11ème Forum Lasers et Plasmas

27/09-01/10/2021 Club Belambra "Belgodere, Golfe de Lozari", Haute Corse

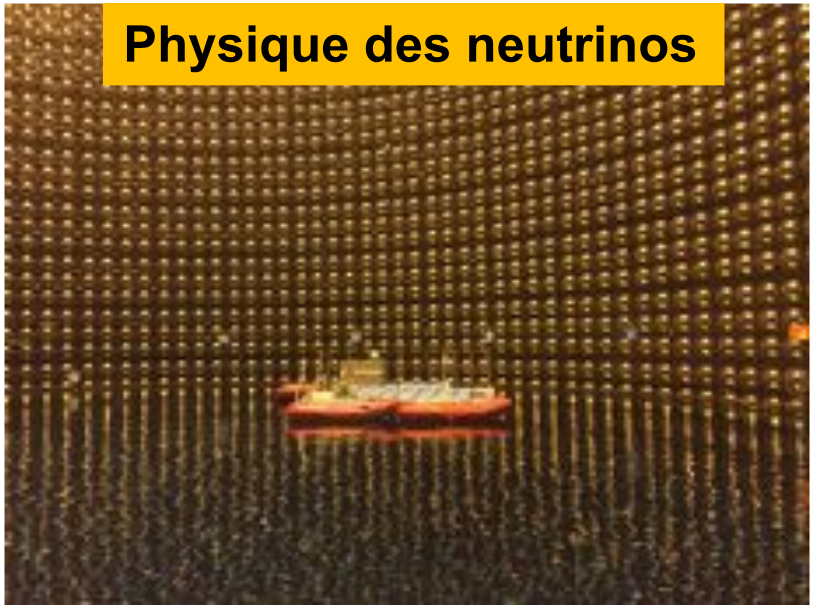
Accélération d’électrons par laser-plasma des expériences aux collisionneurs

Arnd Specka
Laboratoire Leprince-Ringuet, École polytechnique, Palaiseau

Laboratoire Leprince-Ringuet à l'Ecole polytechnique

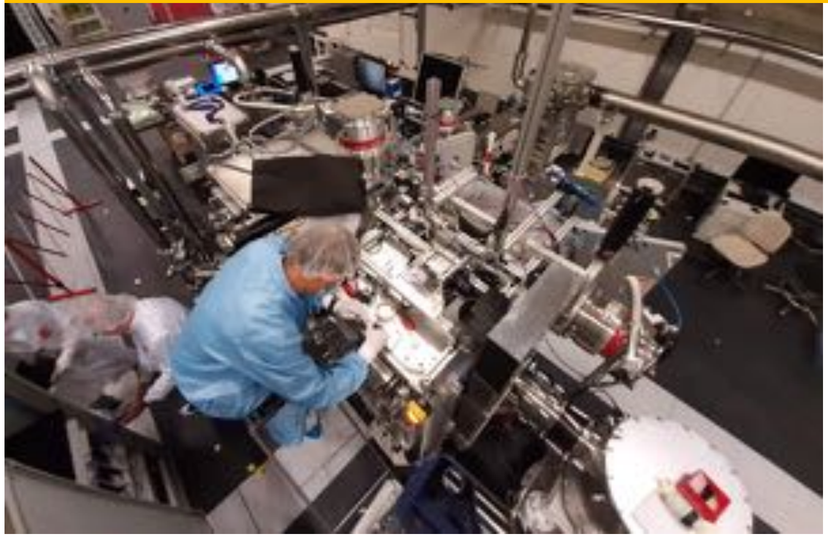
Physique auprès de collisionneurs

Physique des neutrinos



Astronomie gamma

Accélération & Interdisciplinaire



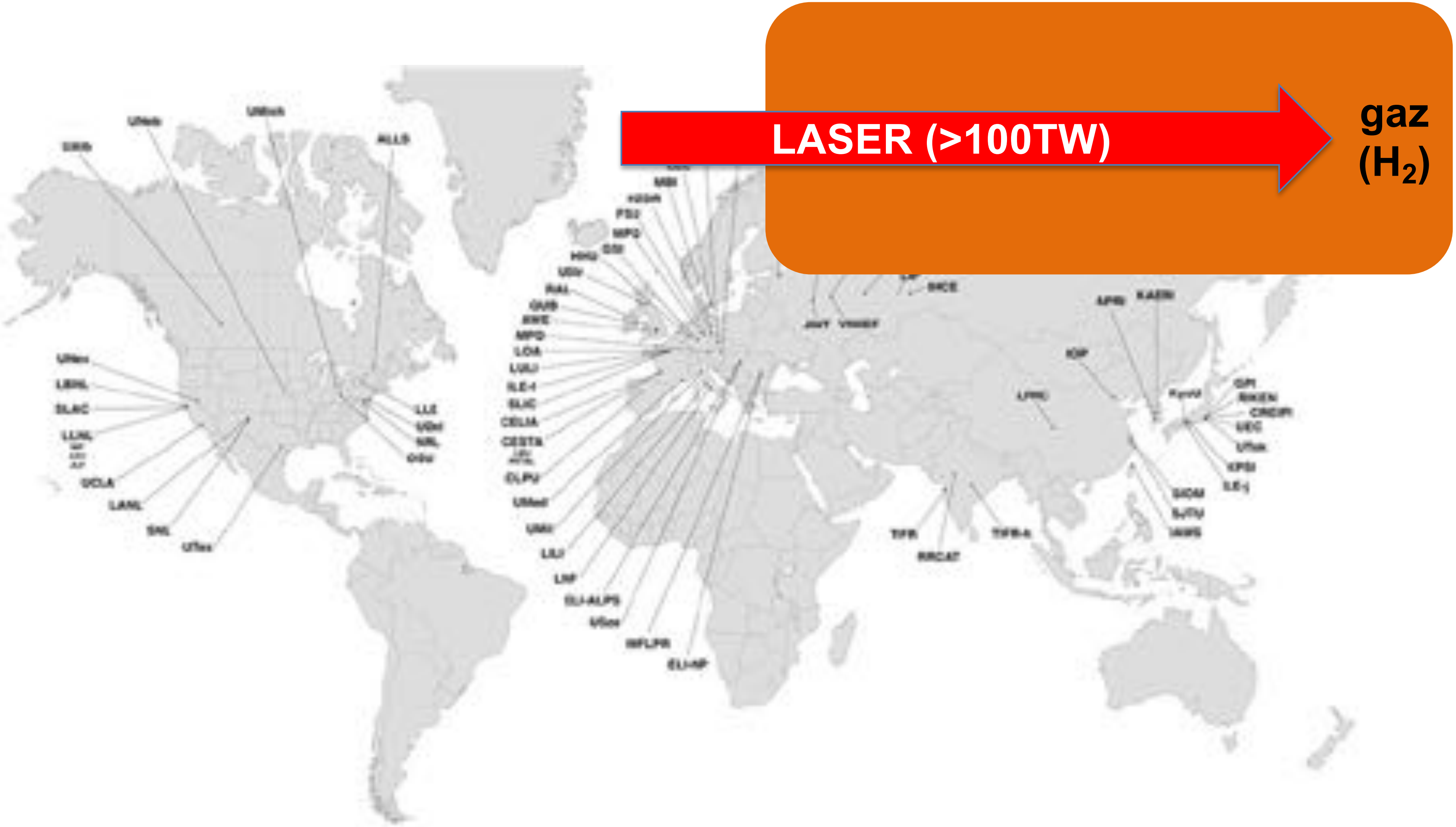
Remarques (pré)liminary remarks

- Des “manips” aux collisionneurs
  - **les bases**
  - **1ères expériences auprès d’APOLLON**
  - **vers les collisionneurs: développement récents (sélection)**
  - **perspectives d’avenir**

- Biais fort:
  - **application to high energy physics**
  - **perspective: European Strategy for Particle Physcis (CERN driven)**

Principe de l’Accélération par Laser et Plasma d’électrons (ALPe)

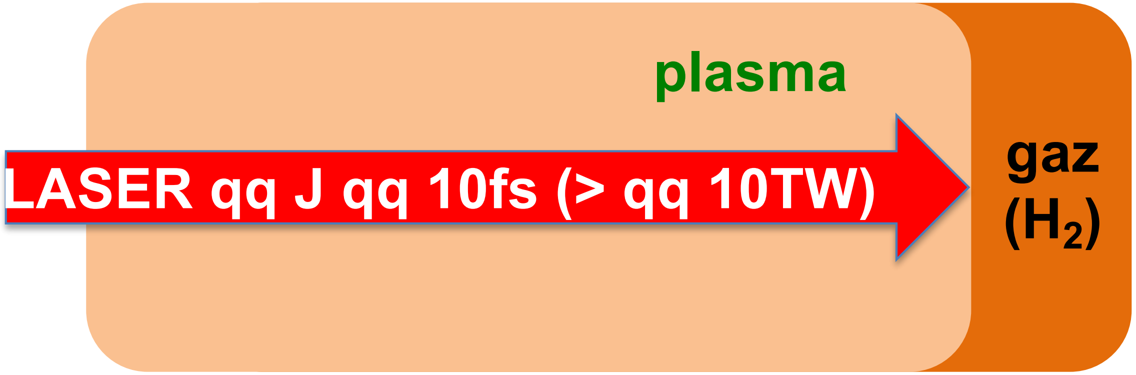
- Les experiences d’ALPe sont ”faciles” à réaliser (si on a un laser)
- La *Chirped Pulse Amplification* (CPA) a “démocratisé” l’ALPe



LASER (>100TW)

gaz
(H_2)

ALPe — étape 1/3: IONISATION

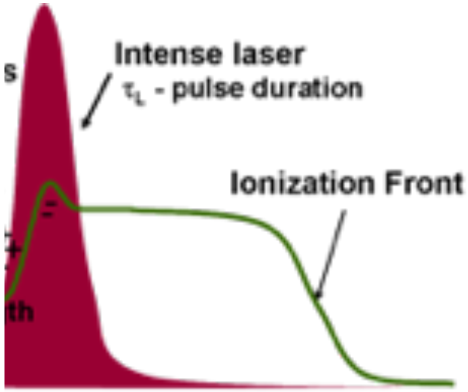


plasma

LASER qq J qq 10fs (> qq 10TW)

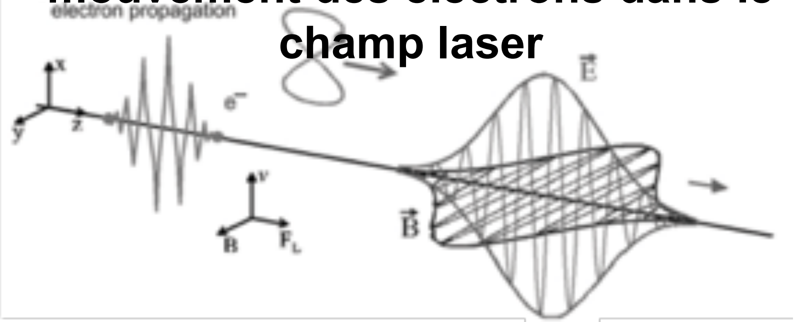
gaz (H_2)

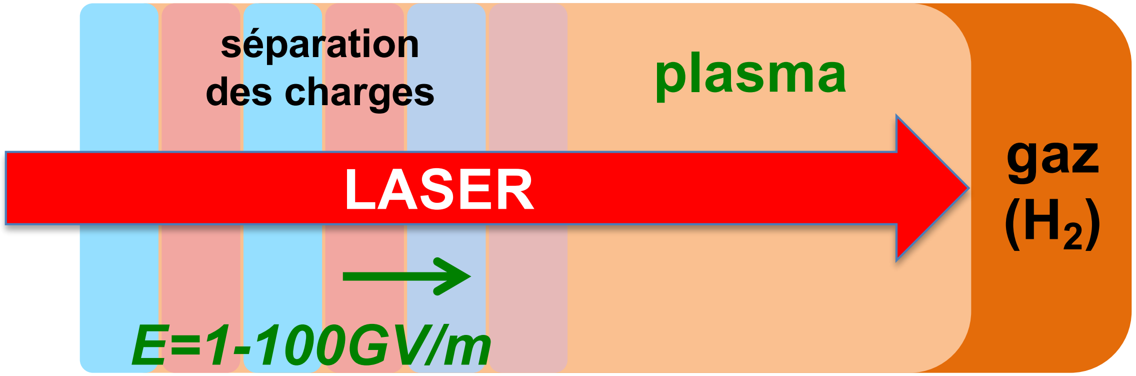
- laser de puissance à impulsion courtes: > ~20TW, 20-100fs, > 1 J
- En pratique: TiSaphire λ_0=0.8µm
- Focalisé à > 10^{18} W/cm2
- ionisation par effet de champ
- plasma sous-dense: $n_e = 10^{16}–10^{19}$ cm^{-3}



ALPe — étape 2/3 : CRÉATION DU CHAMP DE SILLAGE

mouvement des électrons dans le champ laser





séparation des charges

plasma

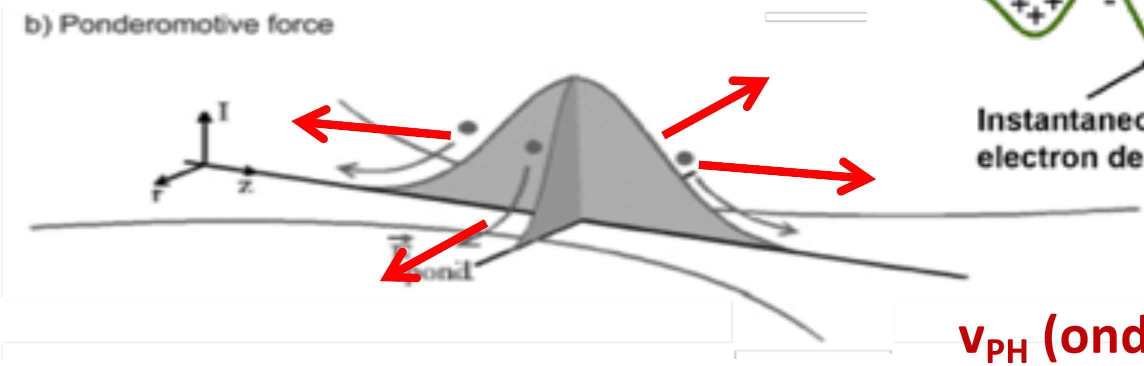
LASER

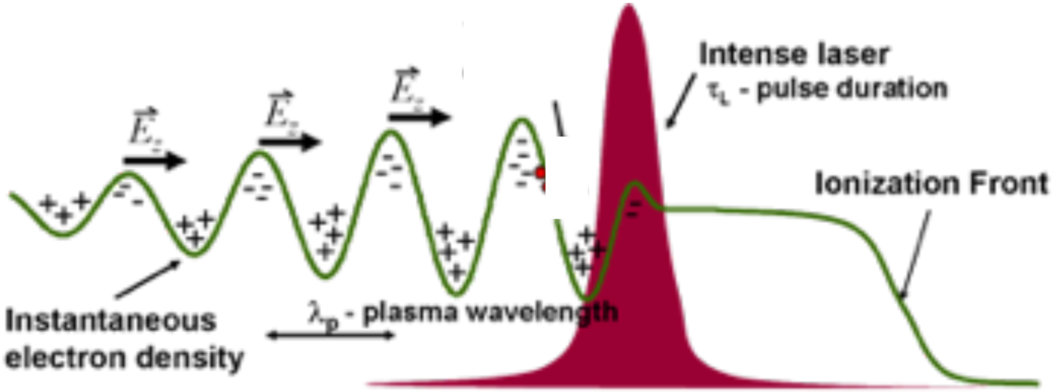
gaz (H_2)

E=1-100GV/m

force effective:

force pondéromotrice

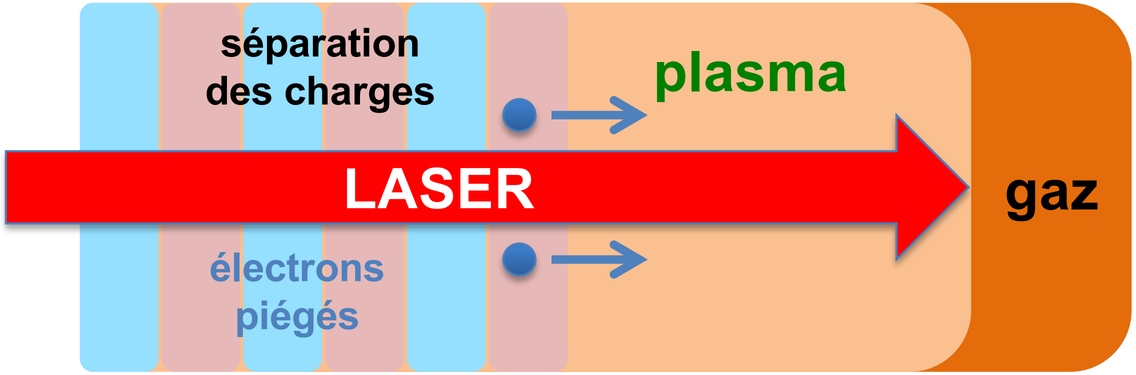




v_{PH} (onde) = v_G (laser) => onde relativiste

ALPe — étape 3/3 : Piégeage et accélération

- Piégage d’electrons du plasma ou d’électrons injectés (source ext.)
- Non-adapté pour l’acceleration de particules de *v<<c*



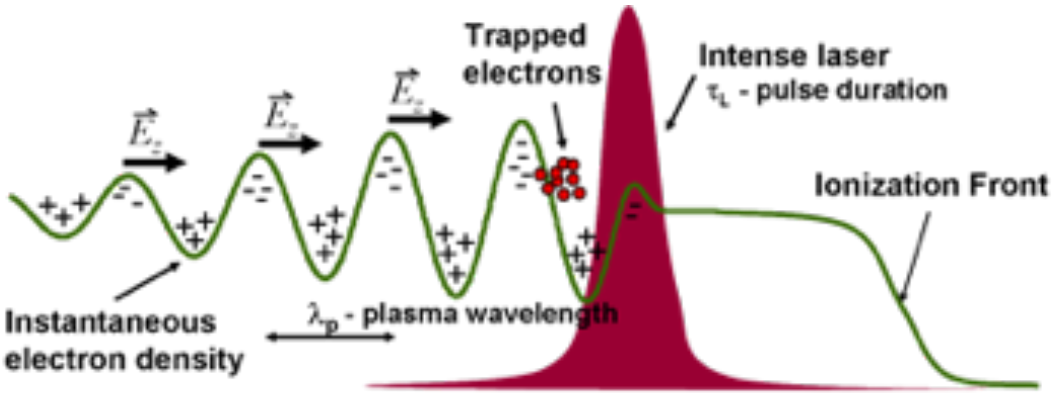
séparation des charges

plasma

LASER

gaz

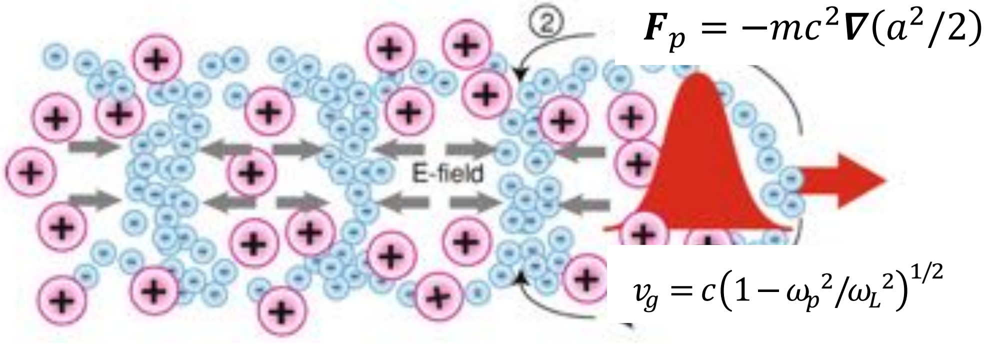
électrons piégés



Plasma wave driven by strong electric fields (1979,1985)

laser field (vector potential a)

T. Tajima & J.M. Dawson,Phys. Rev. Letter 43, 267 (1979)

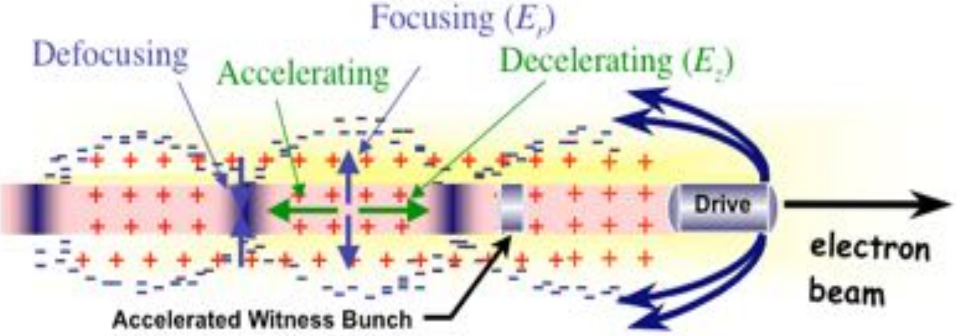


$$\boldsymbol{F}_p = -mc^2 \boldsymbol{\nabla}(a^2/2)$$

$$v_g = c\left(1 - \omega_p{}^2/\omega_L{}^2\right)^{1/2}$$

particle beam field

*P. Chen & J.M. Dawson,*AIP Conf Proc **130**, 201 (1985)



1-D linear theory: plasma wave = forced electron density oscillation

1-D linear approximation $\boldsymbol{a^2 \ll 1}$

$$\underbrace{\left(\frac{\partial^2}{\partial \xi^2} + k_p^2\right)\frac{\delta n}{n_0}}_{\text{plasma wave}} = \underbrace{\nabla^2 \frac{a^2(\xi)}{2}}_{\text{ponderomotive force}}$$

$$\xi = z - ct$$

"LWFA"

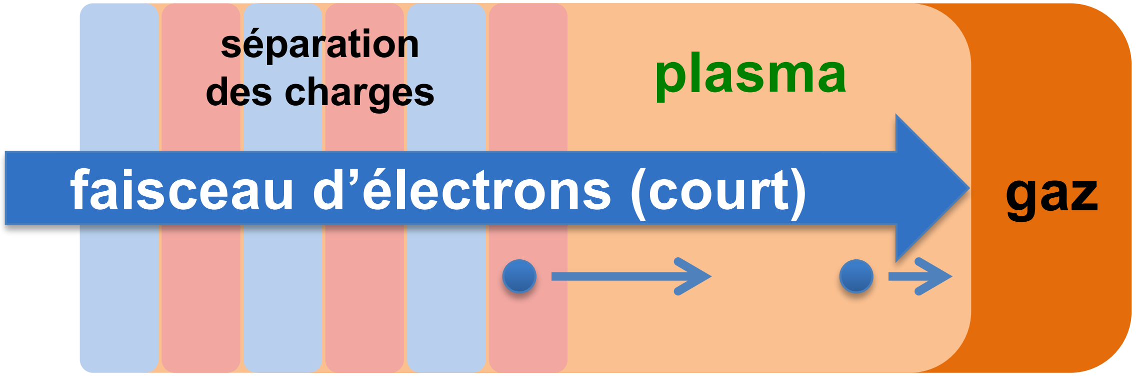
1-D linear approximation $\boldsymbol{n_b/n_0 \ll 1}$

$$\left(\frac{\partial^2}{\partial \xi^2} + k_p{}^2\right)\frac{\delta n}{n_0} = \underbrace{-k_p{}^2 \frac{n_b}{n_0}}_{\text{space charge force}}$$

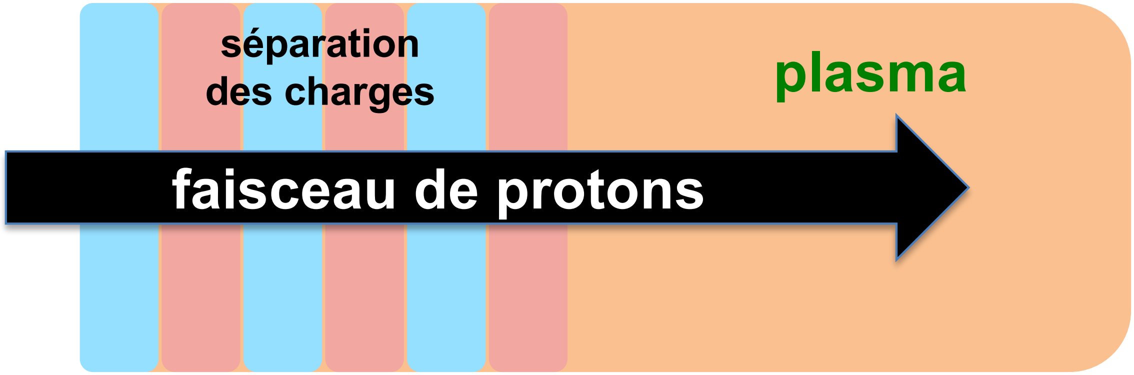
"PWFA"

Création du champ de sillage par d'autres «moteurs» (*drivers*)

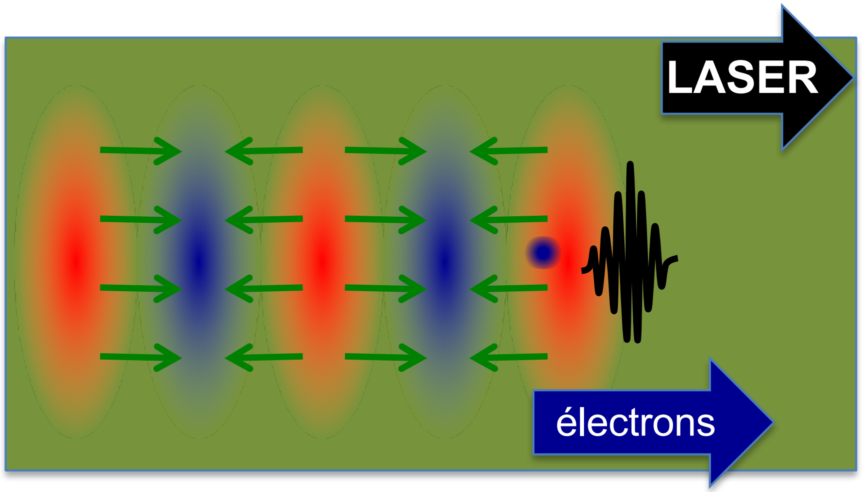
- FACET (SLAC, USA)
- FLASHForward (DESY, D)
- SPARCLab (Frascati, I)

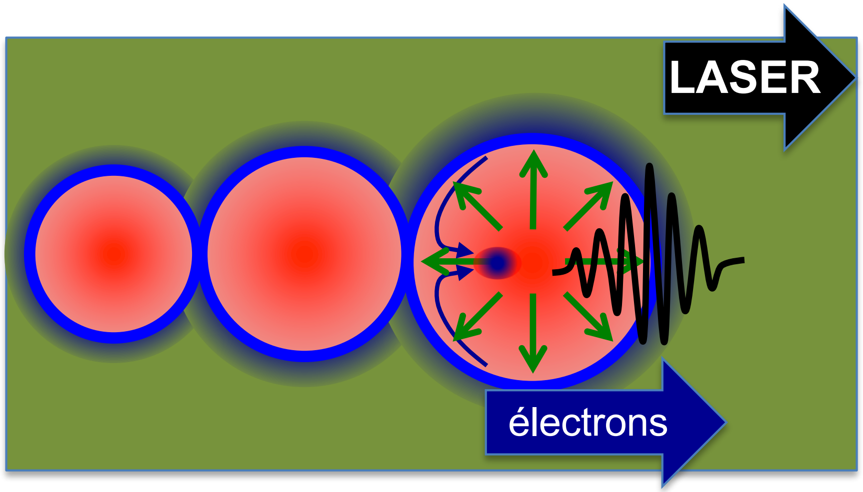


- AWAKE (CERN, CH)



régime non-linéaire v/s régime quasi-linéaire





régime quasi-linéaire *($a_0<1$)*

- ☐ onde plasma longitudinale
- ☐ injection externe
- ☐ peu de auto-focalisation relativiste
- ☐ faibles densités, impulsion O(100fs)

τ : >100 fs

I_0 : 10^{16}-10^{18} Wcm^{-2}

n_e : 10^{16}-10^{17} cm^{-3}

régime non-linéaire (ou de la bulle) *($1<a_0<$''5'')*

- ☐ champ électrique de sillage **central**
- ☐ Forte auto-focalisation
- ☐ forte densités, impulsion O(10fs)

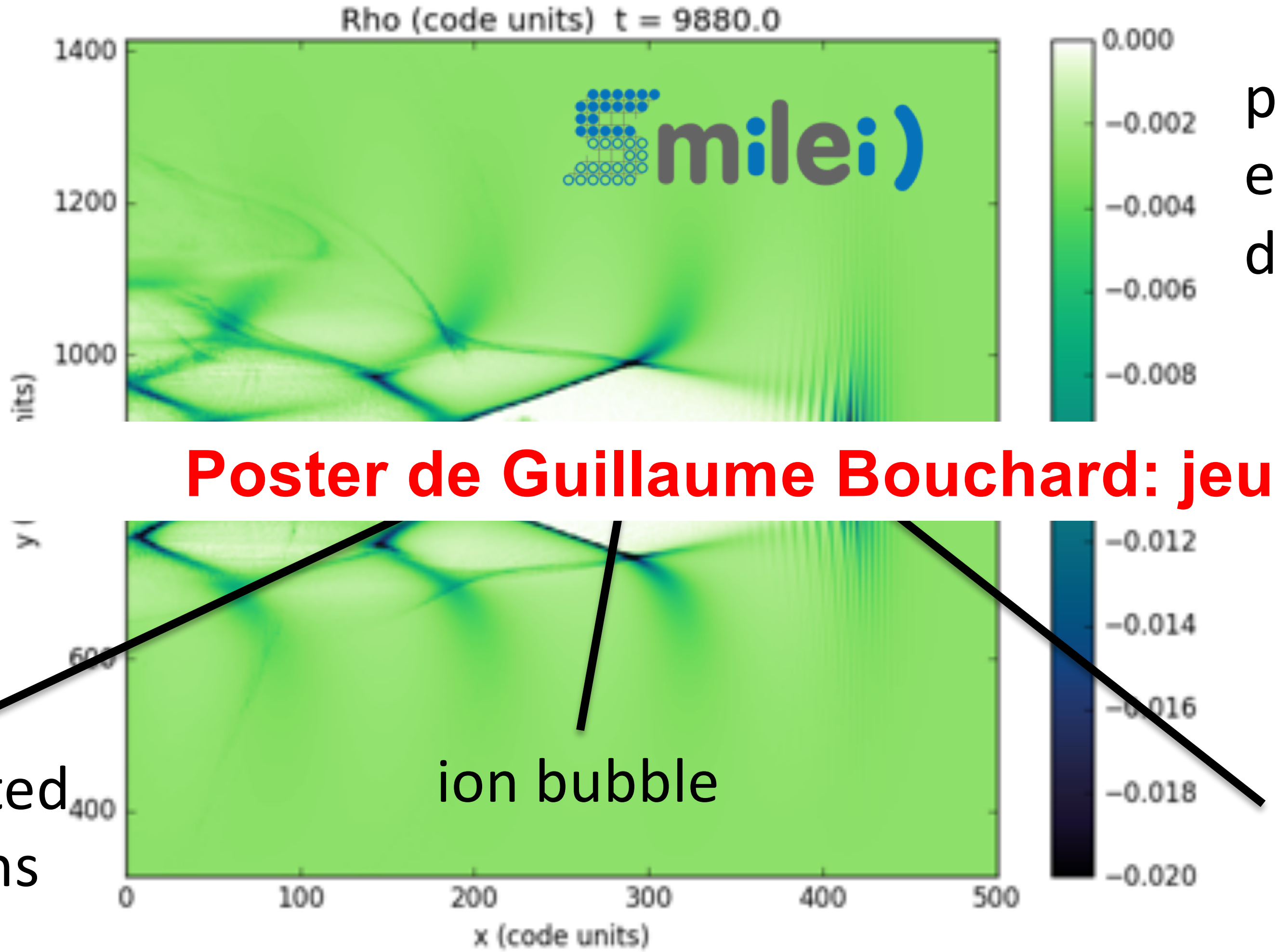
τ : 10 fs –100 fs

I_0 : 10^{18}-10^{20} Wcm^{-2}

n_e : 10^{18}-10^{19} cm^{-3}

Simulation d'ALPe dans le régime de la bulle (blowout)

J. Derouillat et al., Comput. Phys. Commun. 222, 351-373 (2018)



Poster de Guillaume Bouchard: jeudi

plasma electron density

accelerated electrons

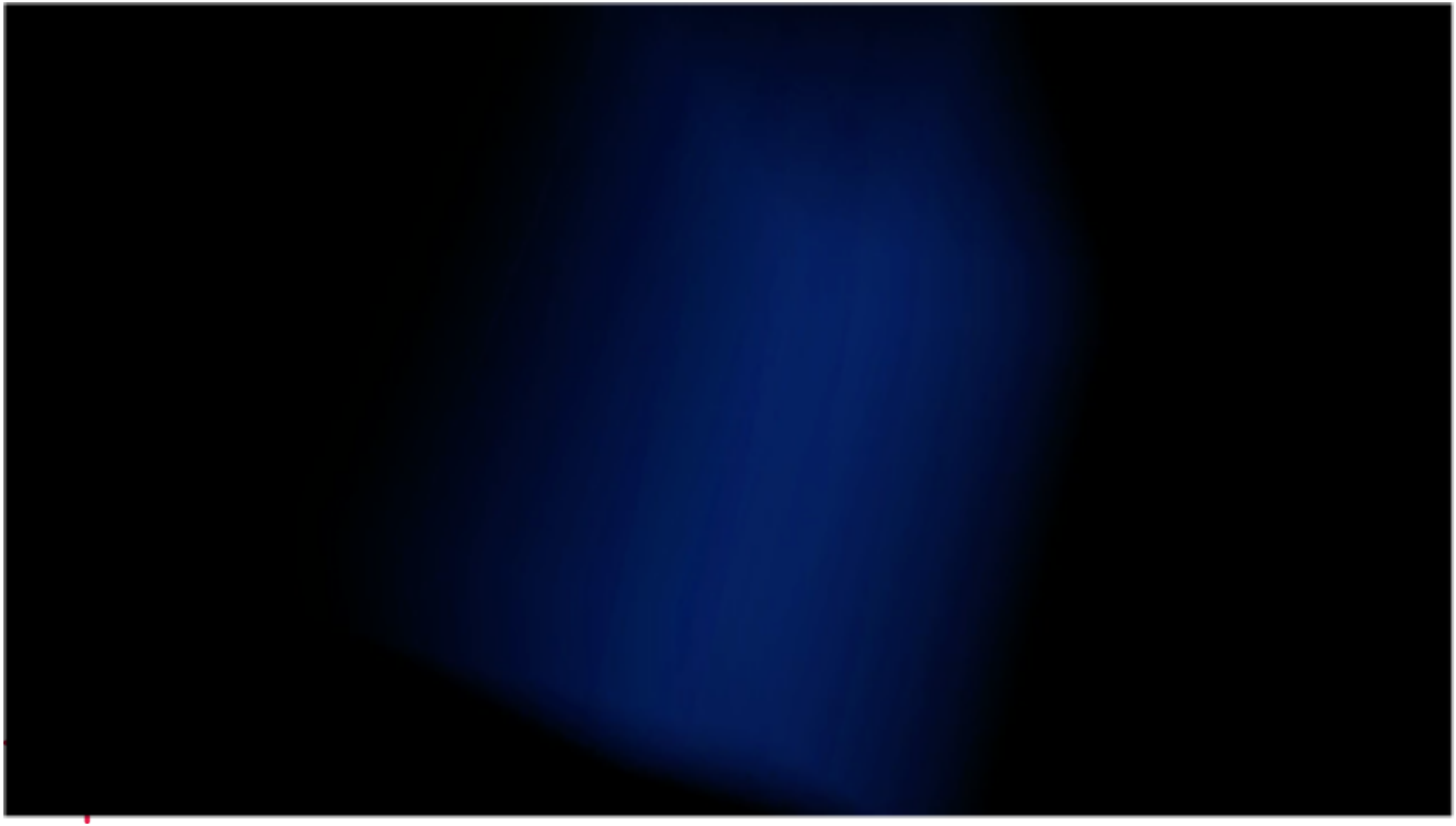
ion bubble

femtosecond laser pulse

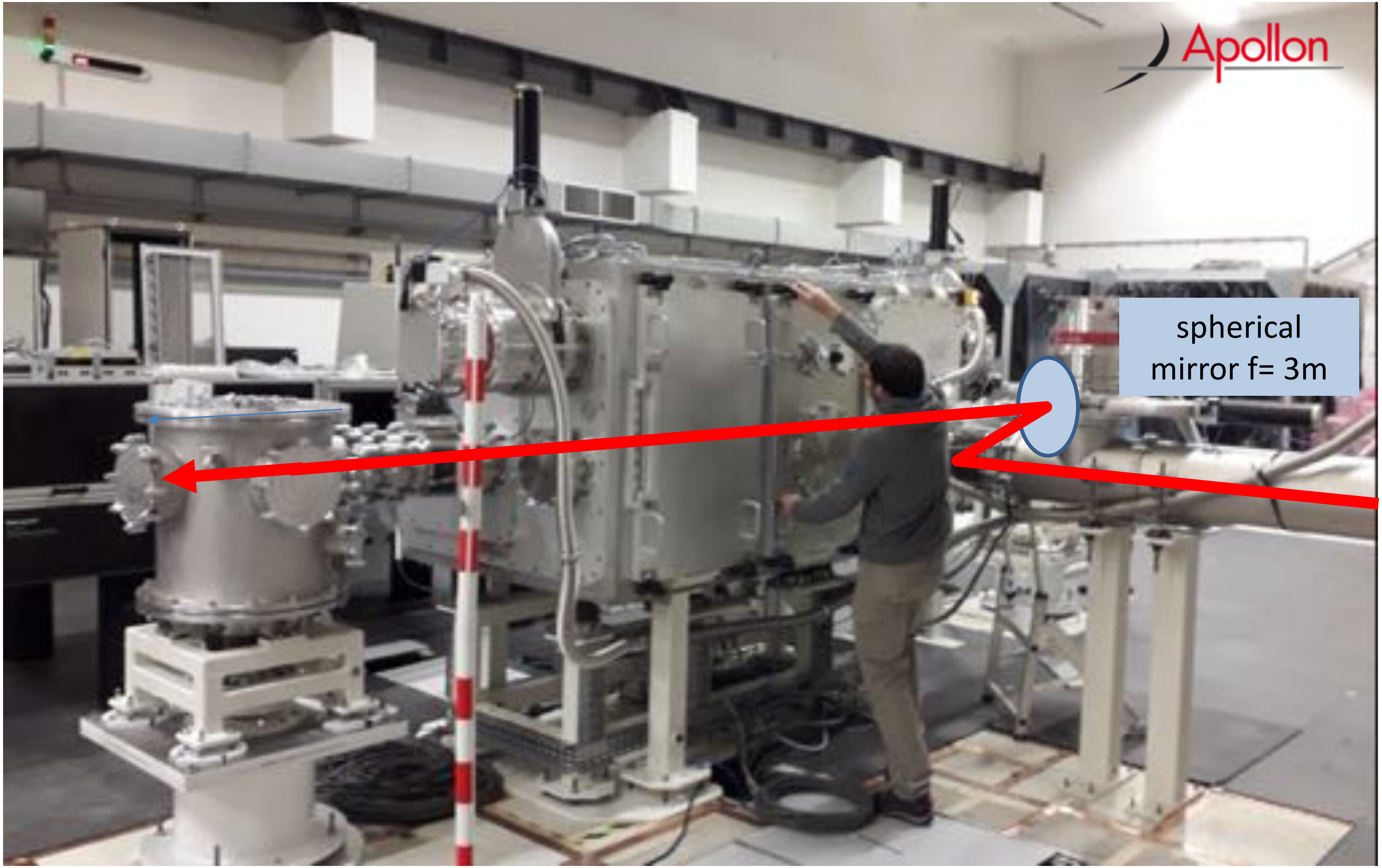
laser propagation direction

3D pic simulation d’ALPe dans le régime de la bulle (blowout)

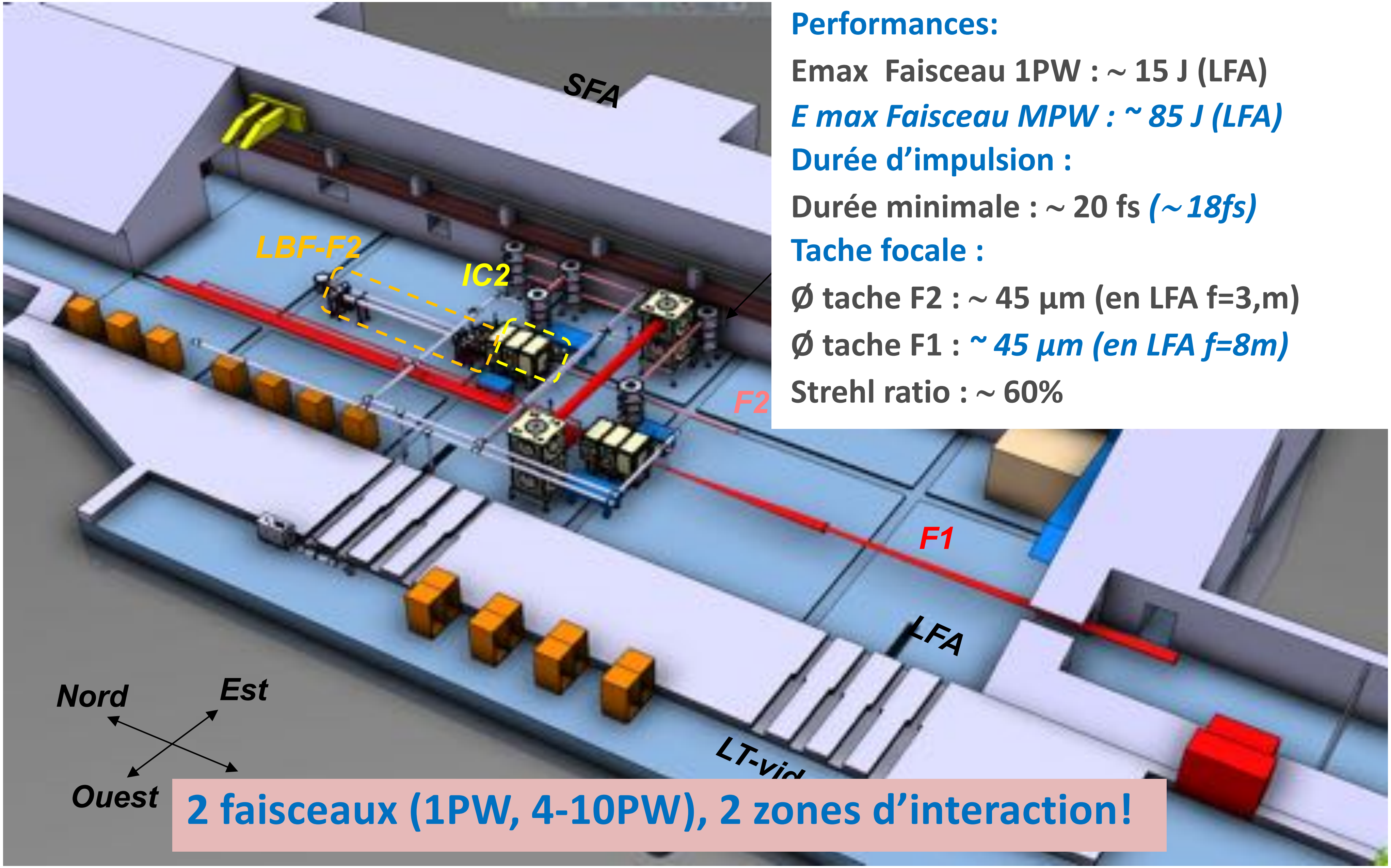
https://www.youtube.com/watch?v=-LX_yT29nAU



Expériences d'acceleration laser plasma d'électrons: un exemple



APOLLON laser: Long Focal Area (LFA) electrons et gammas



Performances:

Emax Faisceau 1PW : ~ 15 J (LFA)

E max Faisceau MPW : ~ 85 J (LFA)

Durée d'impulsion :

Durée minimale : ~ 20 fs *(~18fs)*

Tache focale :

Ø tache F2 : ~ 45 µm (en LFA f=3,m)

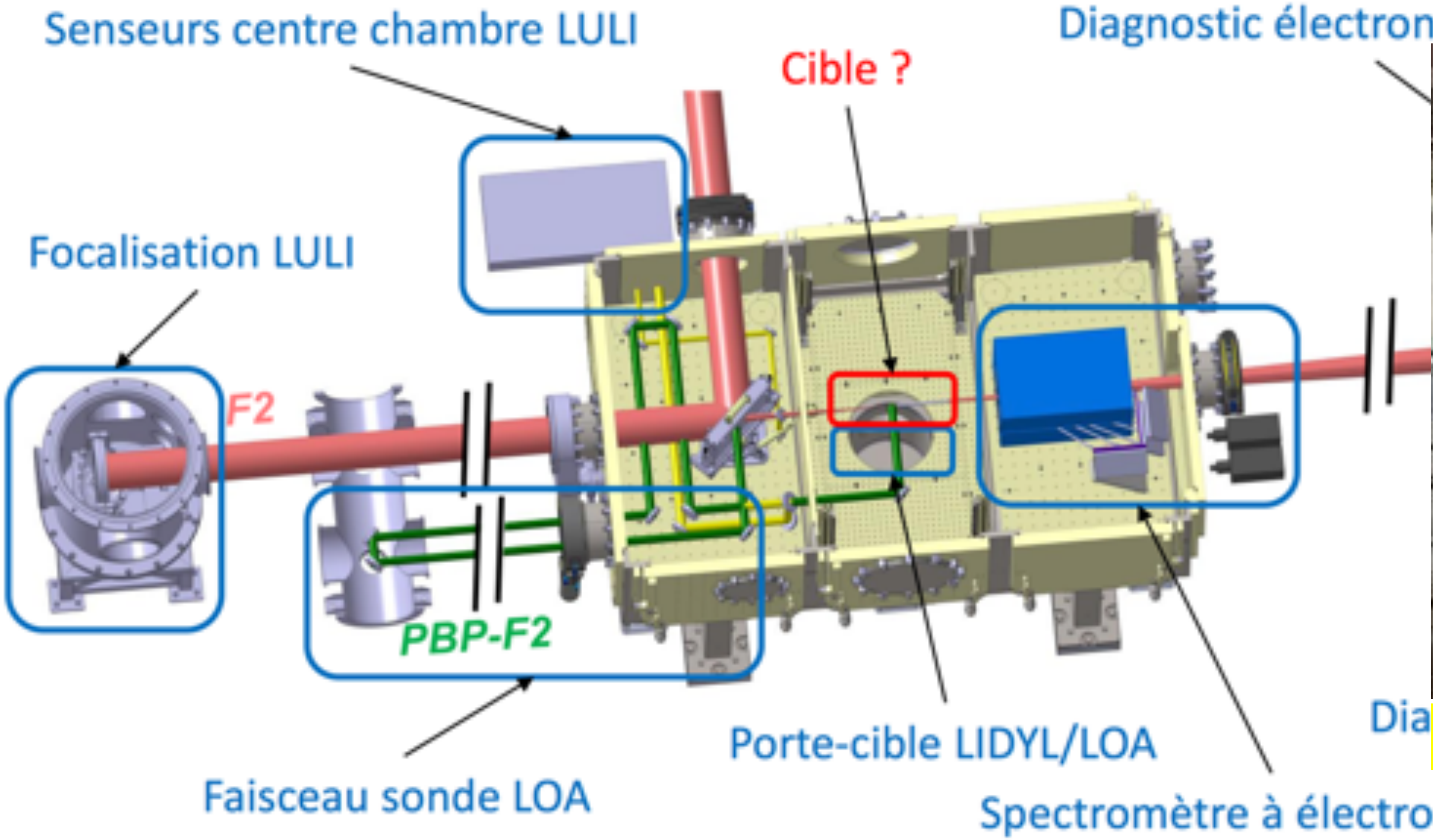
Ø tache F1 : *~ 45 µm (en LFA f=8m)*

Strehl ratio : ~ 60%

2 faisceaux (1PW, 4-10PW), 2 zones d'interaction!

1ère campagne *commissioning* sur APOLLON Nov 2020

- LLR-LOA-LIDYL-LULI
- Laser: Focale = 3m (F/20) , E<12J, 22fs,
- Plasma: gaz jet 5mm et 10mm He+ 2%N_2


Senseurs centre chambre LULI

Cible ?

Diagnostic électrons c

Focalisation LULI

Faisceau sonde LOA

Porte-cible LIDYL/LOA

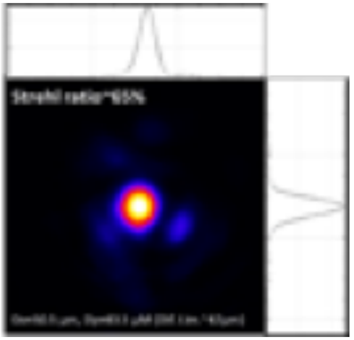
Dia

Spectromètre à électrons


Dipôle et détecteurs sous vide

1ère campagne sur APOLLON en LFA: Observations

- ~800 tirs à 1 par minute (>50% at 12J sur cible) (5 jours utiles)
- Laser: Montée progressive de 6 à 12J, 22 fs, « Strehl » ~60% sur cible
- Observation d'électrons accélérés en régime NL presque immédiat! Sur détecteur large bande (air), et basse et haute E (vide)



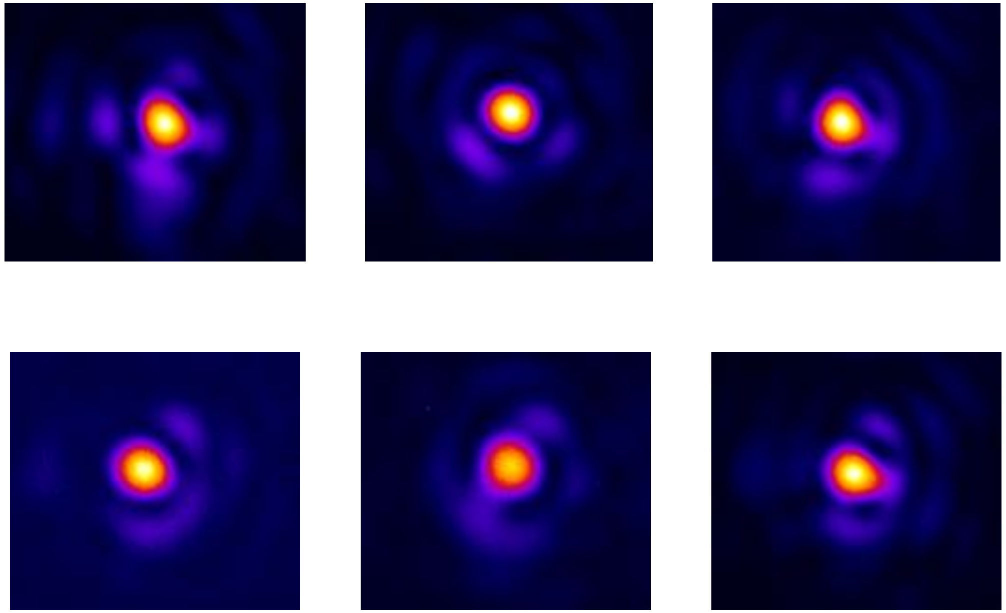
Laser spot on target

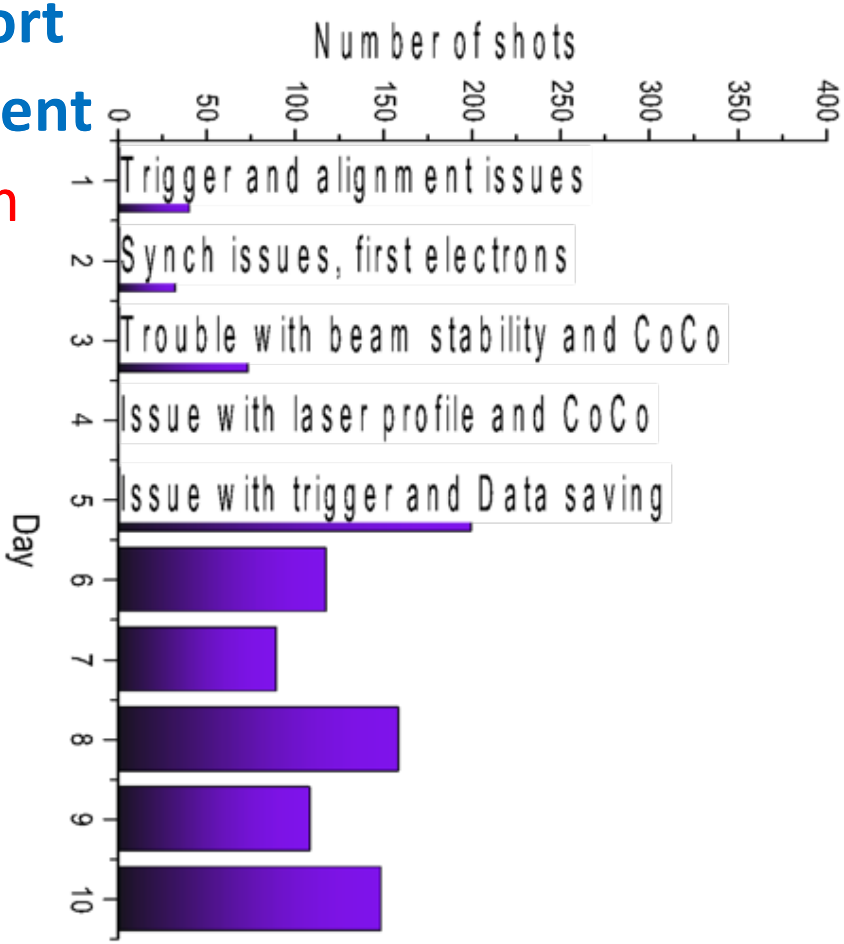
- ΔE large, E fluctuant, angle du faisceau, oscillations
- Exemple de spectre sur le dét. sous vide. écran YAG haute E (0.5-1.5GeV): ~950MeV sur <10mm (fréquemment)

- Identification et résolution de nombreux problèmes techniques: alignement, synchronisation, protection EMP, motorisation, DAQ et ControleComm, cohabitation, modifications "à la volée", radioprotection, diagnostics laser tir à tir

2ème campagne *commissioning* sur APOLLON Avril 2021

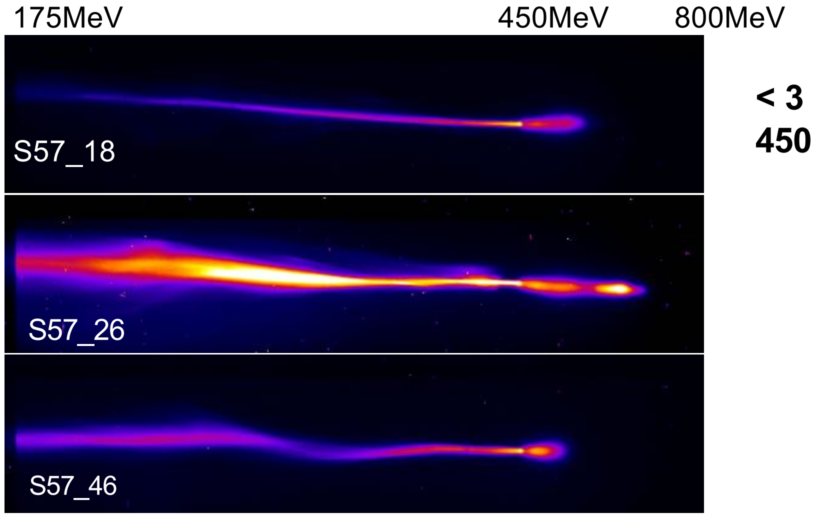
- LPGP-LIDYL-LLR-IJCLAB-LULI
- Laser: Focale = 3m (F/20) , E4.5J, ~22fs,
- Plasma: cellule de gaz 2-20mm He+2%N_2
- **Aimant spectrometre d'électron plus fort**
- **E_{LASER} *ON TARGET* monitoré régulièrement**
- Challenge: injecter laser dans Ø 400 µm





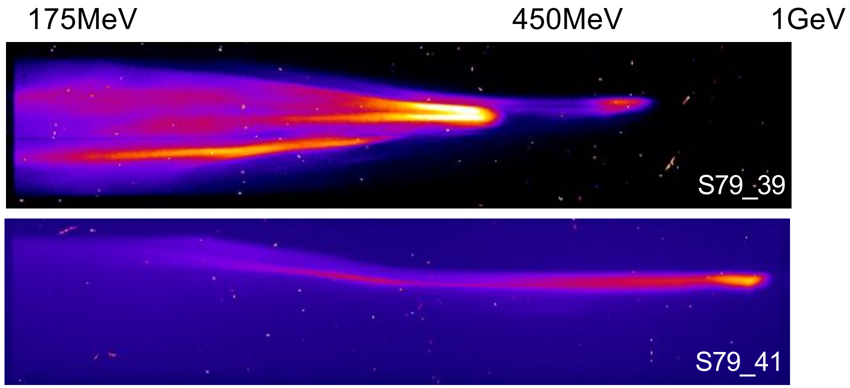
2ème APOLLON e^-Campaign preliminary results (analysis on going)

26/04 Spectra in 6mm long gas cell



< 3 mrad at 450 MeV

30/04 Spectra in 13 mm long gas cell



Electron spectra observed in detection windows:

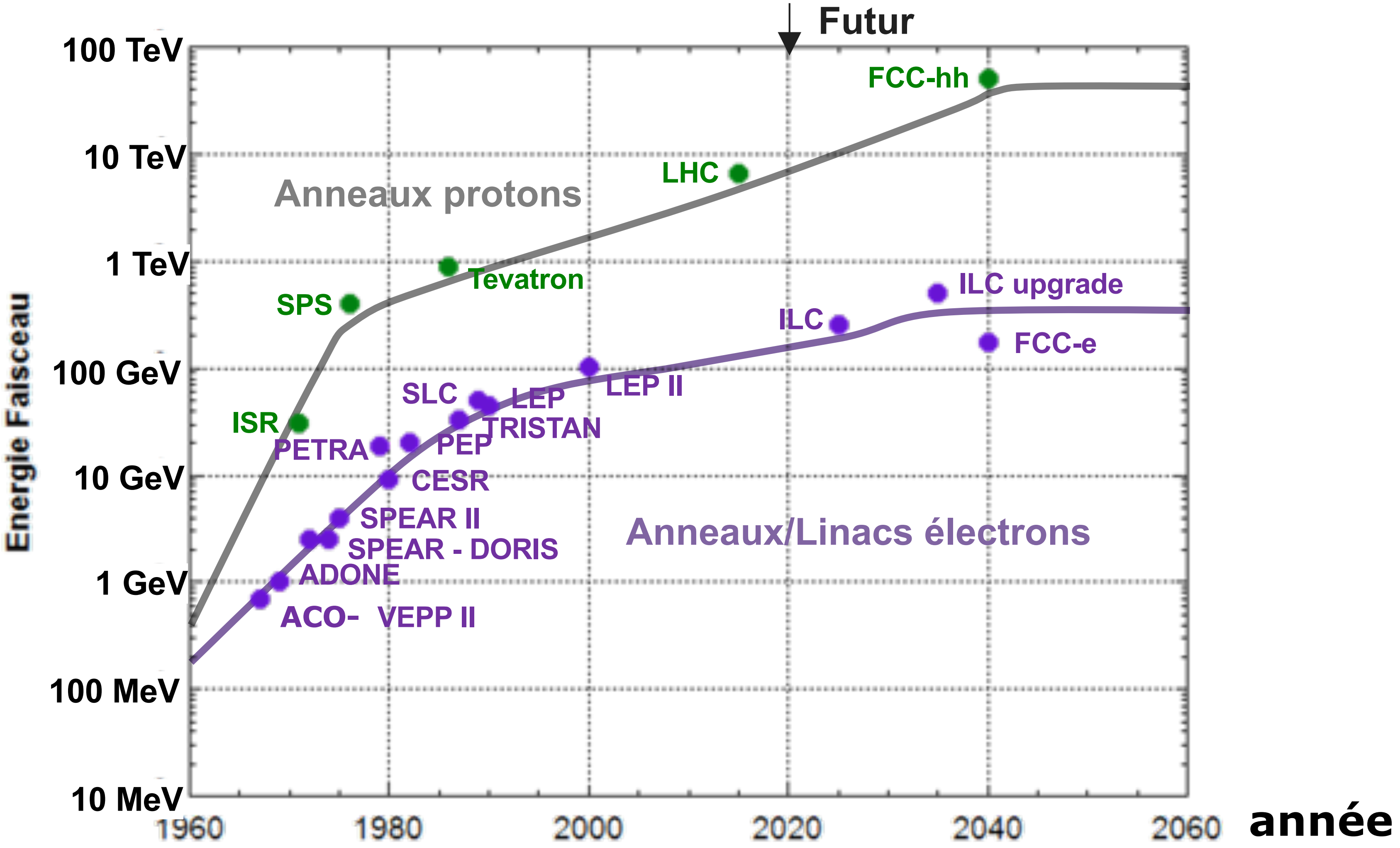
- **175 MeV – 750MeV (LANEX out vac)**
- **450 MeV – 1.6 GeV (YAG in vac.)**

Observed energy range and distribution in agreement with predictions, from simulations performed with focal spot measured in Nov. 2020 as input

Larger shot to shot instability on the 30th of April, link to measured focal spot quality will be studied in future simulations

Voir aussi: Présentation de Gilles Maynard

Motivation: Evolution de l'énergie c.m. des collisionneurs e^+/e^- et p/p



- croissance en énergie ➔machines de plus en plus grandes
- longueur des LINACs déterminée par le gradient accélérateur

Energie d'un accélérateur linéaire

$$W = q \times E \times L$$

énergie finale

charge de la particule

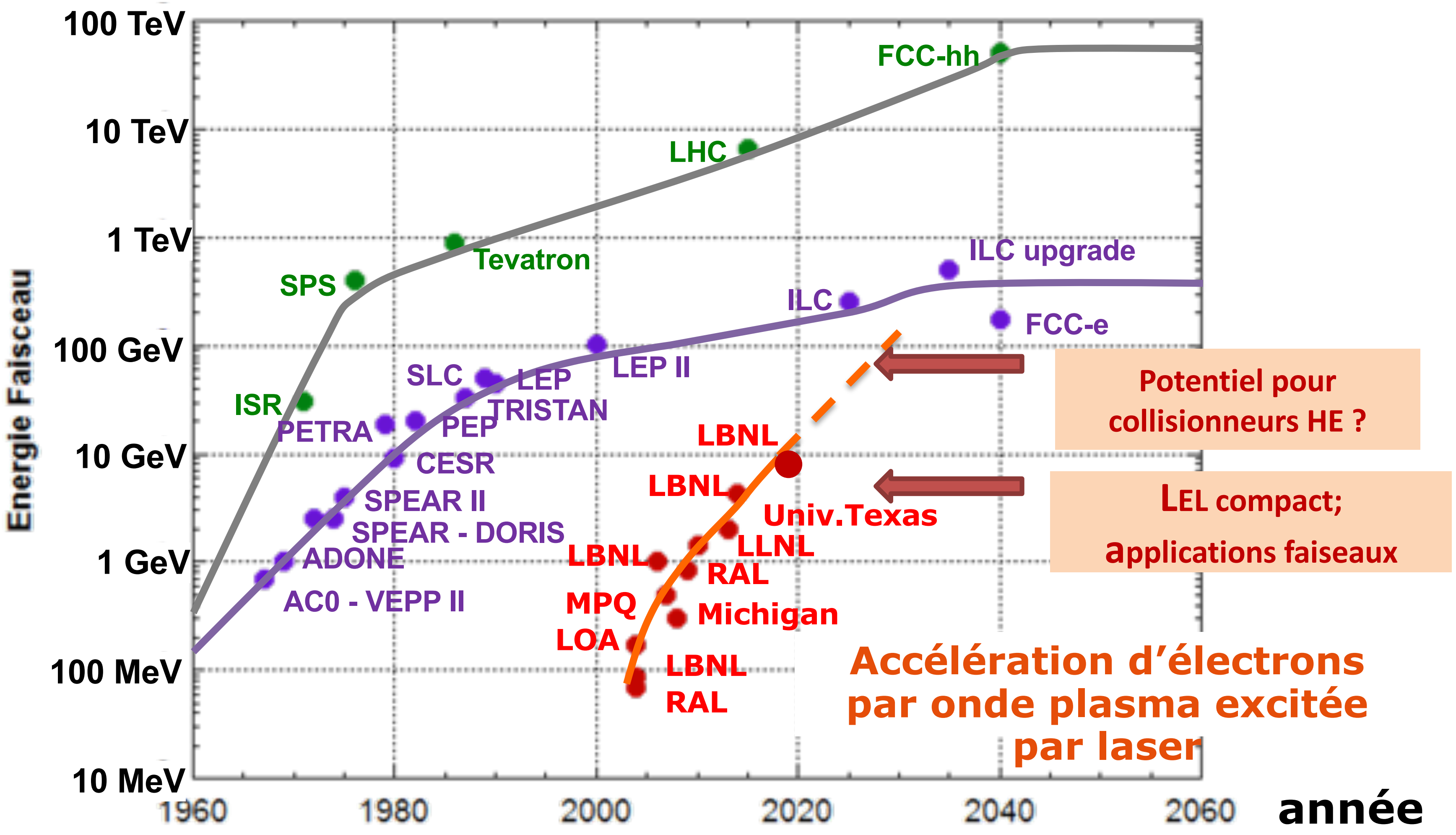
champ électrique accélérateur

longueur d'accélération

augmenter *W* à *L* constant: augmenter *E*

diminuer *L* à *W* constant: augmenter *E*

Evolution des énergies obtenues en accélération laser-plasma



Potentiel pour collisionneurs HE ?

LEL compact; applications faisceaux

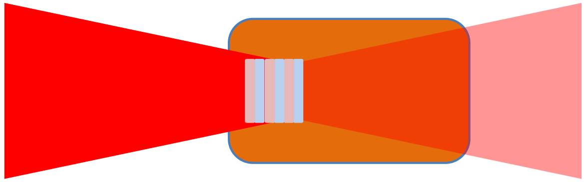
Accélération d'électrons par onde plasma excitée par laser

- gradients en ALP 10 à 1000 fois supérieurs aux LINAC RF
- évolution des énergies maximales plus rapide

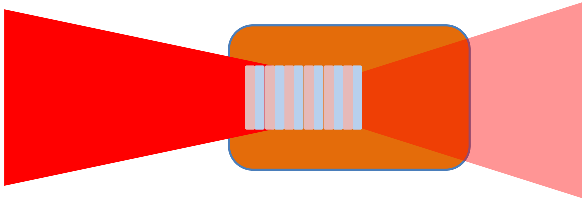
$$W = q \times E \times L$$

La longueur d’accélération : guidage du laser

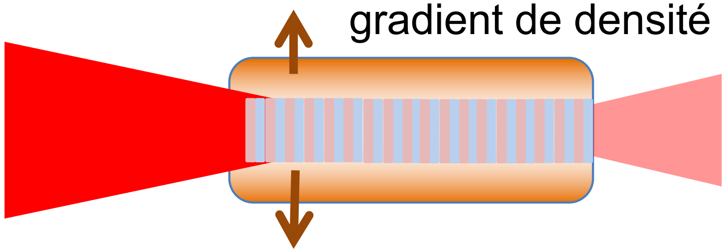
- laser focalisé diverge après le foyer après quelques mm ! -> **limitant!**



- auto-focalisation relativiste du laser dans un plasma augmente la longueur (et aide à l’autoinjection



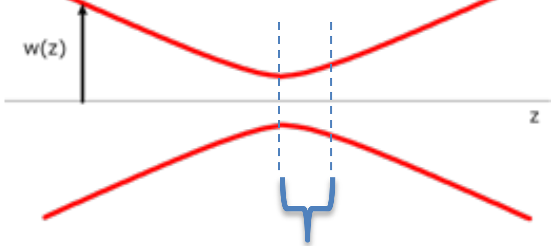
- guidage par modulation transversale de n_e *par exemple* : décharge électrique dans un capillaire, éventuellement assiste par chauffage laser



Guidage du laser dans un canal plasma

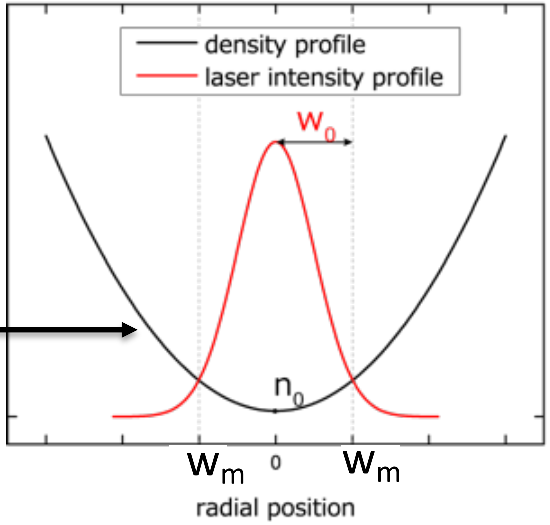
Waveguide can mitigate diffraction to increase acceleration length and beam energy

Vacuum propagation



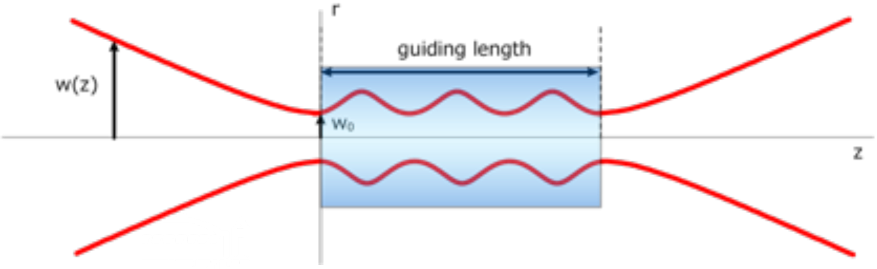
Density profile for guiding

$$n(r) = n_0 + \frac{r^2}{\pi r_e {w_m}^4}$$

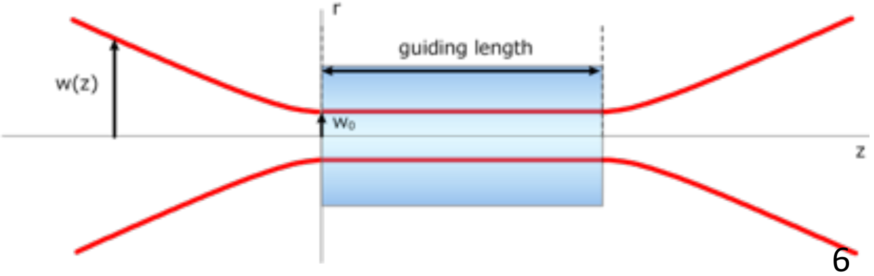


BELLA Z_R≈1cm
Guiding over 10s cm required to maximize beam energy

Mismatched guiding ($w_m > w_0$)



Matched guiding ($w_m = w_0$)



Slide courtesy of A.Gonsalves

Accélération laser-plasma d'électrons : limitations

- **Diffraction du laser: longueur de Rayleigh**
  - **remède: (auto-focalisation), guidage par capillaire, décharge**
- **Déphasage du paquet et de l'onde plasma ($\gamma_{el.} > \gamma_{onde}$)**

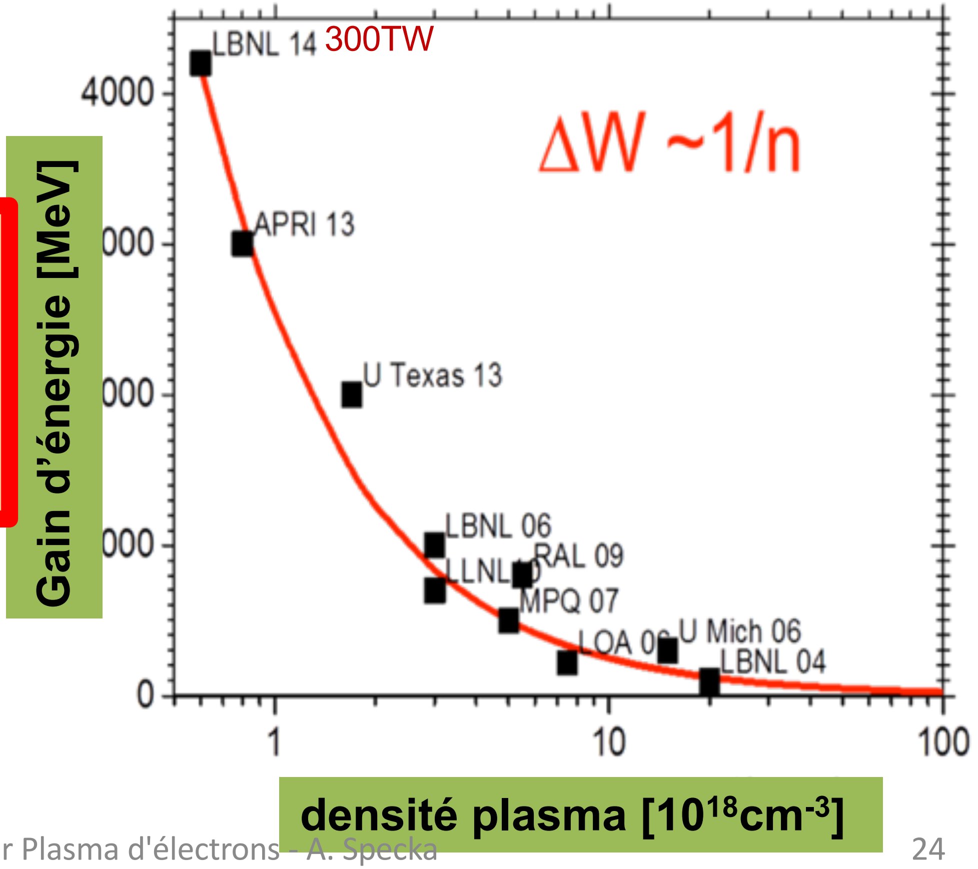
$$L_{max} \propto {n_0}^{-3/2}$$

  - **remède : rampe de densité d'électrons décroissante, multi-étage**
- **Epuisement du laser (*depletion*)**

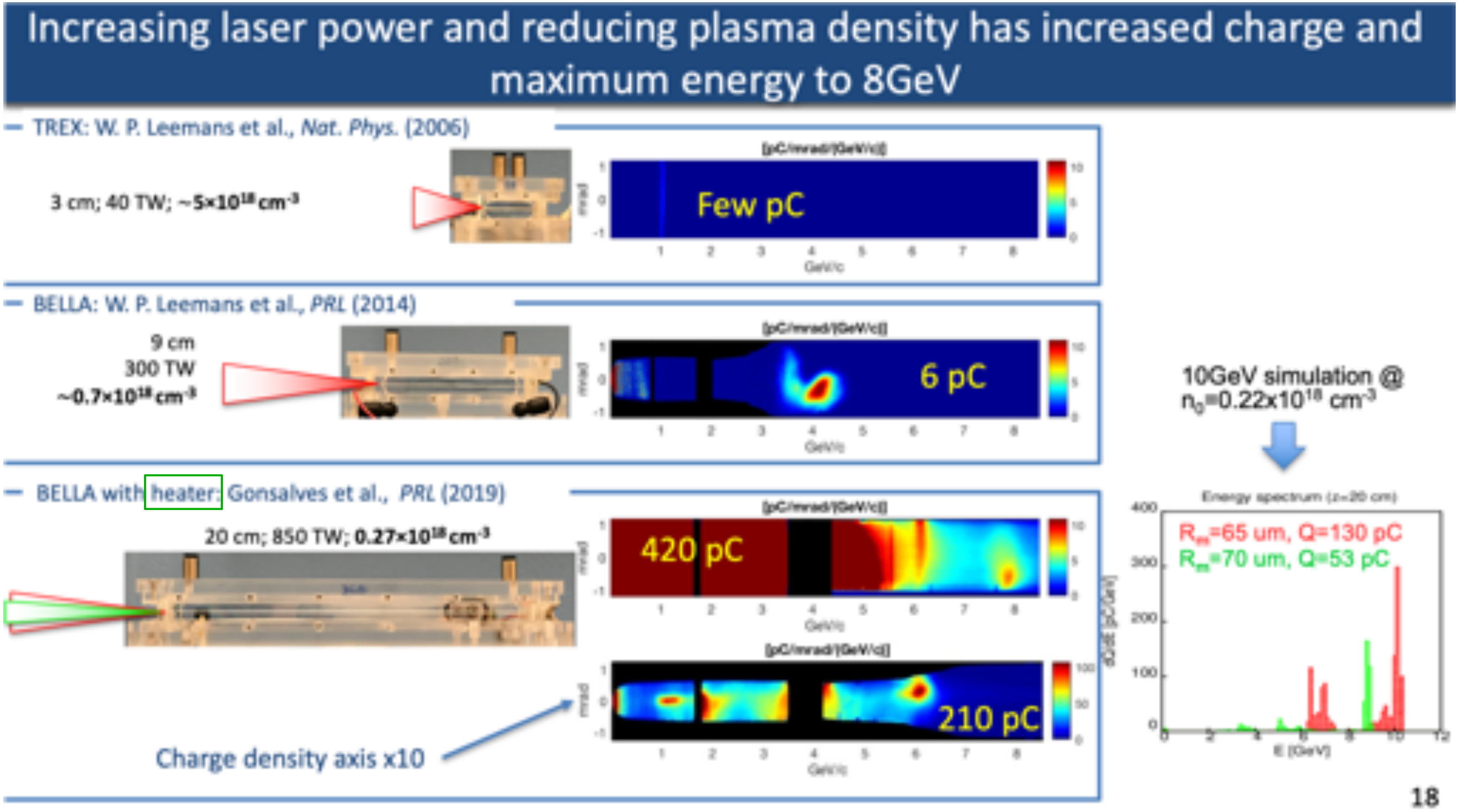
$$L_{deplete} \propto {\lambda_p}^3/{\lambda_L}^2 \propto {n_0}^{-3/2}$$

- **gradient acc.:** $G \sim E_0 = mc\omega_p/e \propto \sqrt{n_0}$
- **gain d'énergie:** $\boldsymbol{W = G \times L_{acc} \propto 1/n_0}$
- **puissance crête laser:** $\boldsymbol{P_{laser} \propto 1/n_0}$

augmenter le gain d'énergie (par étage)
=> baisser la densité plasma
et augmenter la puissance laser



Augmentation de l'énergie et de la charge par guidage du laser



Increasing laser power and reducing plasma density has increased charge and maximum energy to 8GeV

- TREX: W. P. Leemans et al., *Nat. Phys.* (2006)

3 cm; 40 TW; ~5×10^{18} cm^{-3}

- BELLA: W. P. Leemans et al., *PRL* (2014)

9 cm
300 TW
~0.7×10^{18} cm^{-3}

- BELLA with heater: Gonsalves et al., *PRL* (2019)

20 cm; 850 TW; 0.27×10^{18} cm^{-3}

Charge density axis x10

10GeV simulation @ n_0=0.22×10^{18} cm^{-3}

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Gonsalves A. et al., Phys. Rev. Lett. 122, 084801 (2019)

Slide courtesy of A.Gonsalves

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  - **remède : rampe de densité d'électrons décroissante, multi-étage**
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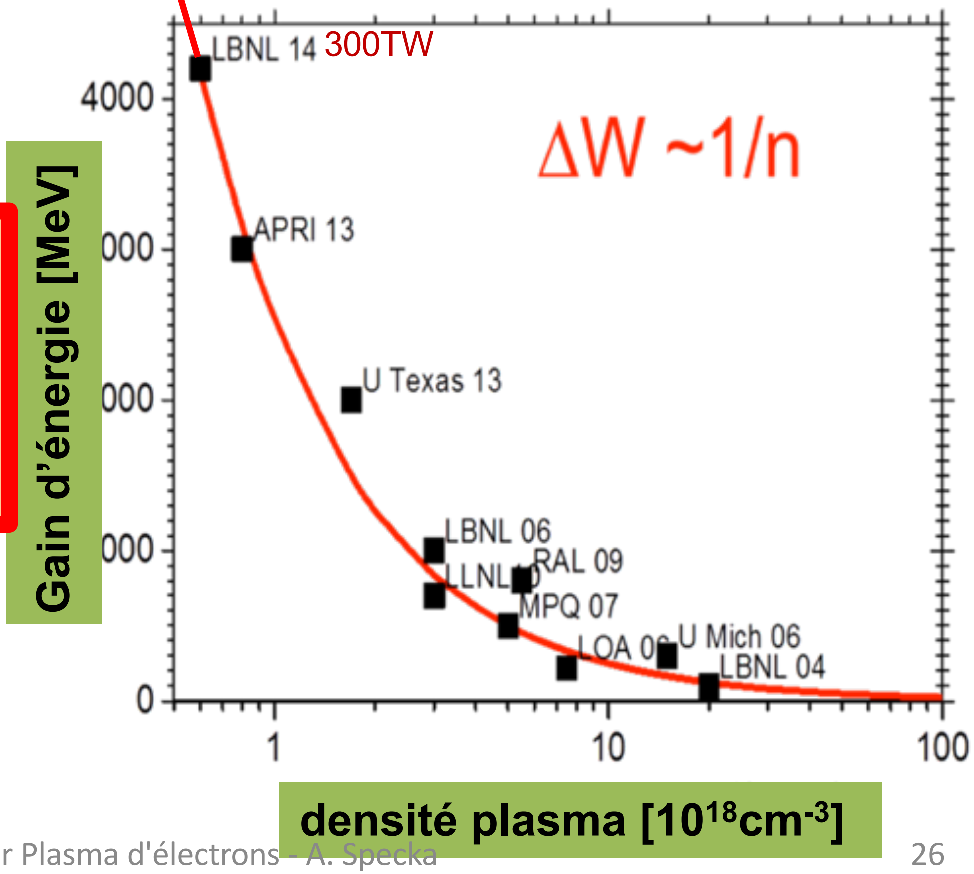
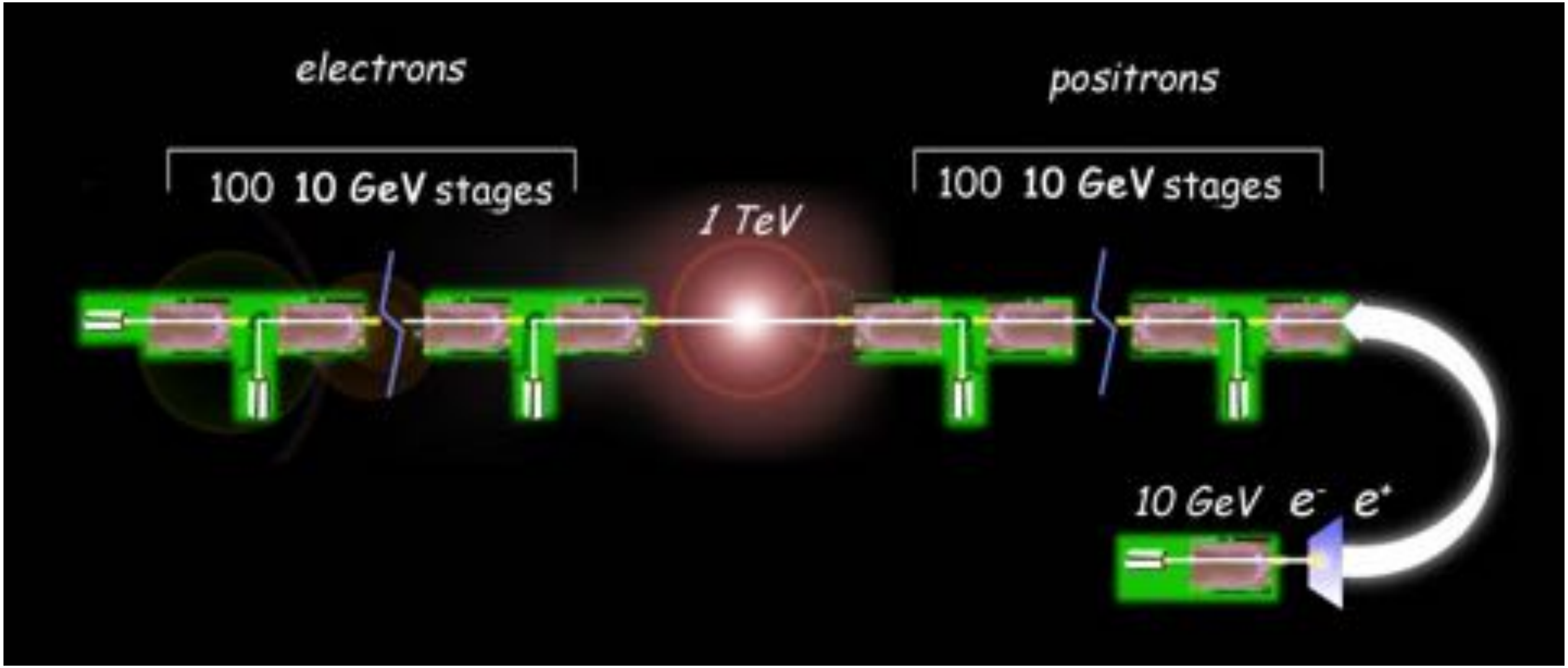
augmenter le gain d'énergie (par étage)
=> baisser la densité plasma
et augmenter la puissance laser



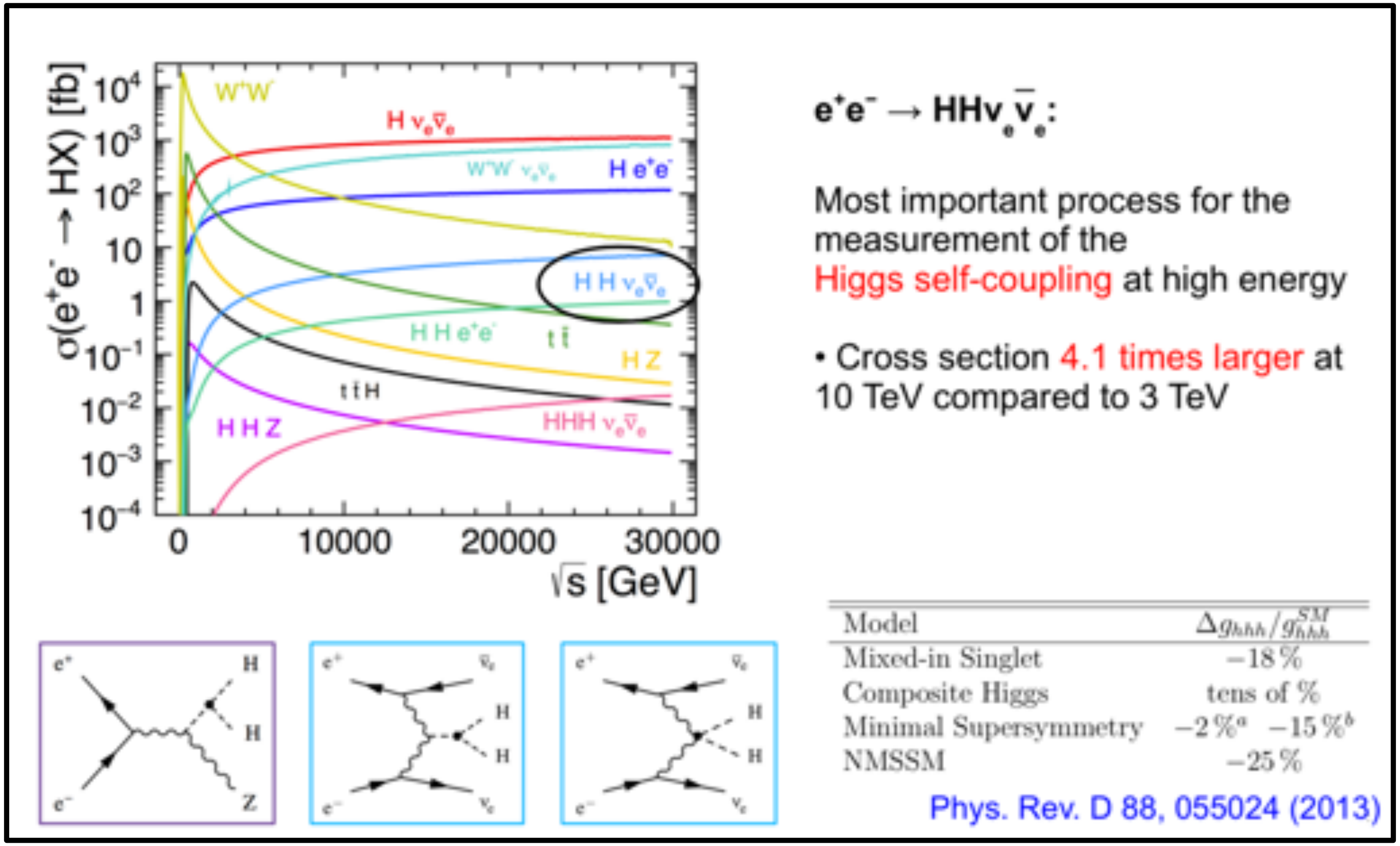
Rêves d'un collisionneur base sur les accélérateurs plasma



https://www2.lbl.gov/publicinfo/newscenter/features/2008/apr/af-bella.html

- LBNL LPA collider "strawman design" (2008)
- Existe pour les autres "moteurs" (faisceaux electrons, protons)

Enjeu de physique des futurs collisionneurs: 1 exemple (sur N)



$e^+e^- \to HH\nu_e\bar{\nu}_e$:

Most important process for the measurement of the Higgs self-coupling at high energy

- Cross section 4.1 times larger at 10 TeV compared to 3 TeV

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

Phys. Rev. D 88, 055024 (2013)

"So what we really want is a proton collider at least at 100 TeV (the more the better), and lepton colliders towards 10 TeV (also here more is better) In all cases luminosities at least around ~10^{35} cm^{-2} s^{-1} are needed."
(S.Stapnes)

La deuxième figure de mérite d'un collisionneur

- ○ Énergie dans le centre de masse (invariant de Lorentz) : $\sqrt{s}=2xE_F$
- ○ Luminosité (densité de flux de particules pour 2 faisceaux)
- ○ La luminosité determine le nombre d'évenements produits:

$$N = \sigma \times \int L \ dt \qquad \sigma\text{: section efficace}$$

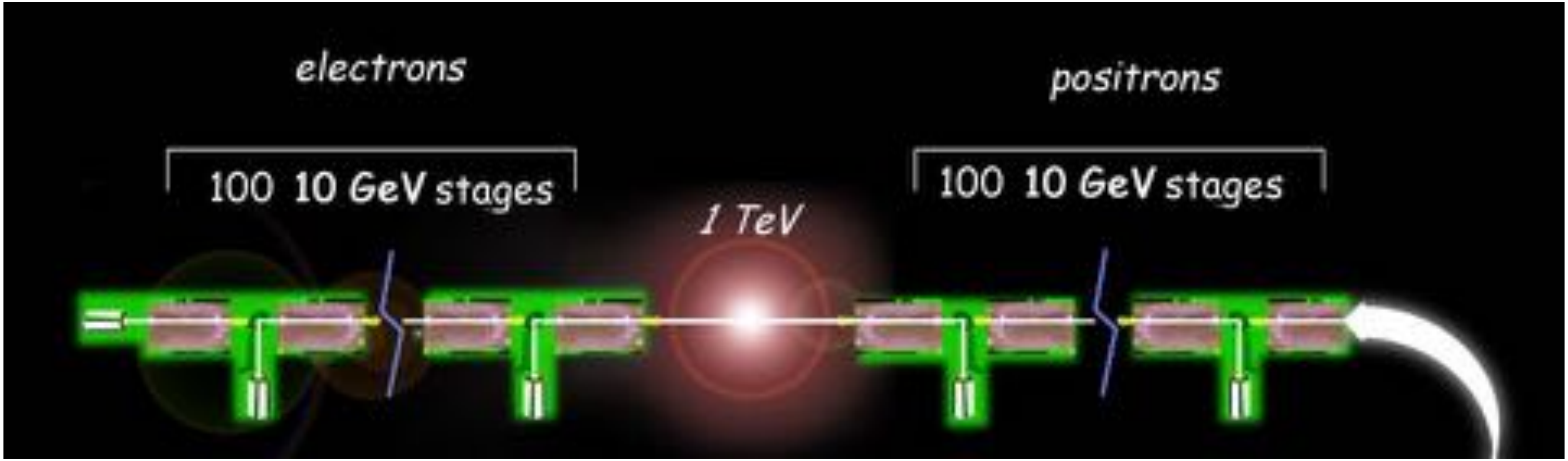
- ○ **N = 1 femto-barn x 10^{35} cm^{-2}s^{-1} x 10^{7}s = 1000**

injecteur; efficacité **driver; heat-load**

○ $$L = \frac{N(e^+) \times N(e^-) \times \text{taux de répetition}}{(\text{taille faisceau en } x) \times (\text{taille faisceau en } y)}$$

transverse and longitudinal beam quality

Rêves d'un collisionneur base sur les accélérateurs plasma



- **Injector**: produce high charge, high-quality, relativistic e- bunch
- **Many stages**: preserve high charge, high-quality, relativistic e- bunch
- **Final focus** (beam delivery): focus both beams tightly
- **Positrons**, spin polarization, driver (laser) in- and out- coupling, energy efficiency, energy dissipation in plasma

State if the art of the art of laser wakefield acceleration experiments (2020)

Property	**State of the art value [*]**	**Laser driver**	**Reference**	**Remarks**
Energy	**3 GeV** (± 15%, ~50pC) **7.8 GeV** (± 5%, ~5pC)	26J/30fs/30um 31J/30fs/60um	Kim (2017) - GIST Gonsalvez (2019) - LBNL	In single stage
Energy spread	**1%** (@ 10pC, 200MeV) **5-30%** (@50-3GeV) **5%**-100% (@ 400MeV, 80pC) **0.4%**-20% (@ 300-350MeV,~10pC)	1.1J/35fs/20um 1-5J/20-50fs/15-30um 2-5J/30fs/30um 2-3J/33fs/32um	Rechatin (2009) - LOA Many references (2010-2018) Mirzaie (2015) Shangai MOE Wang(2016) Shangai MOE	Still one order from FEL application requiring 0.1%
Normalized transverse emittance	~ **0.1 π mm.mrad**(@250MeV, ~15pc) ~ **0.01 π mm.mrad** (@200MeV-600MeV)	1.5J/30fs/20um	Weingartner (2012) - MPQ Qin (2018) - Shangai MOE	Measurement at the resolution limit
Bunch length	**5-10 um**	1.1J/35fs/20um	Lundh (2011) - LOA Kaluza(2014) - Jena Heigholt(2015) - UMu	Measurement at the resolution limit
Charge	~ 300 pC (@ 300-350MeV, 12-17%) **>1nC** (@ 330 MeV >15%-)	2.5J/40fs/20um 10J/40fs/>25um	Couperus (2017) - Jena Götzfried(2020) - LMU	Beam loading
Repeatability	**2.4%E, 11%Q** (@1Hz, 368MeV, 25pC) **4%-11% E**, **23%Q**(@1kHz, 2.5MeV, 3pC)	2J/42fs/25um 10mJ/25fs/6um	Maier (2020) - DESY/UHH Rovige (2020) - LOA	
Repetition rate	~ **1 Hz** @ >1 GeV ~ **1 kHz** @ 1-3 MeV	>25J/30fs/>30um ~mJ/ <25fs /6um	Kim (2017) - GIST, Gonzalves (2019) He (2015)- UMi, Salehi(2017) - UMd Guenot (2017) - LOA	Limited by laser

Table courtesy of K. Cassou

State if the art of the art of laser wakefield acceleration experiments (202

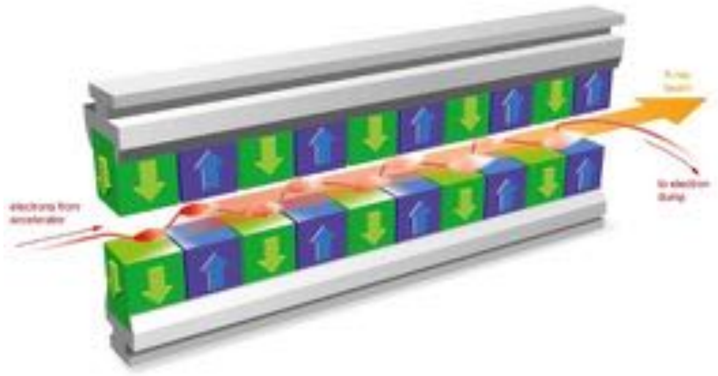
Property	**State of the art value [*]**	**Laser driver**	**Reference**	
Energy	**3 GeV** (± 15%, ~50pC) **7.8 GeV** (± 5%, ~5pC)	26J/30fs/30um 31J/30fs/60um	Kim (2017) - G Gonsalv	stage
Energy spread	**1%** (@ 10pC, 200MeV) **5-30%** (@50-3GeV) **5%**-100% (@ 400MeV, 80pC) **0.4%**-20% (@ 300-350MeV,~10pC)	1.1J/35fs/20u 1-5J/20- 50fs/	010-2018) Shangai MOE) Shangai MOE	Still one order from FEL application requiring 0.1%
Normalized transverse emittance	~ **0.1 π mm.mrad**(@250MeV, ~ ~ **0.01 π mm.mrad** (@200	fs/20um	Weingartner (2012) - MPQ Qin (2018) - Shangai MOE	Measurement at the resolution limit
Bunch length	**5-10 um**	1.1J/35fs/20um	Lundh (2011) - LOA Kaluza(2014) - Jena Heigholt(2015) - UMu	Measurement at the resolution limit
Charge	~ MeV, 12-17%) V >15%-)	2.5J/40fs/20um 10J/40fs/>25um	Couperus (2017) - Jena Götzfried(2020) - LMU	Beam loading
Re	**%Q** (@1Hz, 368MeV, 25pC) **1% E**, **23%Q**(@1kHz, 2.5MeV, 3pC)	2J/42fs/25um 10mJ/25fs/6um	Maier (2020) - DESY/UHH Rovige (2020) - LOA	
Repe rate	**~ 1 Hz** @ >1 GeV **~ 1 kHz** @ 1-3 MeV	>25J/30fs/>30um ~mJ/ <25fs /6um	Kim (2017) - GIST, Gonzalves (2019) He (2015)- UMi, Salehi(2017) - UMd Guenot (2017) - LOA	Limited by laser

1. **Aucune experience réalise toutes ces valeurs au même temps.**
2. **Qualité de faisceau: contrôle du mécanisme d'injection!**

Table courtesy of K. Cassou

Application : source rayons X cohérente compacte

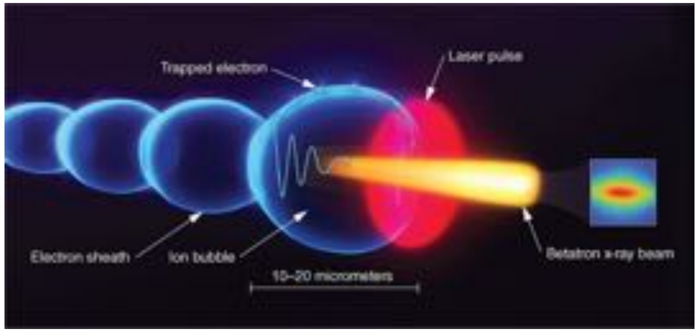
magnetic ondulator



SASE FEL
100‘seV - keV

M. Fuchs et al, Nature Physics, Vol 5 (2009)

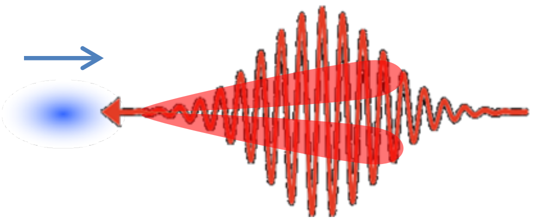
plasma undulator



“Betatron“ radiation
1keV – 10‘s keV

S. Corde et al, Rev. Mod. Phys., Vol 85 (2013)
S. Kneip et al, Nature Physics Vol 6 (2010)

laser beam

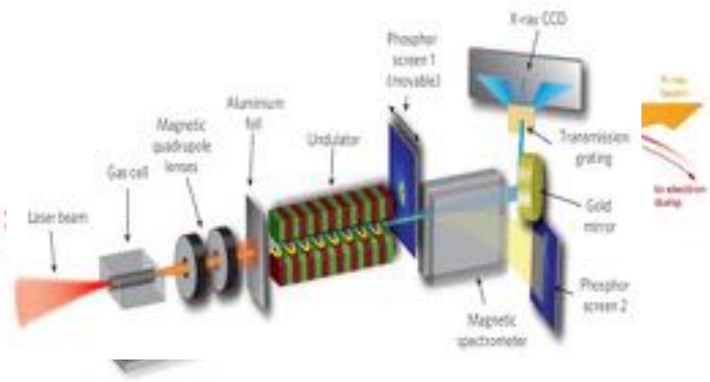


Compton backscatter
10‘s keV - MeV

K. Taphuoc, Nature Photonics, 6 (2012)

Application : source rayons X cohérente compacte

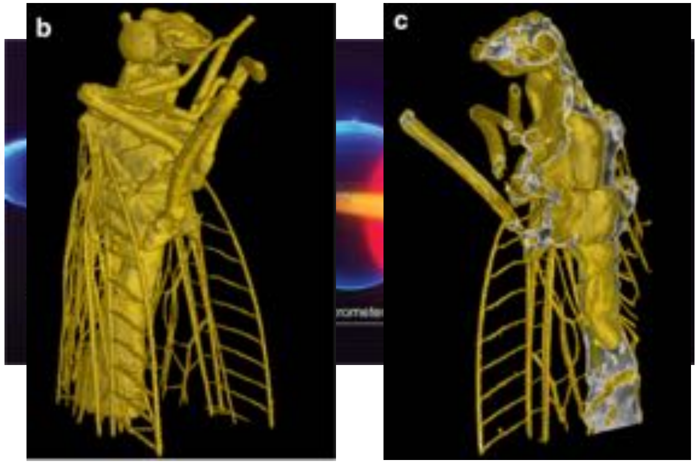
magnetic ondulator



(SASE) FEL
100'seV - keV

M. Fuchs et al, Nature Physics, Vol 5 (2009)

plasma undulator

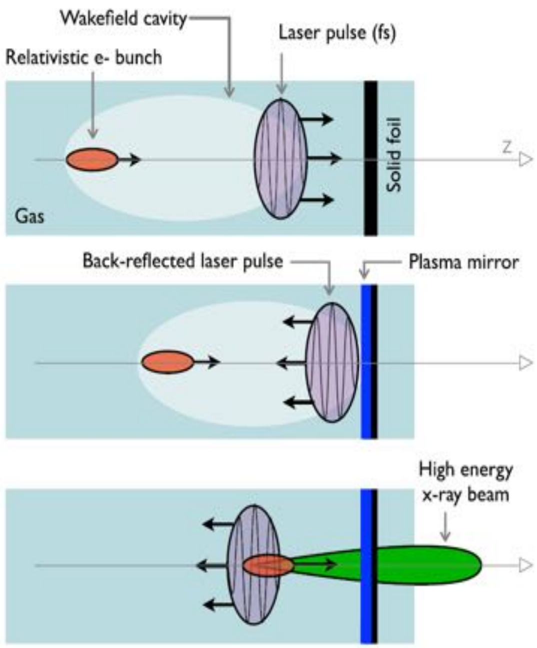


J. Wenz et al, Nature Communications 2015

"Betatron" radiation
1keV – 10's keV

S. Corde et al, Rev. Mod. Phys., Vol 85 (2013)
S. Kneip et al, Nature Physics Vol 6 (2010)

laser beam

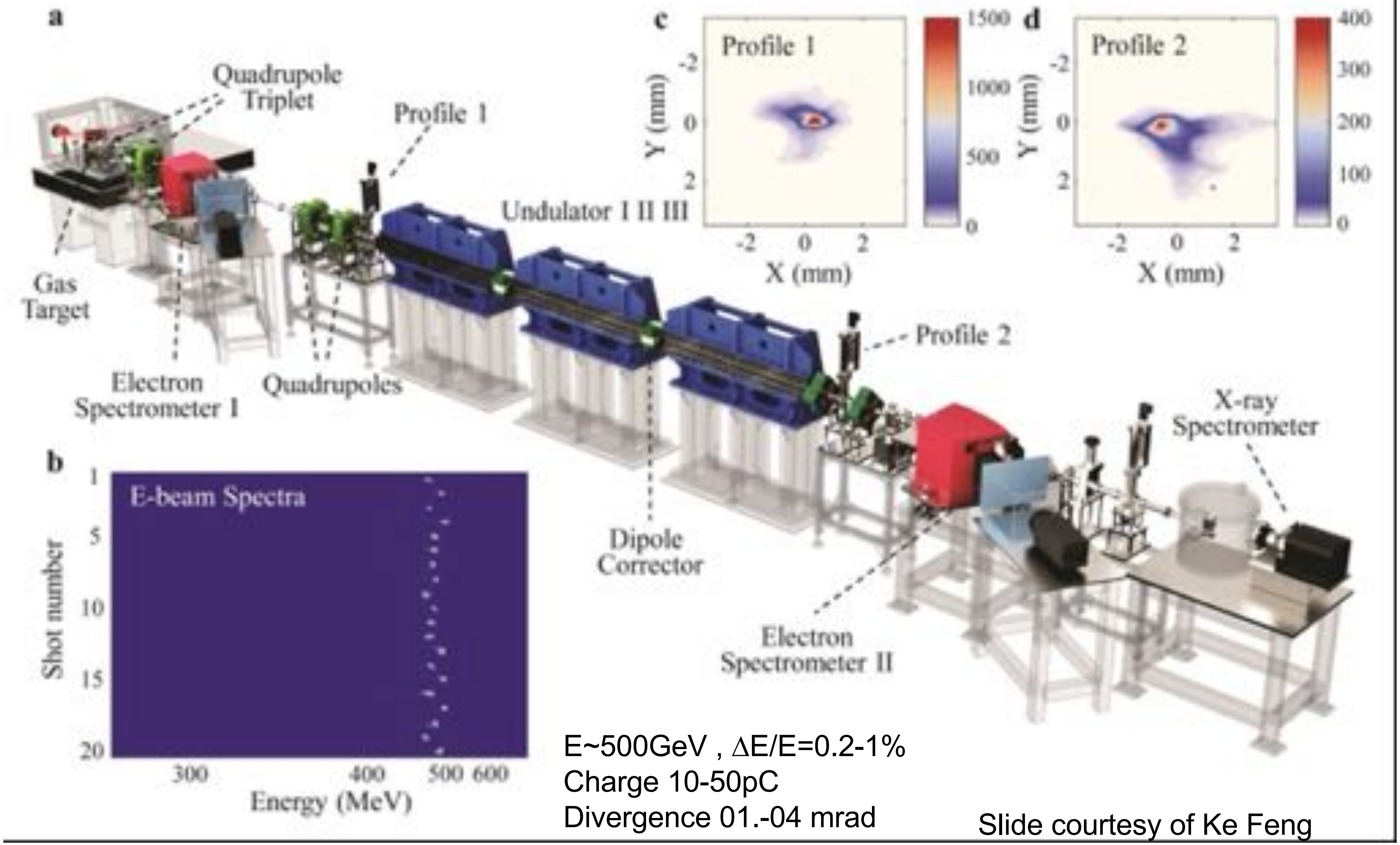


Compton backscatter
10's keV - MeV

K. Taphuoc, Nature Photonics, 6 (2012)

Laser à electron libres (LEL) pompé ALPe (Shanghai)

Wang, W. et al. Nature 595, 516–520 (2021)

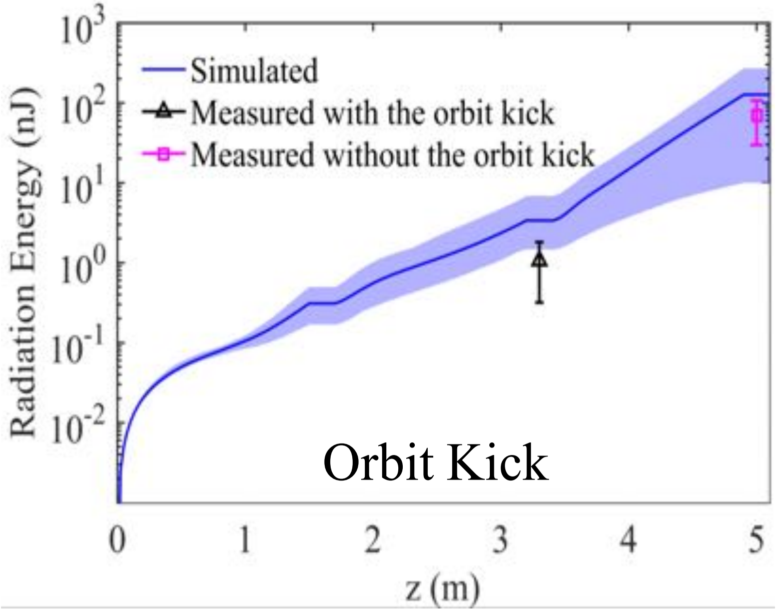


E~500GeV , ΔE/E=0.2-1%
Charge 10-50pC
Divergence 01.-04 mrad

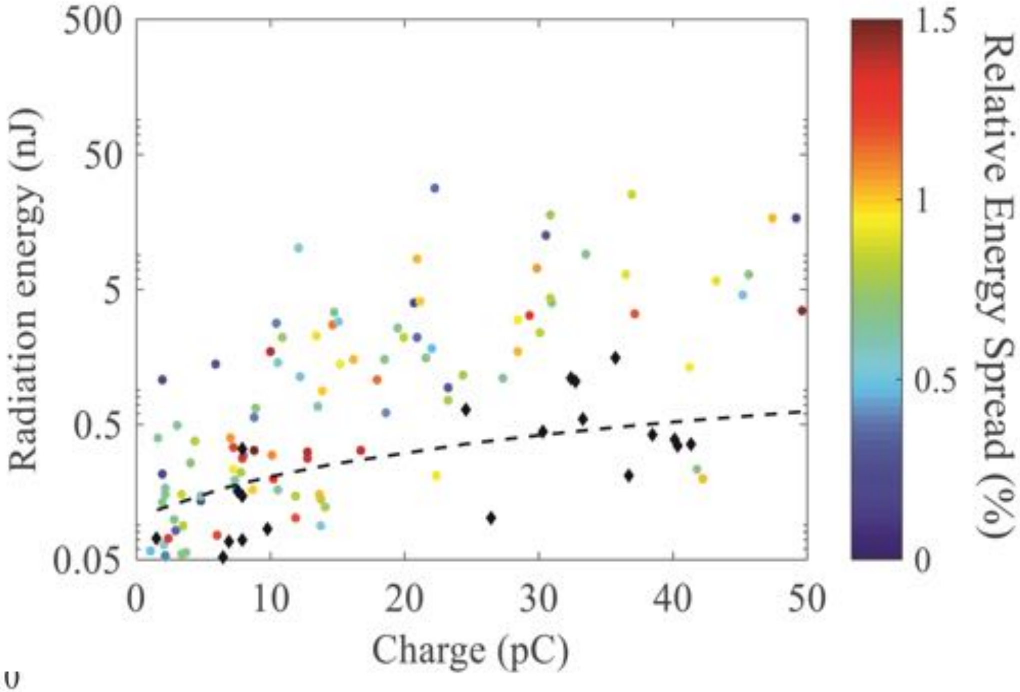
Slide courtesy of Ke Feng

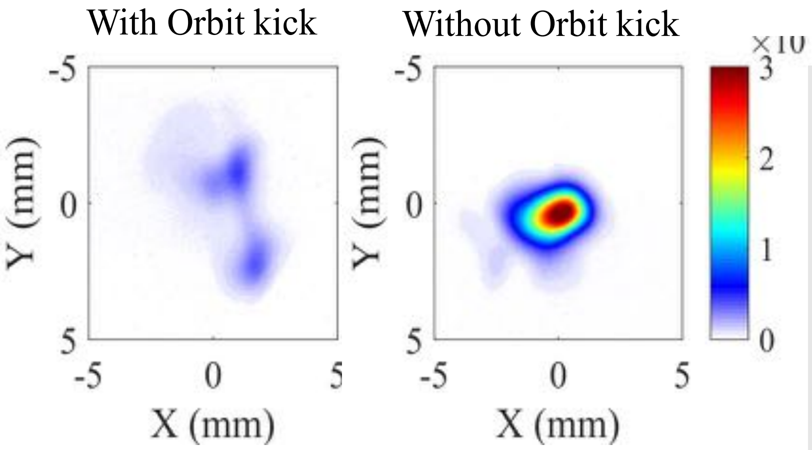
First observation XFEL Lasing (27nm) using a LWFA

Wang, W. et al. Nature 595, 516–520 (2021)



Spontaneous emission calibration





Demonstration of exponential gain:

Orbit kick method: The gain process was spoiled by kicking the *e* beam at the entrance of the third undulator; The maximum power gain in the third undulator approximates 100-fold.

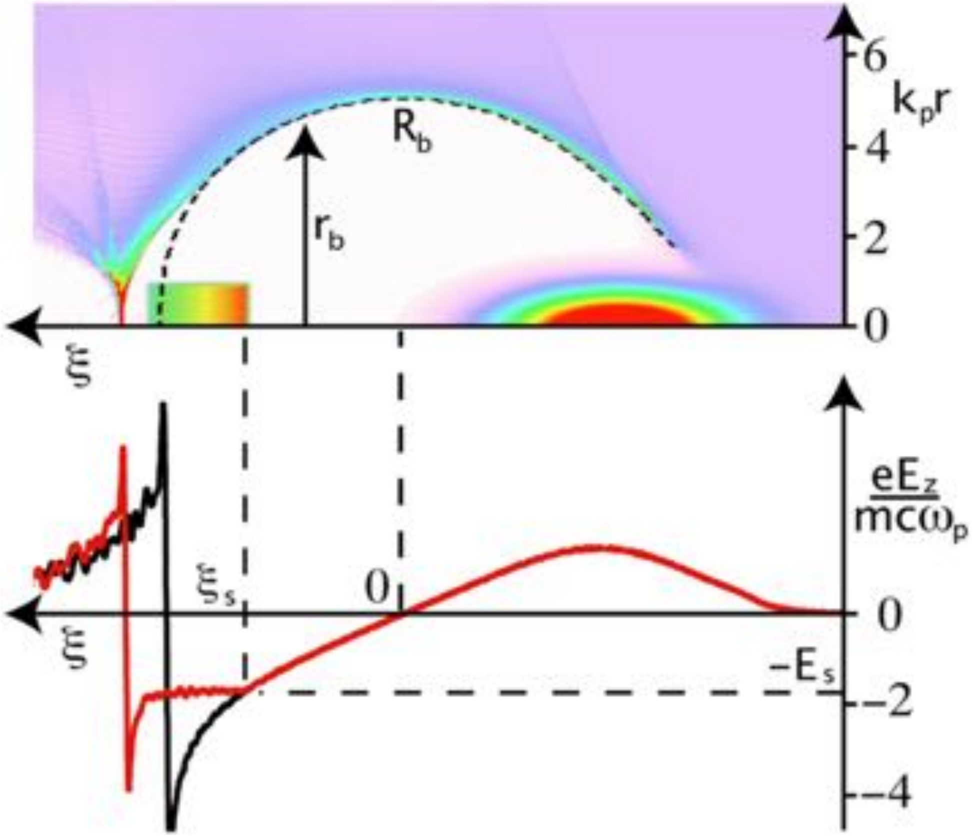
Spontaneous emission calibration: The spontaneous emission curve was fitted by spoiling the energy spread of the *e* beam.

Slide courtesy of Ke Feng

Beam loading in plasma accelerators

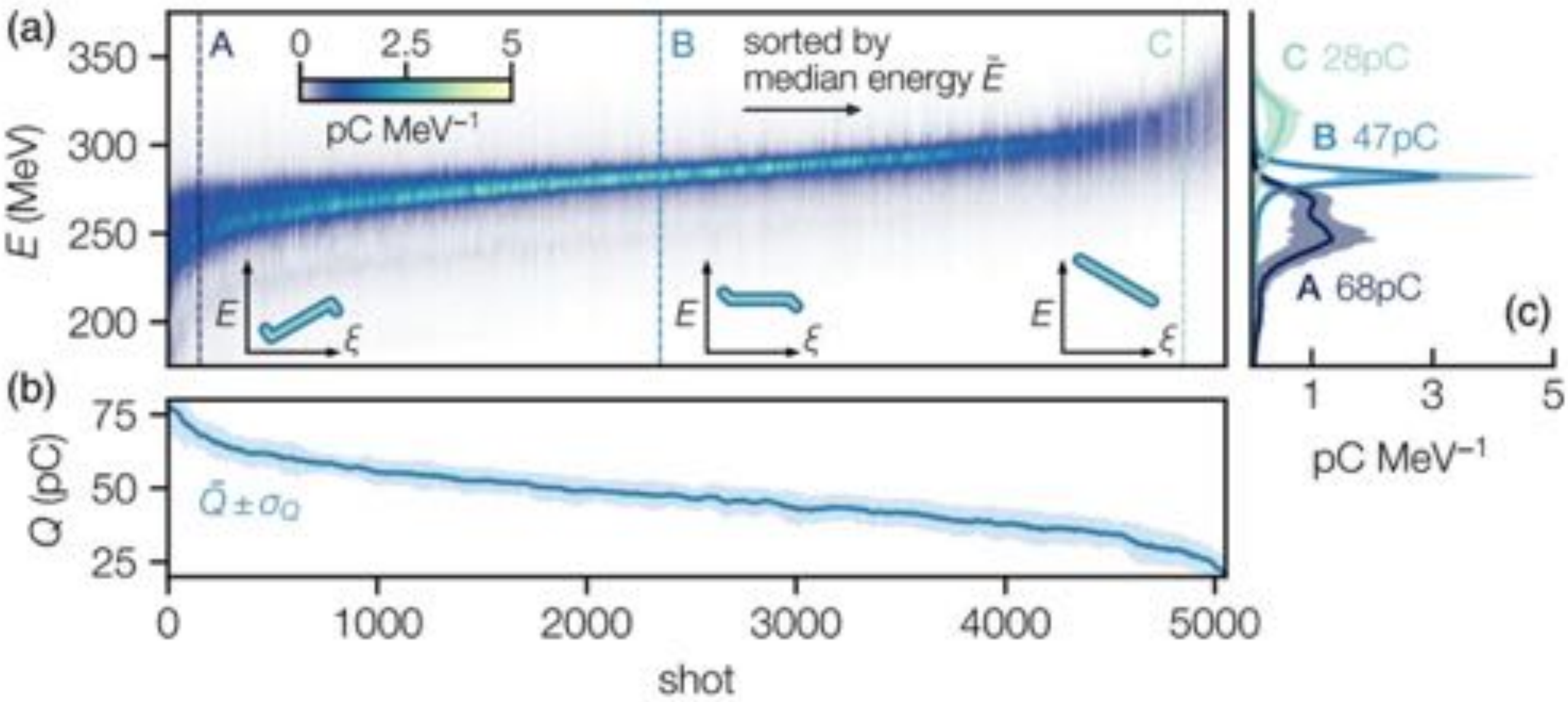
- Self-fields of bunch superimpose the wakefield
- → reshaping plasma accelerating structure
- Reduction of effective acceleration gradient
- Injection of an optimum charge with a specific shape

→ flattening of the accelerating field, low energy spread



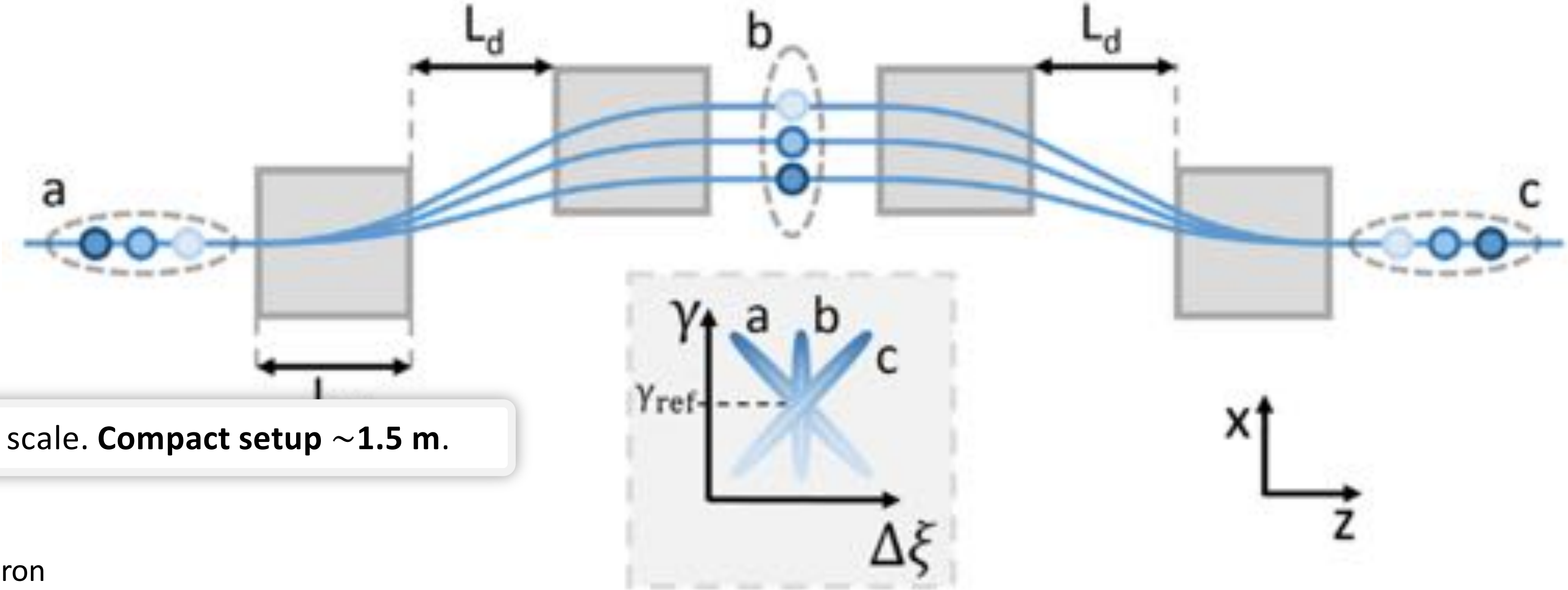
Tzoufras et al., Physics of Plasmas ***16****, 056705 (2009)*

Demonstration of optimal beam loading in LWFA



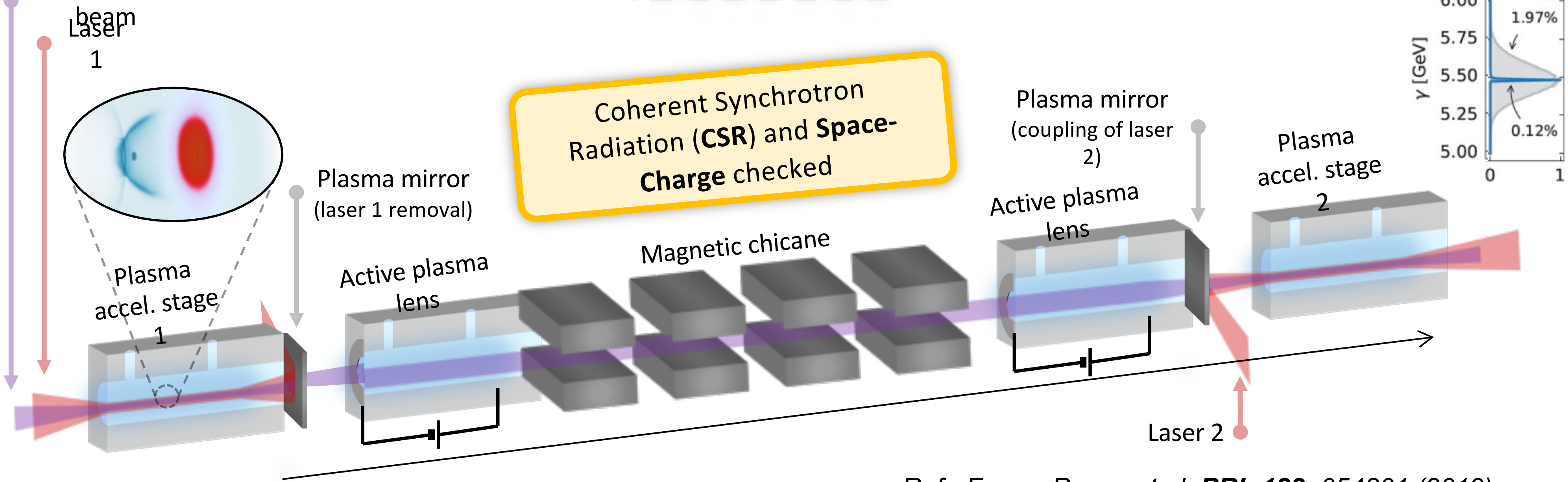
Kirchen, Manuel, et al. " Physical Review Letters 126.17 (2021): 174801.

Compensation du E- chirp dans un compensation in 2-stage LWFA



Not to scale. **Compact setup** ∼**1.5 m**.

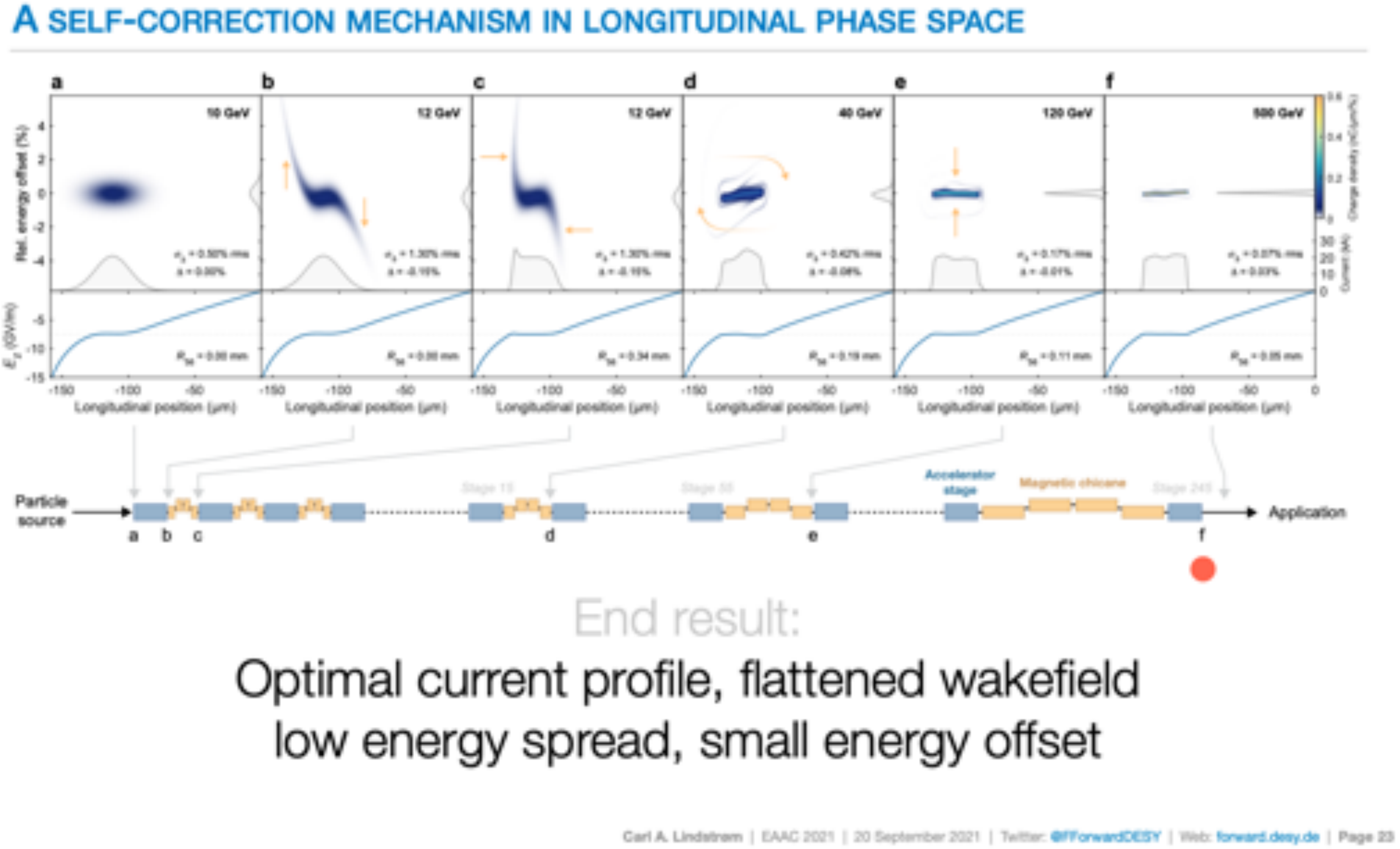
Coherent Synchrotron Radiation (**CSR**) and **Space-Charge** checked



Ref.: Ferran Pousa et al. **PRL 123,** 054801 (2019)

Accélérateur multi-étage: stabilisation de phase passive

Lindstrom,[arXiv:2104.14460]



A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE

End result:

Optimal current profile, flattened wakefield
low energy spread, small energy offset

Carl A. Lindstrøm | EAAC 2021 | 20 September 2021 | Twitter: @FForwardDESY | Web: forward.desy.de | Page 23

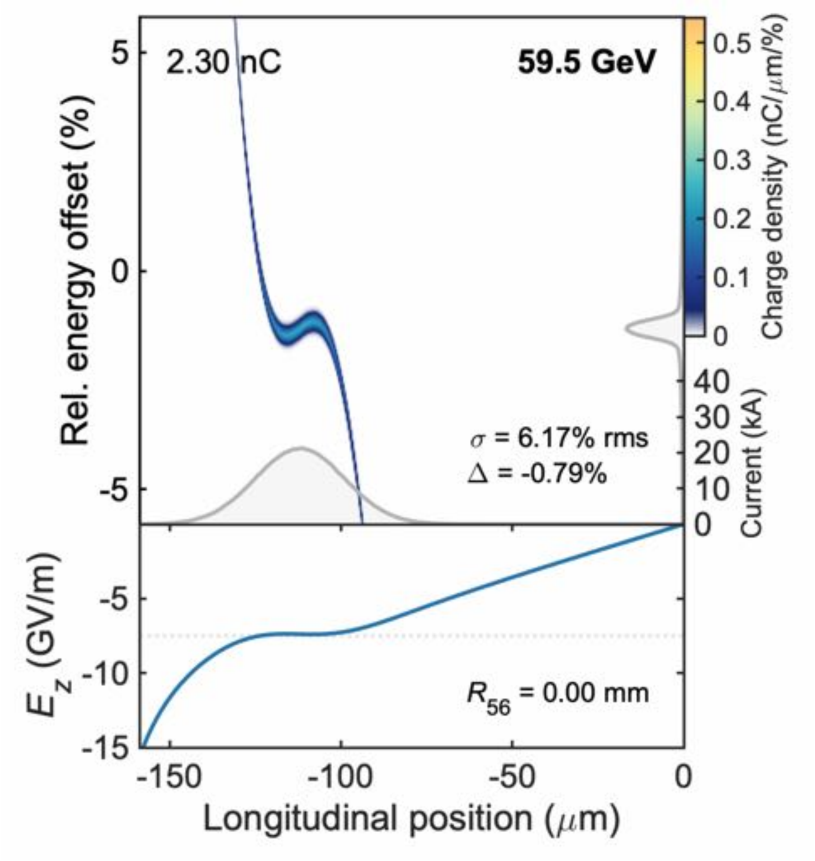
Stabilisation de phase passive (Lindstrøm , 2021)

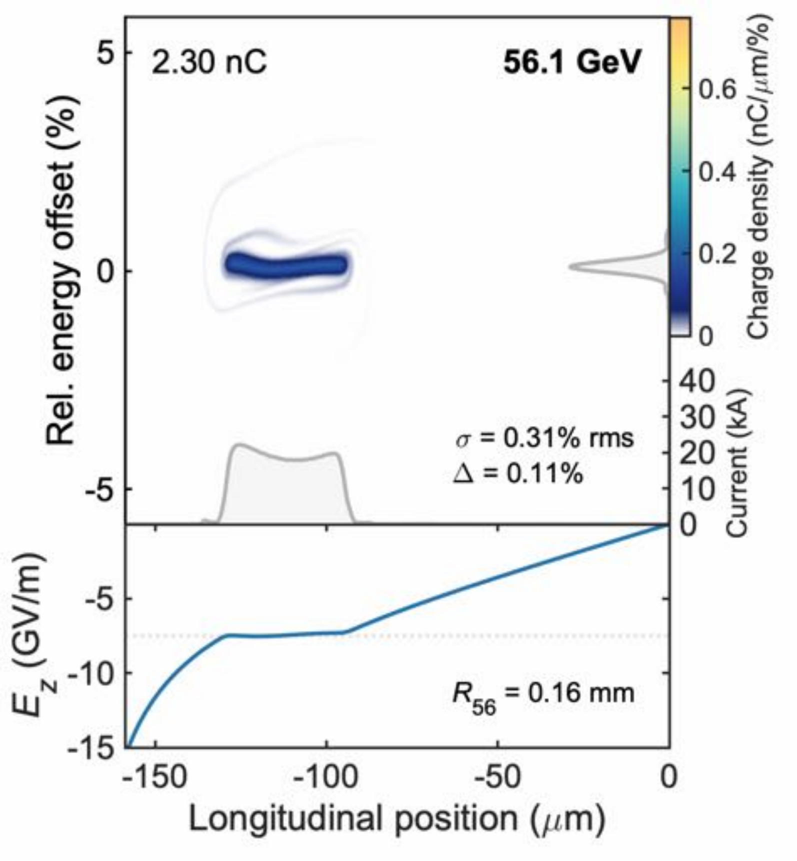
A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE

Lindstrom,arXiv:2104.14460

No R_{56}—no correction
(same as before)

With multistage correction



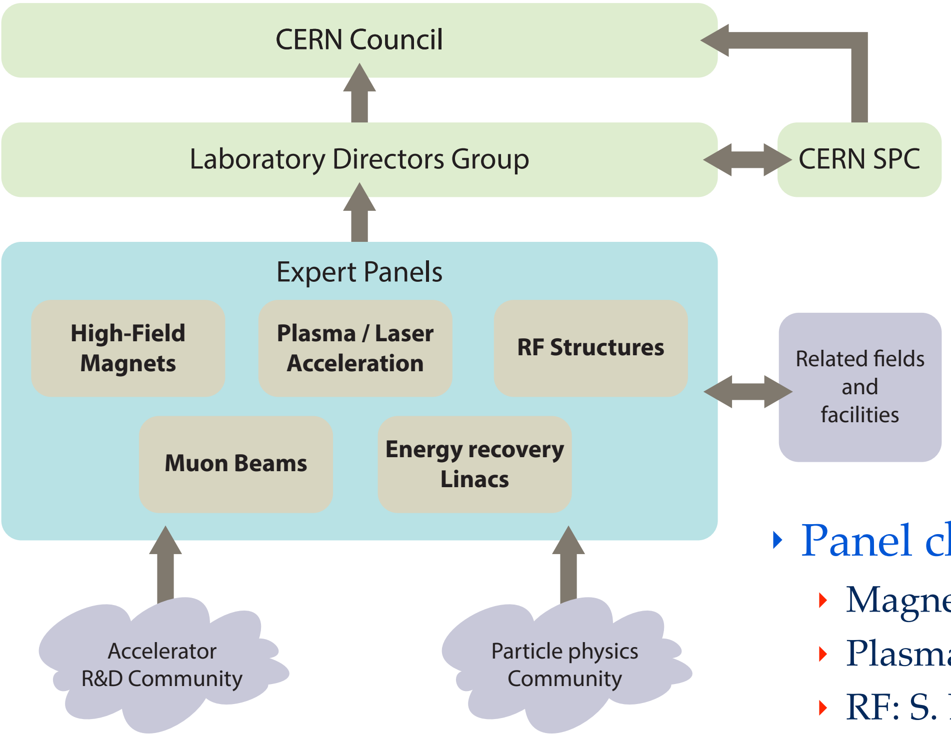


Résumé

- Avec des lasers PW il est facile de produire des paquets d'e^- de qqs 100aines de pC, de ~1GeV avec qualité moyenne
- La physique de l'accélération est bien comprises et reste simple à $P_{LASER} > 1$ PW. (cf. présentation de Gilles Maynard)
- La qualité et la stabilité du laser sont primordiales pour obtenir des faisceaux d'e^-
- APOLLON a démontré son potentiel pour ALPe >1GeV
- A l'international, de nombreuses activités pour l'amélioration de la qualité de faisceau ont abouti!
- Progrès nécessite de nombreux développements annexes: guidage, manipulation des faisceau d'e^-, synchronisation, stabilisation active, machine learning, simulations « en temps réel »

Plasma accelerators community is requested to produce R&D roadmap for collider R&D (European Strategy of Particle Physics)

Accelerator R&D Panels



CERN Council

Laboratory Directors Group

CERN SPC

Expert Panels

High-Field Magnets

Plasma / Laser Acceleration

RF Structures

Muon Beams

Energy recovery Linacs

Related fields and facilities

Accelerator R&D Community

Particle physics Community

Slide: Dave Newbold, coordinator

- Panel chairs
  - Magnets: P. Vedrine (IRFU)
  - Plasma: R. Assmann (DESY)
  - RF: S. Bousson (IJCLab)
  - Muons: D. Schulte (CERN)
  - ERL: M. Klein (Liverpool)
  - A big thank you to all members of the international accelerator community who have contributed

Until 2026:

- **9 (?) deliverables**
- **R&D milestones at existing facilites**

Parameters for High Energy Study Case

Study multi-stage electron (positron) accelerator from 175 GeV to 190 GeV:

Parameter	**Unit**	**Specification**
Beam energy (entry into module)	GeV	**175**
Beam energy (exit from module)	GeV	**190**
Number of accelerating structures in module	-	$\geq$2
Efficiency wall-plug to beam (includes drivers)	%	$\geq$10
Bunch charge	pC	833
Relative energy spread (entry/exit)	%	$\leq$0.35
Bunch length (entry/exit)	μm	$\leq$70
Convoluted normalized emittance $(\gamma\sqrt{\epsilon_h\epsilon_v})$	nm-rad	$\leq$135
Emittance growth budget	nm-rad	$\leq$**3.5**
Polarization	%	80 (for e^-)

- → Full lattice
- → In/out coupling
- → All magnetic elements
- → Correctors
- → Diagnostics
- → Collective effects
- → Emittance, efficiency

- → Include realistic imperfections
- → Betatron radiation
- → Estimate of realistic performance
- → Estimate realistic footprint
- → Estimate realistic benefits in cost and size
- → Understand scaling with beam energy for different technologies (laser, e^-, p driven, DLA/THz)

- **"Livrable" important envisagé pour 2026**
- **complication: 4 technologie (laser, e, p, DLA)**

Perspectives d’avenir

- Les accélérateurs plasma font partie de la FdR euopéene
  - **EuPRAXIA sur la ESFRI roadmap -> Applications XFEL**
  - **CERN expert panel définira l’implémetation de FdR R&D pour HEP**
- Simulations
  - **Design study d’une section accélératrice 175GeV->190GeV**
  - **”start-to-end” avec entrées/sorties et transports**
  - **Aussi: acceleration de positrons, polarization de spin**
- Experiénces (at existing facilities: APOLLON, PALLAS)
  - **Source d’electrons (injecteur) haute qualité**
  - **Source de positrons**