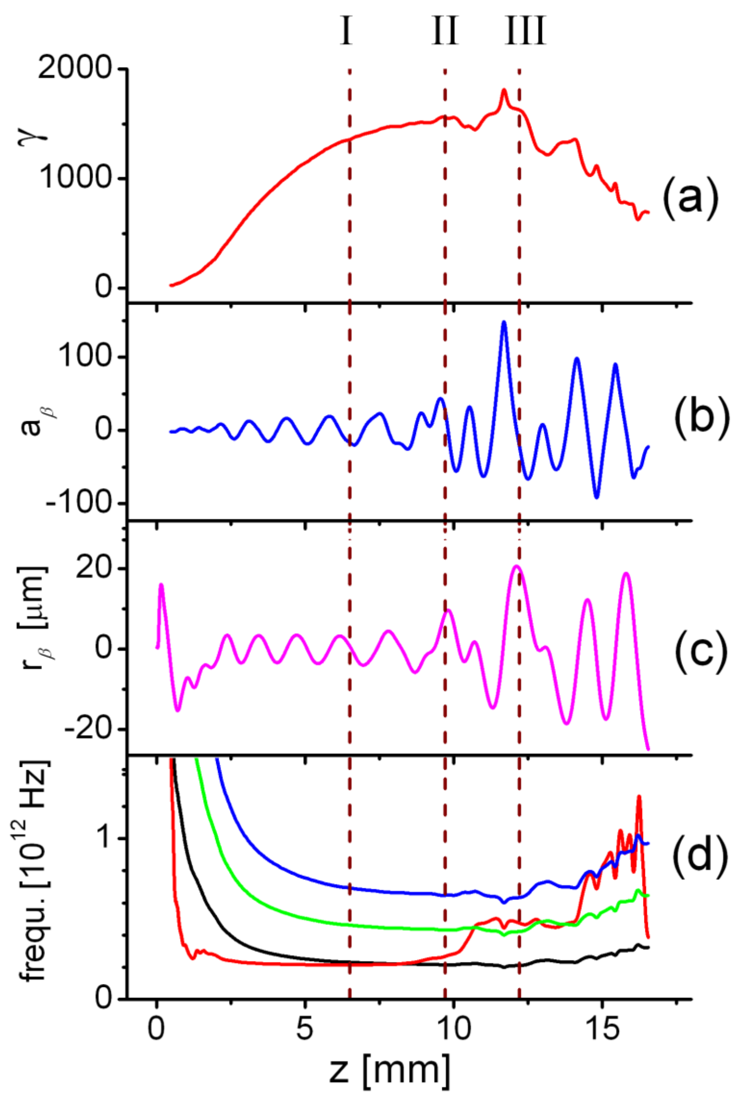
Cipiccia et al., Nature Physics, 2011

- Three different regimes:
  - Non resonant (I)
  - Weakly resonant (II)
  - Strongly resonant (III)

$$\ddot{y} + \Gamma\dot{y} + \omega_\beta^2 y = F_{Ly}/(m\gamma)$$

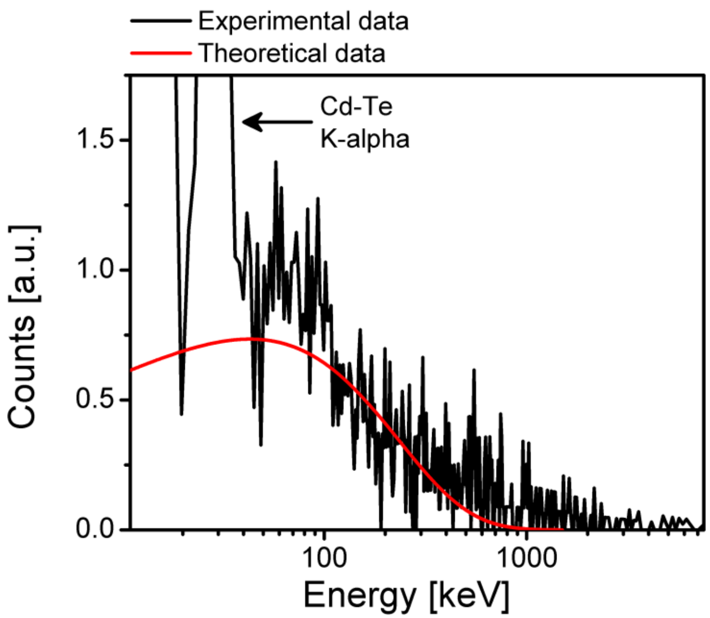
$$\Gamma = \dot{\gamma}/\gamma \qquad F_{Ly} = e(dA/dt - \dot{y}\,\partial A/\partial y)$$

$$\tilde{\omega} = \omega'_0\left(\frac{1}{2\bar{\gamma}_z^2} + \frac{1}{2\gamma'^2_g}\right) \quad \bar{\gamma}_z = \gamma(1 + a_\beta^2/2)^{-1/2}$$



ASTRA Gemini: Experimental Results

Case II Weakly Resonant

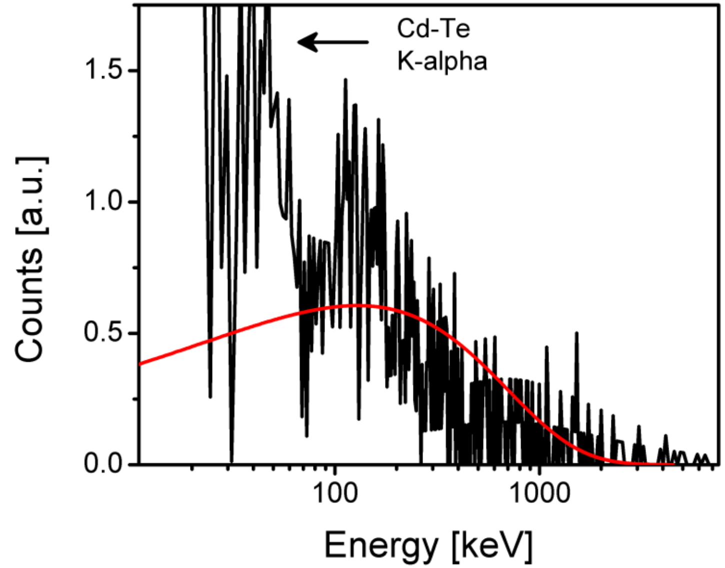


E_c = 150 keV

r_β = 7 mm

a_β = 50

Case III: Strongly Resonant:

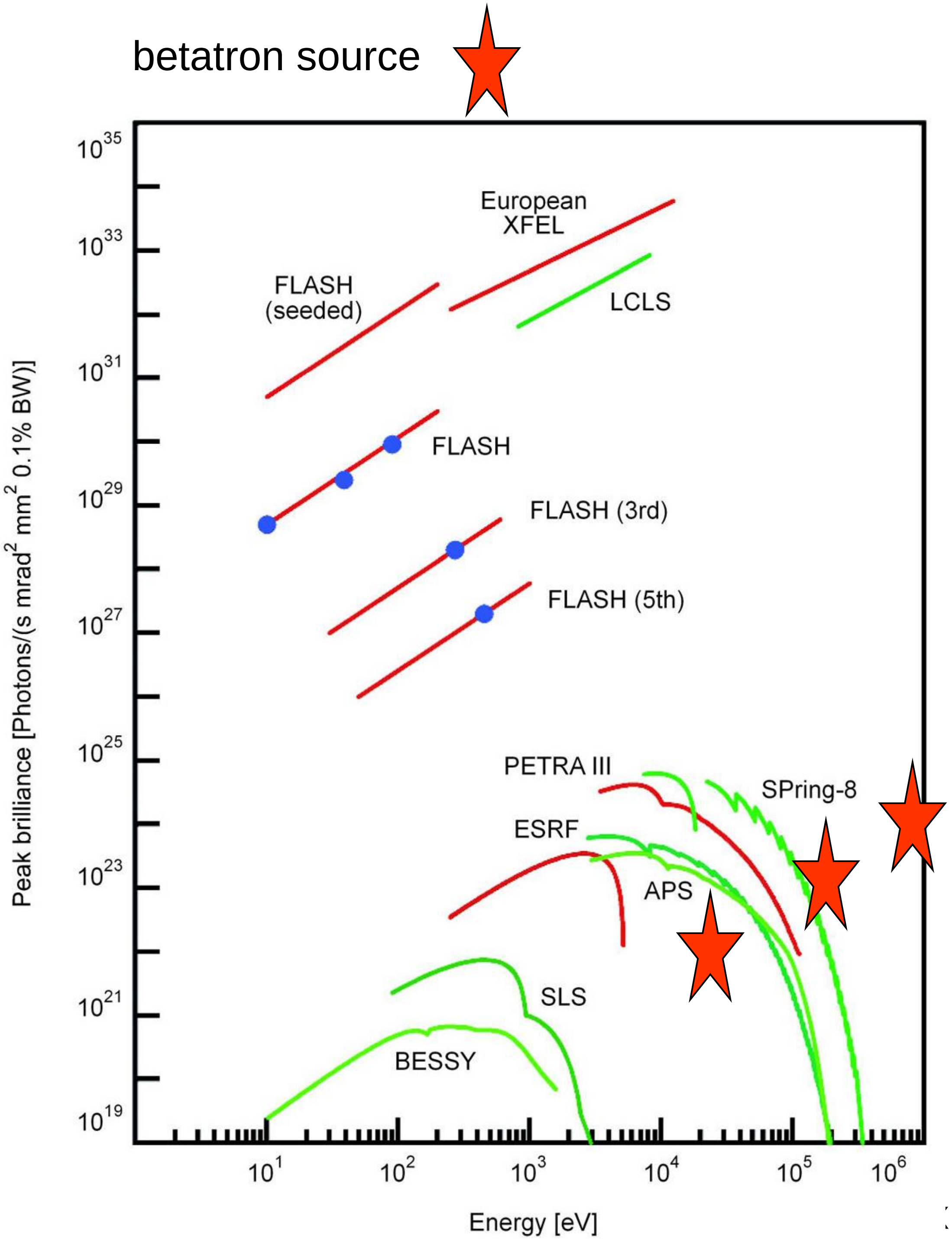


E_c = 450 keV

r_β = 20 μm

a_β = 150

Brilliance



Betatron peak brilliance

10^{22} - 10^{23} photons/s mrad^2 mm^2 0.1% B.W

Laser: 18 J, $a_0 = 4$

10^{24} photons/s mrad^2 mm^2 0.1% B.W

Scaling up photon energy

Current:

- Laser Energy: 4-5 J
- Pulse length: 50-60 fs
- Initial a_0: 2
- E_c = 10 – 150 keV
- No. photons/shot: >3 x 10^{10}

Bigger laser:

- Laser: 18 J, a_0 = 4
- Max electron energy : 1.5 GeV
- Electron beam charge: 300 pC
- N photon/shot 5-25 MeV = $6x10^8$
- Max repetition rate: 10 Hz
- 10^{10} 10 MeV photons per second:
- 10 mW of 10 MeV photons

Radiation Reaction studies

- Semi-classical:
  - Radiation reaction in a Coulomb field
- Stochastic:
  - Interaction with two-colour pulses
  - Chirped pulses
  - Longitudinal *vs.* transverse beam cooling

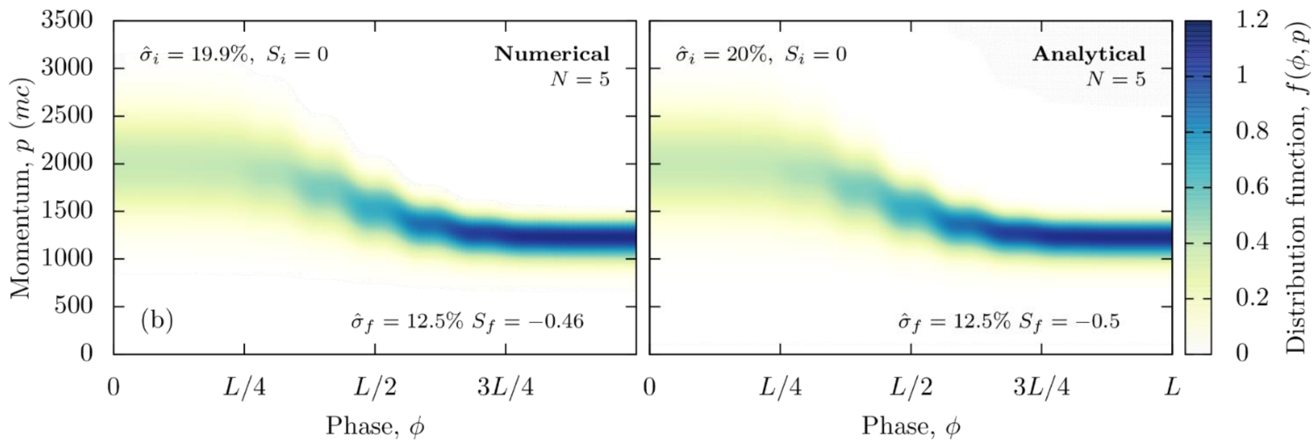
Radiation reaction

- **Lorentz-Abraham-Dirac:** relativistic equation of motion including radiation reaction
- **Landau-Lifshitz:** treat radiation reaction as a small perturbation to external forces
- Often claimed LL is valid, provided quantum effects can be ignored [Spohn 2000; Kravets *et al.* 2013]
- Quantum effects can typically be ignored provided the observed electric field $\hat{E} \ll E_S$, where $E_S = 1.3 \times 10^{18}$ V/m is the Schwinger critical field
- **Semi-classical extension:**
  - Classical models overestimate radiation as quantum effects become important
  - Following Kirk *et al.* (2009) and Thomas *et al.* (2012), scale the radiation reaction force by a function of the quantum nonlinearity parameter, $\chi = \frac{\hat{E}}{E_S}$

$$g(\chi) = (1 + 12\chi + 31\chi^2 + 3.7\chi^3)^{-4/9}$$

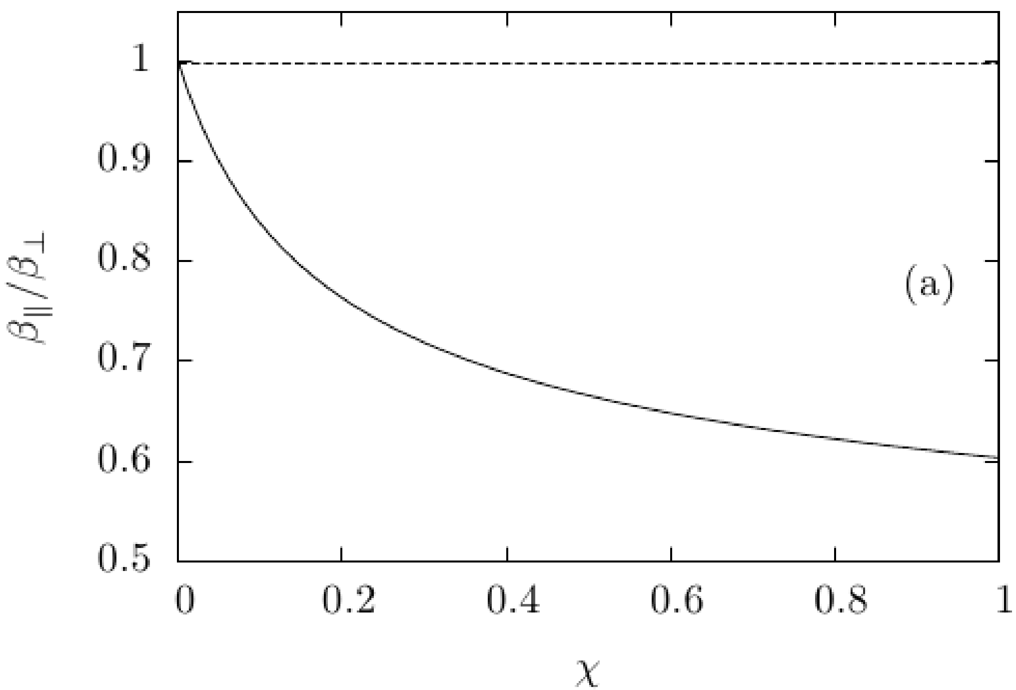
Analytical solution of Vlasov equation with LL

- Analytical solution to the Vlasov equation with radiation reaction according to the classical LL model, for an electron bunch in a plane wave [Yoffe *et al.* 2015]
- Distribution F satisfies $\frac{dF}{d\phi} = -\beta F$, where $\phi = \omega t - \boldsymbol{k} \cdot \boldsymbol{x}$ is the phase and $\beta < 0$ results in phase space contraction (beam cooling) and leads to solution of the form $F(\phi, \boldsymbol{v}) = \frac{F(\phi^0, \boldsymbol{v}^0)}{G(\phi)^4}$ with $\boldsymbol{v}_0$ replaced by $\boldsymbol{v}$ using the LL equations of motion
- Reduced (longitudinal) distribution f satisfies $f(\phi, v_\phi) = \frac{f\left(\phi^0, \frac{v_\phi}{G(\phi)}\right)}{G(\phi)^2}$
- Comparison of analytical and numerical results (5-cycles, 8×10^{21} W/cm^2, 7 fs FWHM; 1 GeV electrons with 20% initial spread)



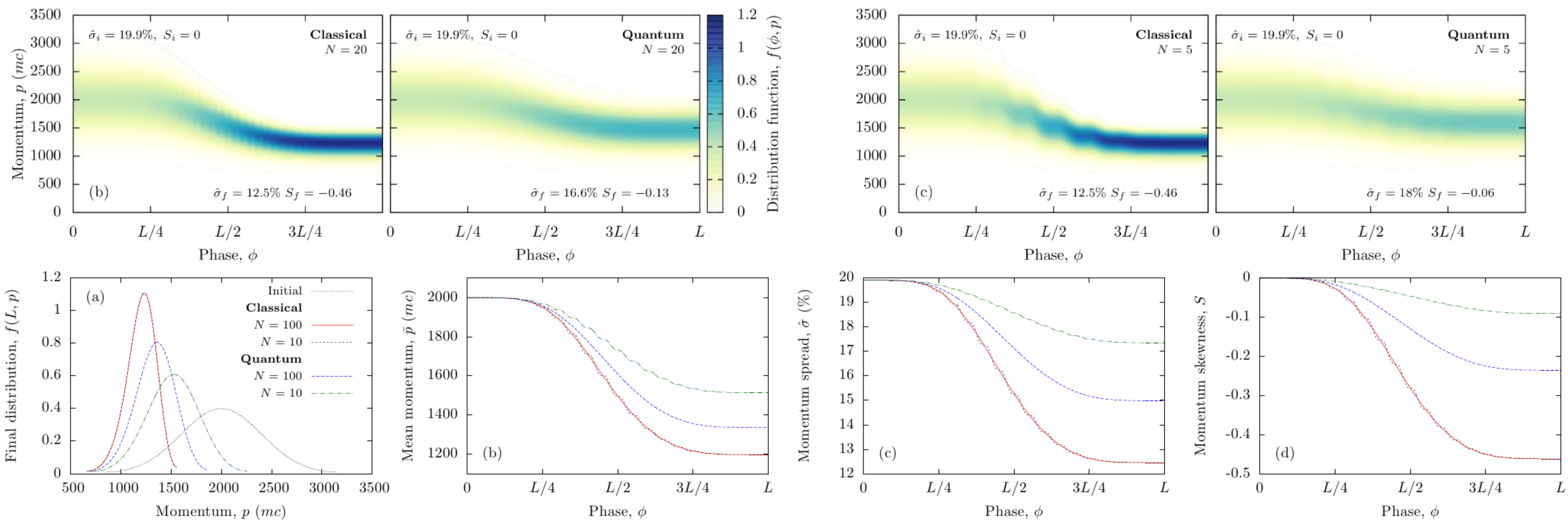
Longitudinal *vs.* transverse cooling

- Analytical solution to the Vlasov equation - two contributions to cooling: $\beta = \beta_{\parallel} + \beta_{\perp}$
- **Classical**: $\hat{\beta}_{\parallel} = \hat{\beta}_{\perp}$ - equal cooling in longitudinal and transverse directions
- **Semi-classical**: reduction in beam cooling by $g(\chi)$: $\beta_{\perp} = g(\chi)\hat{\beta}_{\perp}$
  Dependence of χ on v_{ϕ} produces an additional heating term,
$$\frac{\beta_{\parallel}}{\beta_{\perp}} = 1 - \frac{2}{9}\chi g^{9/4}(\chi)(12 + 62\chi + 11.1\chi^2) \leq 1$$
- Reduced longitudinal beam cooling compared to transverse



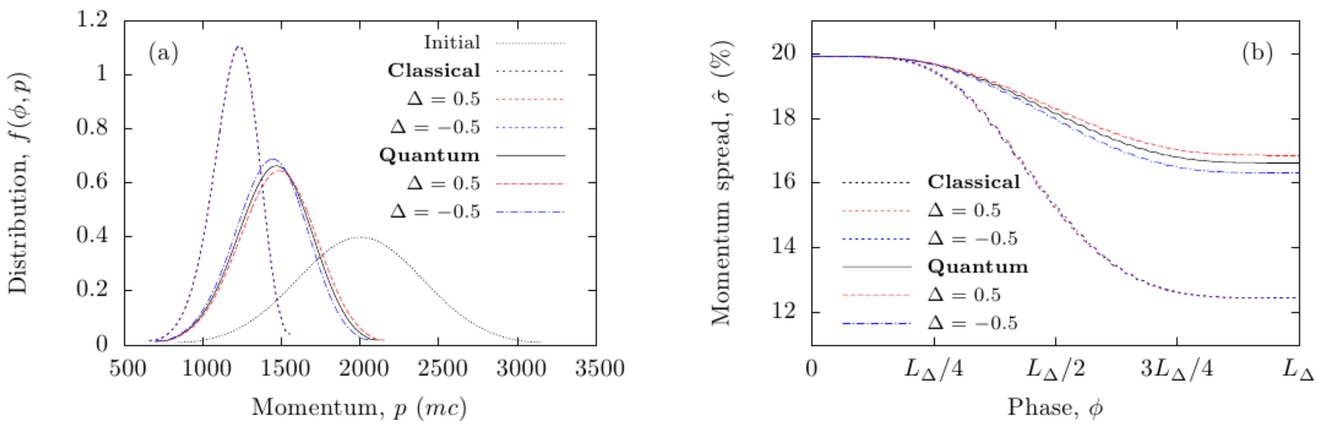
Classical *vs.* semi-classical beam cooling

- Comparison of classical and semi-classical longitudinal beam cooling
  - Top: $N = 5$ (8×10^{21} W/cm^2, 7 fs FWHM) and $N = 20$ (2×10^{21} W/cm^2, 27 fs FWHM) plane-wave pulses;
  - Bottom: $N = 10$ (4×10^{21} W/cm^2, 13 fs FWHM) and $N = 100$ (4×10^{20} W/cm^2, 135 fs FWHM) plane-wave pulses;
  - 1 GeV electron bunches, with initial spread 20% and zero skewness
- Final spread increased from 12.5% to 16.6% ($N = 20$) and 18% ($N = 5$) – **REDUCED BEAM COOLING**
- Skewness reduced - semi-classical final distribution more Gaussian than the classical



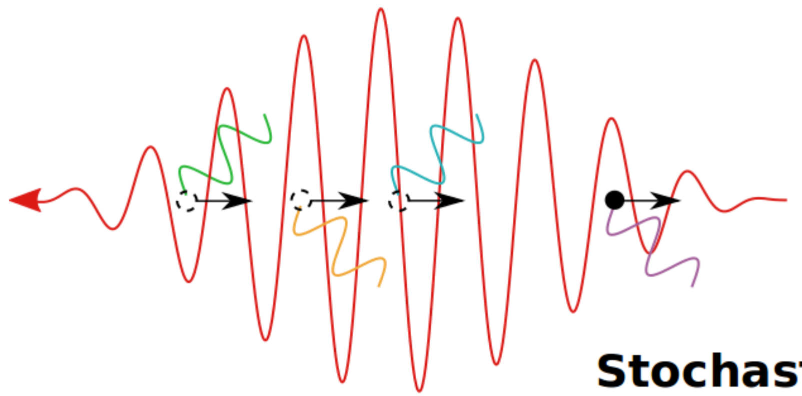
Beam cooling with chirped pulses

- Semi-classical model: properties of the final state electron beam depend on the distribution of energy within the pulse - not only the total amount as in the classical case.
- The chirp modifies the distribution of energy within the pulse – how does this affect beam cooling?
- Number of cycles and total energy fixed to facilitate comparison

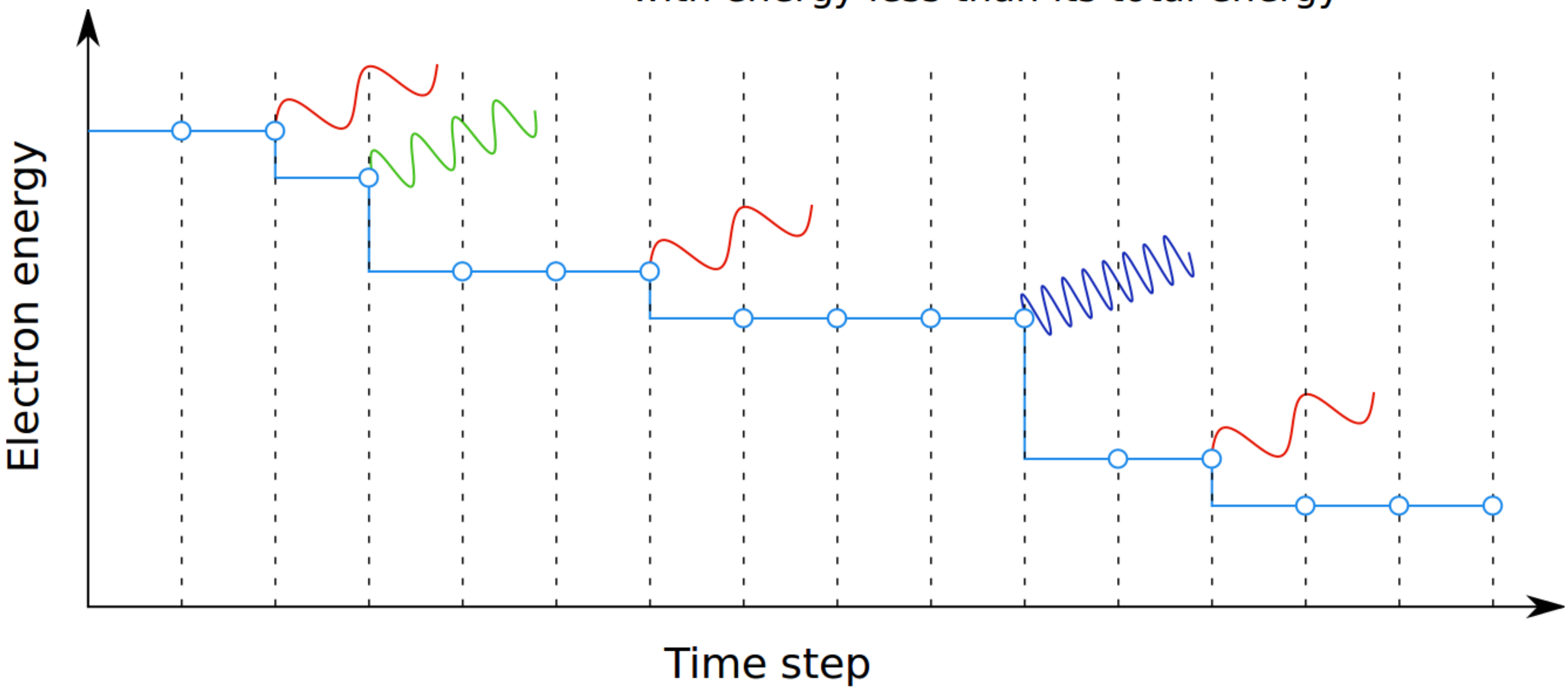


- Classical predictions insensitive to the chirp – as expected
- **Positive chirp**: pulse length reduced due to decreasing wavelength, so increase in peak intensity and increase in χ. This suppresses radiation reaction effects, and hence **beam cooling is reduced**.
- **Negative chirp**: pulse length increases due to increasing wavelength, requiring a decrease in peak intensity to maintain total energy. Decrease in χ leads to **further beam cooling**.

Stochastic effects



Stochastic:
Electron emits (multiple) photons, each with energy less than its total energy



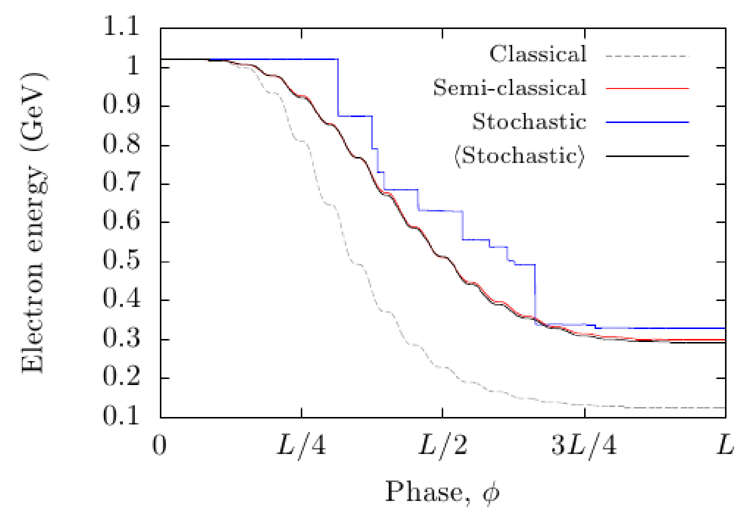
Stochastic radiation emission

- As χ increases, stochastic nature of photon emission becomes important.
- Stochastic model based on the differential probability $dW = \Gamma d\phi$ [Ritus 1985; Green and Harvey 2014]

$\Gamma = \int_0^{\Omega} d\tilde{\Omega}\, P(\Omega, \tilde{\Omega})$ and $P(\Omega, \tilde{\Omega}) = \frac{\alpha m}{\sqrt{3}\pi\Omega^2}\left[\left(\frac{\Omega-\tilde{\Omega}}{\Omega} + \frac{\Omega}{\Omega-\tilde{\Omega}}\right) K_{2/3}(\tilde{\chi}) - \int_{\tilde{\chi}}^{\infty} dx\, K_{1/3}(x)\right]$

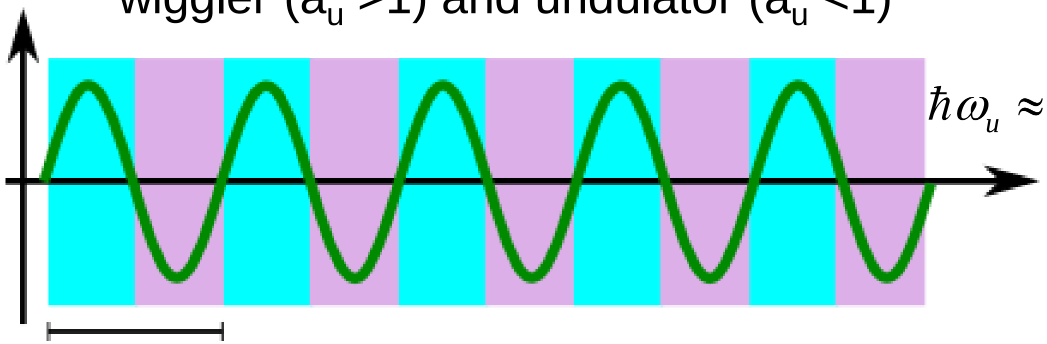
The invariant parameters $\Omega = \frac{k_a p^a}{m}$, $\tilde{\Omega} = \frac{k_a \kappa^a}{m}$, and $\tilde{\chi} = \frac{2m\tilde{\Omega}}{[3\hbar a(\phi)\Omega(\Omega-\tilde{\Omega})]}$.

- Electron propagates according to Lorentz force. At each step emits a photon if random number $r \in [0,1) < dW$.
- Determine random outgoing momentum by finding $\tilde{\Omega}$ such that $\int_0^{\tilde{\Omega}} dx\, P(\Omega, x) = \zeta\Gamma$ with $\zeta \in [0,1)$.
- <u>Comparison of stochastic and semi-classical models:</u>
  - $N = 10$ pulse with intensity $I = 4.3 \times 10^{22}$ W/cm^2
  - Classical prediction shows significant beam cooling
  - Single stochastic prediction displays "steps"
- Ensemble of 1,000 stochastic runs in excellent agreement with semi-classical model, despite $\langle\chi\rangle \simeq 0.8$



Summary – radiation sources

wiggler (a_u >1) and undulator (a_u <1)



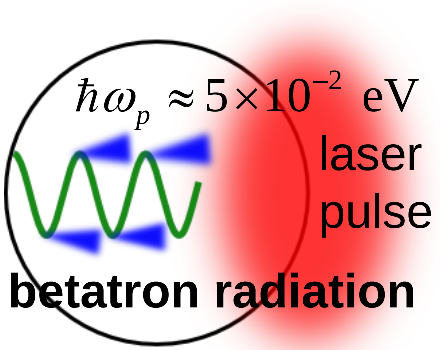
$\hbar\omega_u \approx 10^{-4}$ eV

λ_u : mm to cm; γ: $10^3 - 10^4$; $\hbar\omega$: up to 100's keV

$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$N_{phot/cycle} \approx .015\, a_{\beta,0}^2 \text{ for } a_{\beta,0} < 1$$

$$N_{phot/cycle} \approx .033\, a_{\beta,0} \text{ for } a_{\beta,0} > 1$$

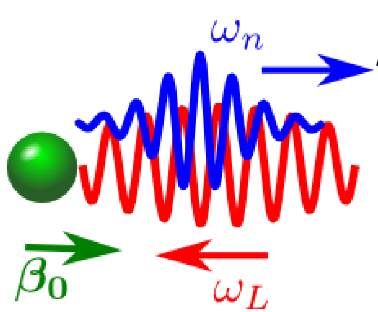


$$\lambda_\beta = \sqrt{2\gamma}\lambda_p$$

$$\hbar\omega \approx 1.4\hbar\omega_p\gamma^{3/2} \text{when } a_\beta < 1 \text{ (10 keV)}$$

$$\hbar\omega_c \approx \hbar\omega_p\gamma^{3/2}a_\beta \text{ when } a_\beta > 1 \text{ (10 MeV)}$$

- Max: $\gamma \approx 10^4$ (5 GeV)
- Undulator: <10 keV
- Wiggler: <100 keV
- Betatron: <20 MeV
- Thomson: <400 MeV
- Compton: Linear and nonlinear < 5 GeV



$\hbar\omega_0 \approx 1$ eV

Thomson/Compton back-scattering

$$\hbar\omega \approx 4\hbar\omega_0\gamma^2 \text{when } a_0 < 1 \text{ (4 - 400 MeV)}$$

$$\hbar\omega_c \approx 3\hbar\omega_0\gamma^2 a_0 \text{ when } a_0 > 1 \text{ (< 1 GeV - nonlinear Compton)}$$

Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)

University of Strathclyde

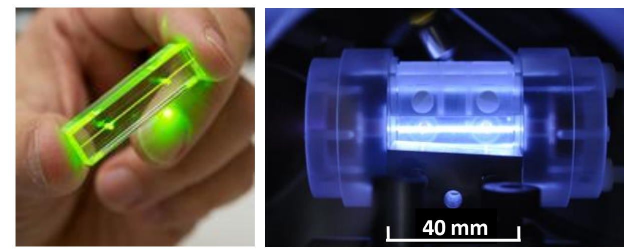
SCAPA

- Expansion of ALPHA-X laser-plasma accelerator facilities at Strathclyde with new laboratories.

- In-depth programme of **Applications**.
- Accelerator and source **Research & Development**.
- Knowledge Exchange & **Commercialisation**
- Engagement in European and other large projects.
- **Training:** Centre for Doctoral Training in the Application of Next Generation Accelerations

- **3 shielded areas** with **7 accelerator beam lines**.

- High-intensity femtosecond laser systems:
  - a) 350 TW (with provision for PW) @ 5 Hz,
  - b) 40 TW @ 10 Hz,
  - c) sub-TW @ 1 kHz.
- High-energy **proton, ion and electron** bunches.
- High-brightness fs duration **X-ray & gamma-ray** pulses.



Compact GeV electron accelerator and gamma-ray source

APPLICATIONS

- **Radiobiology**
- **Ultrafast Probing**
- **High-Resolution Imaging**
- **Radioisotope Production**
- **Detector Development**
- **Radiation Damage Testing**

University of Strathclyde Science

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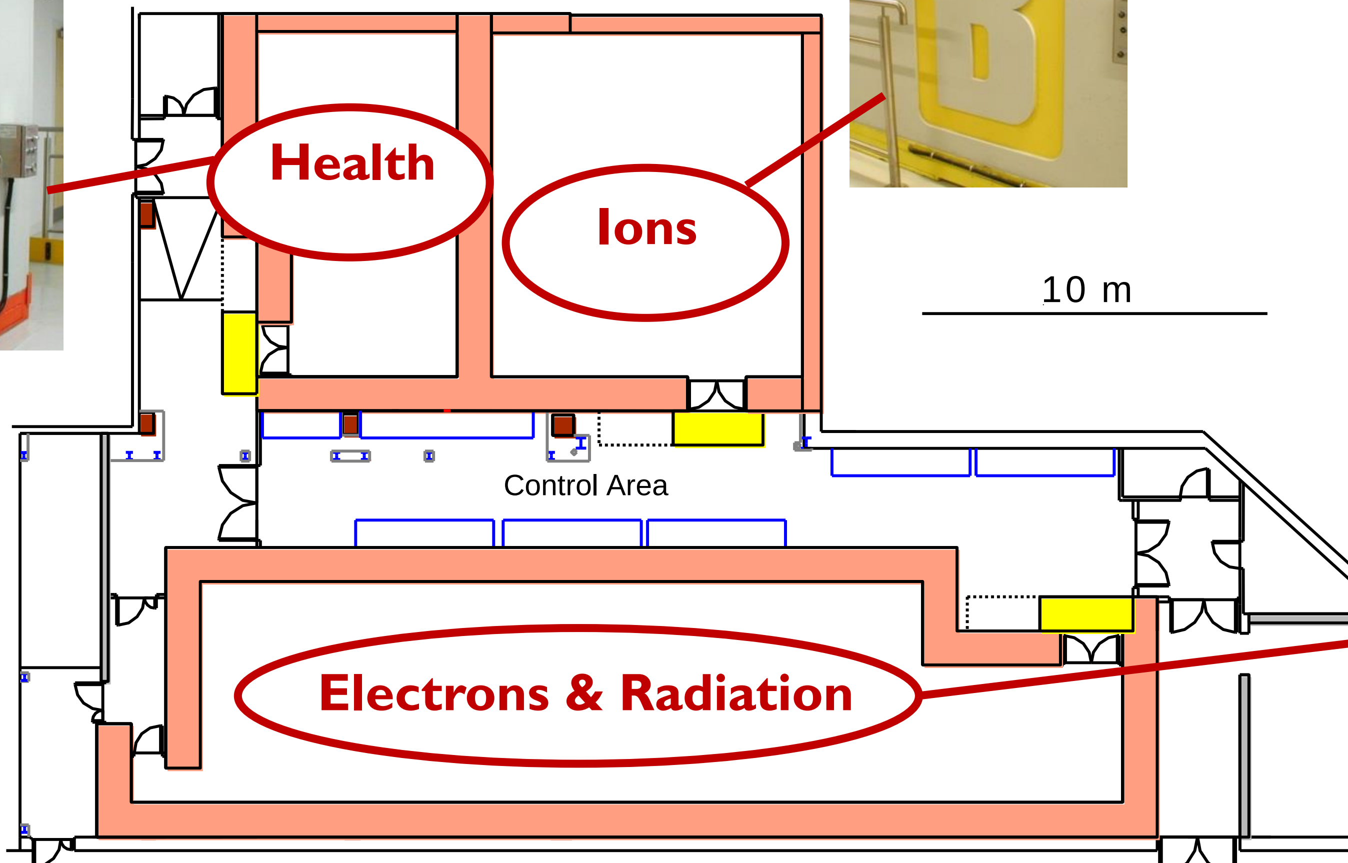
Concrete doors on air skates



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Lancaster U., Cockcroft Institute / STFC - ASTeC, STFC – RAL CLF, U. St. Andrews, U. Dundee, U. Abertay-Dundee, U. Glasgow, Imperial College, IST Lisbon, U. Paris-Sud - LPGP, Pulsar Physics, UTA, CAS Beijing, U. Tsinghua, Shanghai Jiao Tong U., Beijing, Capital Normal U. Beijing, APRI, GIST Korea, UNIST Korea, LBNL, FSU Jena, U. Stellenbosch, U. Oxford, UCL, LAL, PSI, U. Twente, TUE, U. Bochum, IU Simon Cancer Center, Indianapolis, MGS Research, Inc., Madison, Royal Marsden, ELI-NP, ELI-ALPS, ELI-Beamlines ....

Support: Strathclyde University, EPSRC, CSO, EU-FP7 Laserlab & EUCARD, STFC


FIN
Thank you