Laser Acceleration toward 100 GeV
- Experimental suggestions -

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Route Toward Reality
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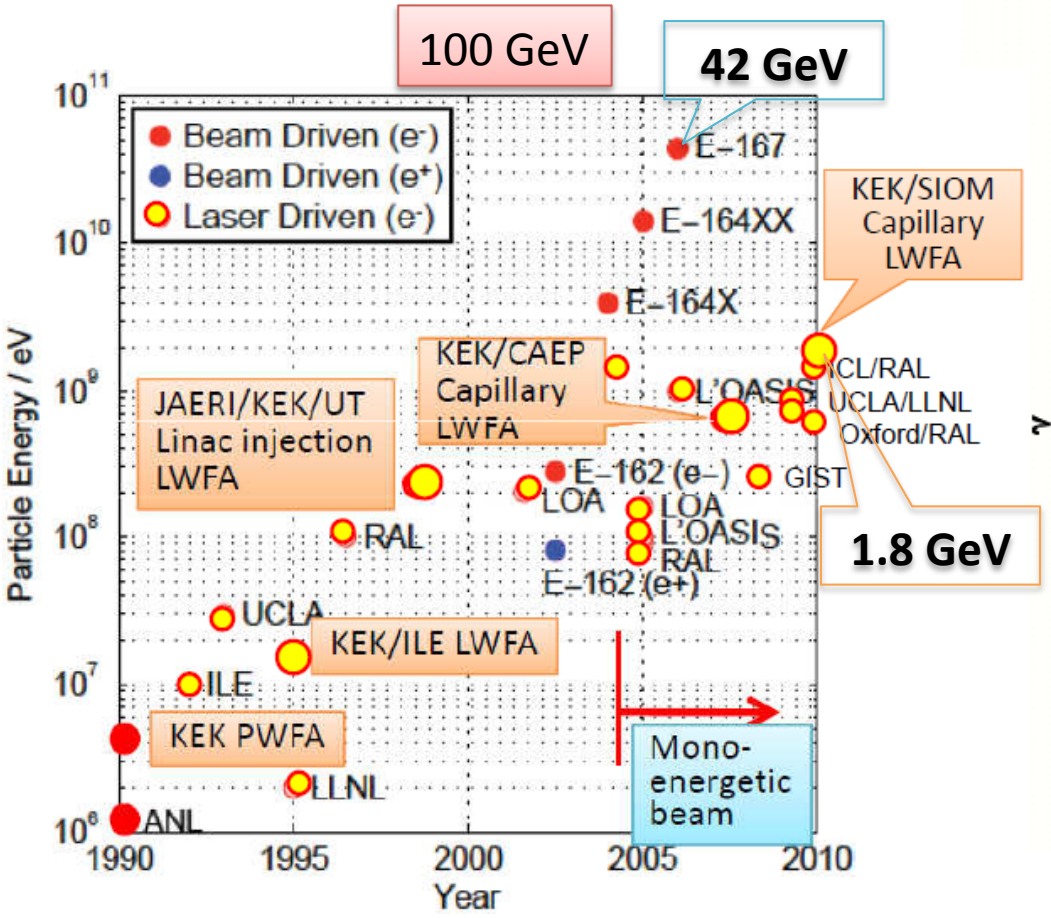
Outline

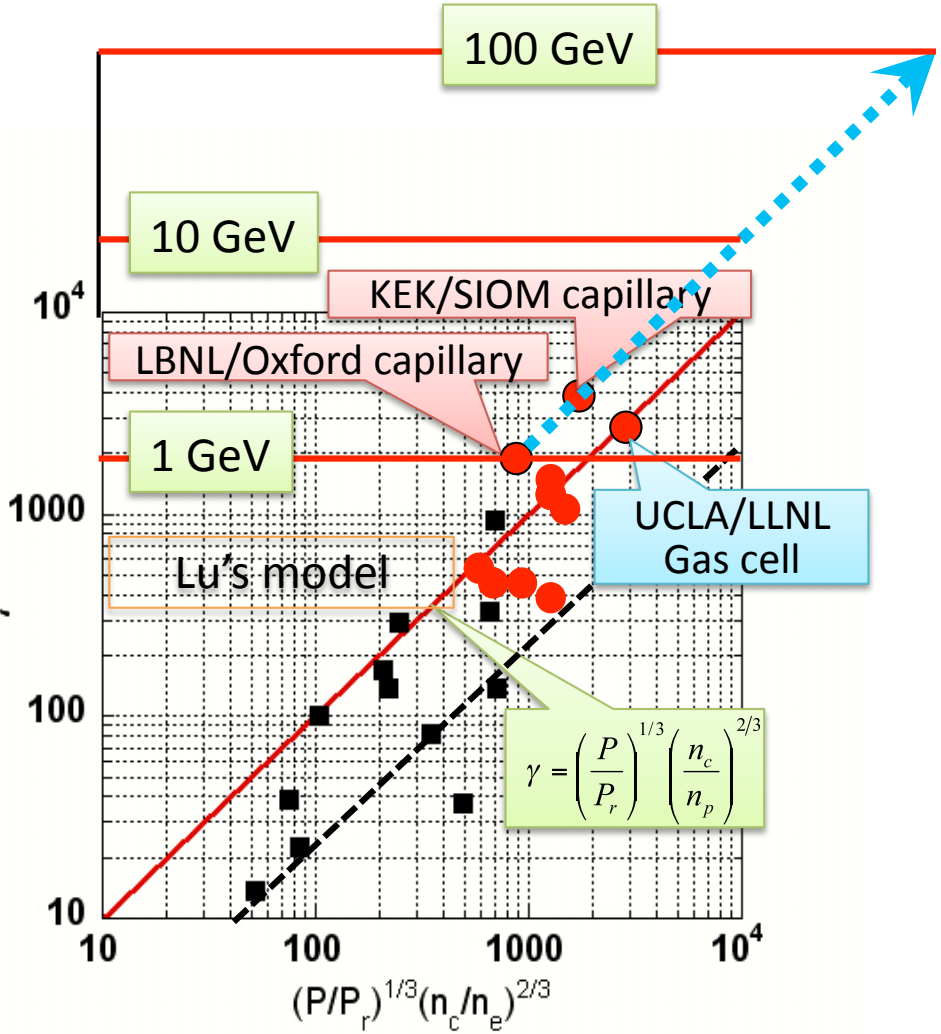
- Worldwide experimental progress and energy scaling
- Design of LWFA toward 100 GeV
- Positron production and acceleration by laser
- Long plasma channel generation at kHz rep rate
- Plasma channel coupler for staging
- Design of 10 – 100 GeV beam diagnostics
- Resonant LWFA at kHz rep rate

Evolution of the maximum electron energy by single-stage laser-plasma accelerators since 1990



M.J. Hogan, AAC2010

Energy gain scaling of LWFA

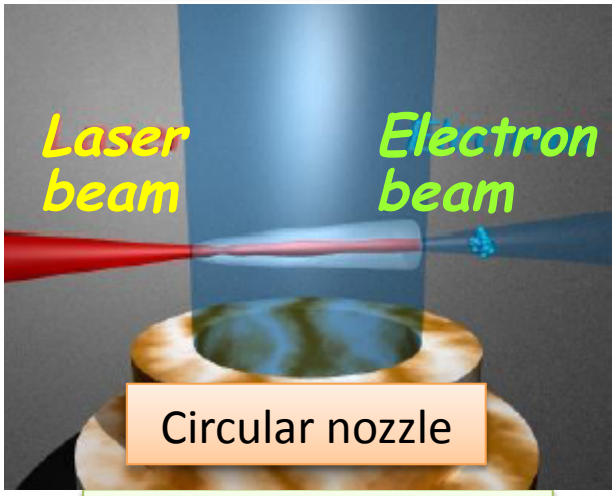


Plasma channel enhances energy gain by a factor of 2

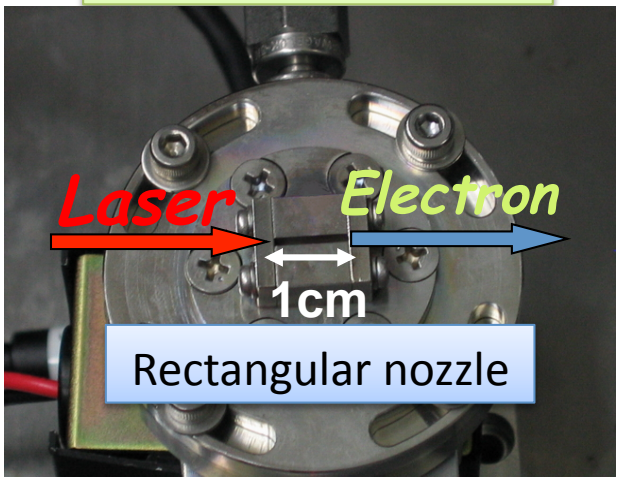
Plasma Accelerators lower than 10 GeV

Higher than 10 GeV

Millimeter-scale plasma

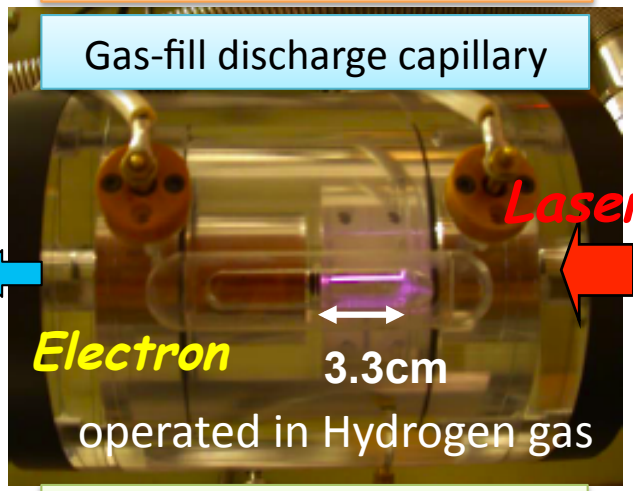


Super-sonic gas jet

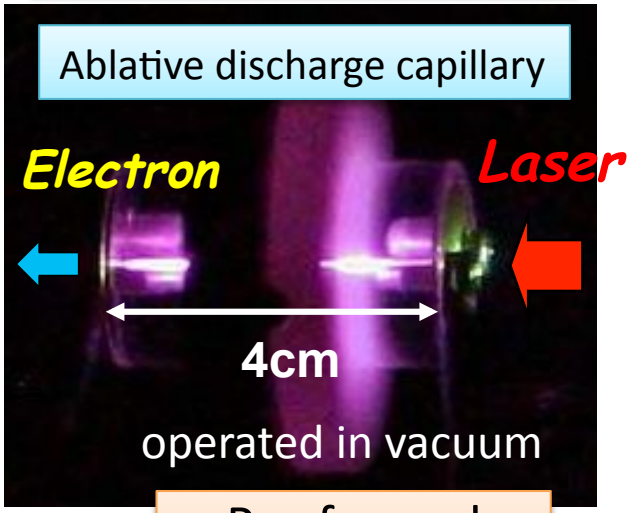


Self-guiding plasma channel

Centimeter-scale plasma



Capillary plasma channel



Pre-formed plasma channel

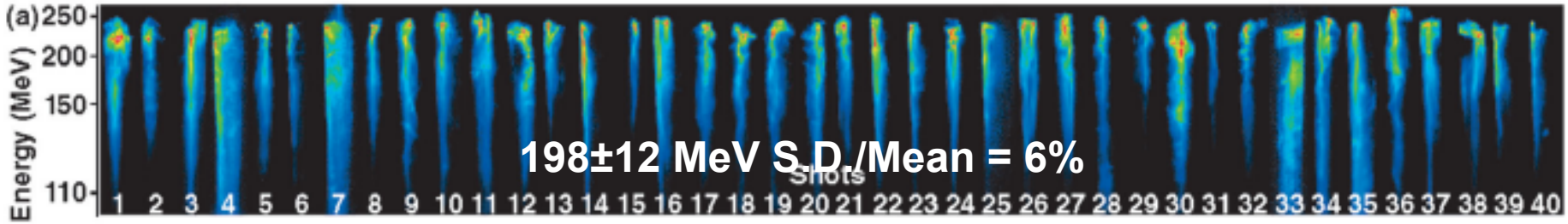
Meter-scale plasma

- How to produce a long scale plasma?
- Self-guiding or pre-formed plasma channel?
- How to make staging?

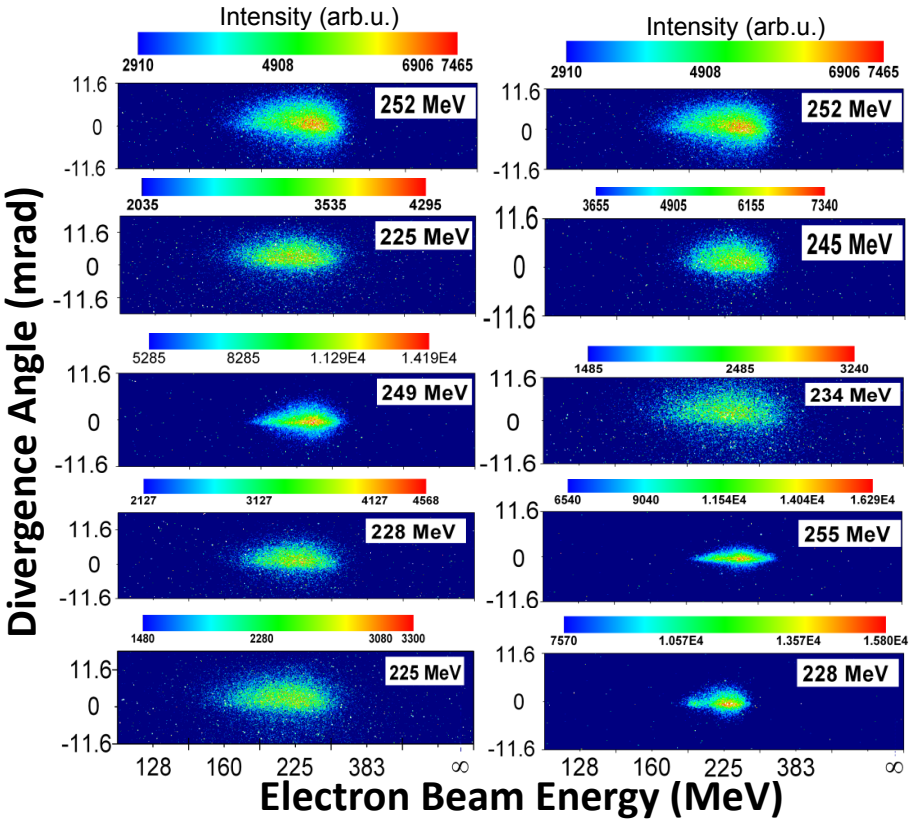
should be answered.

Stability in self-injection is as high as laser stability

Laser: P = 20TW 42fs FWHM, Intensity: 1.7x10^{18} W/cm^2 (a_0=0.89), n_e=7.8x10^{18} cm^{-3}



A steady-state-flow gas-fill capillary experiment at MPQ, Germany



J. Osterhoff et al., PRL 101, 085002 (2008)

1 cm gas jet experiment
at GIST-APRI, Korea

Mean laser power 37TW, 35fs
SD/Mean pulse energy = 4.6%
n_e~ 7 × 10^{18}cm^{-3}

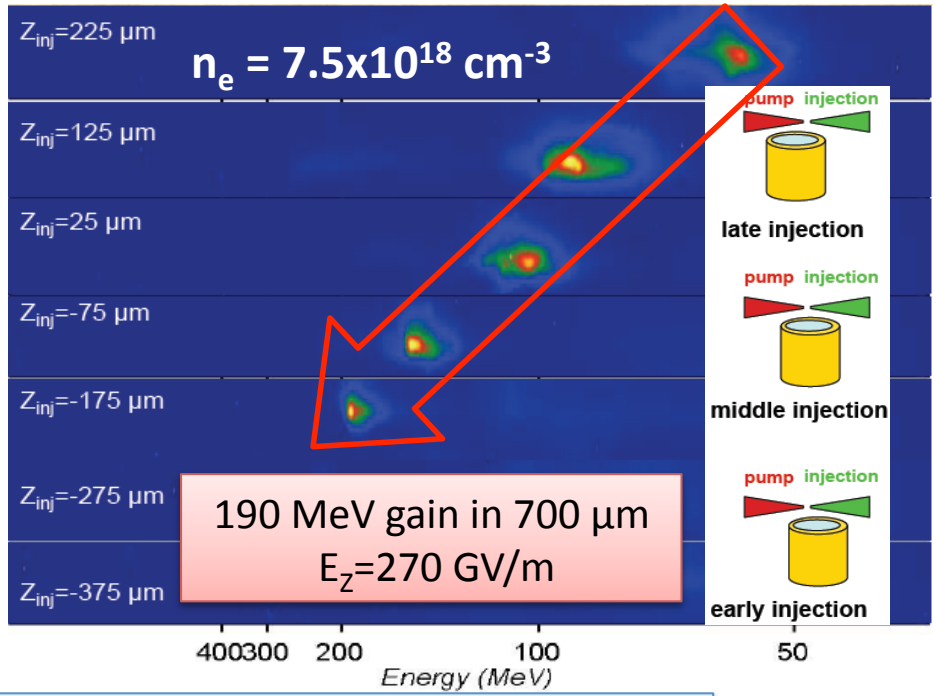
Mean electron energy = 236.9 MeV
SD/Mean E = 5 %; Charge: ~100pC
Divergence angle: ~a few mrad

N. Hafz et al., nature photonics, 2, 571, 2008

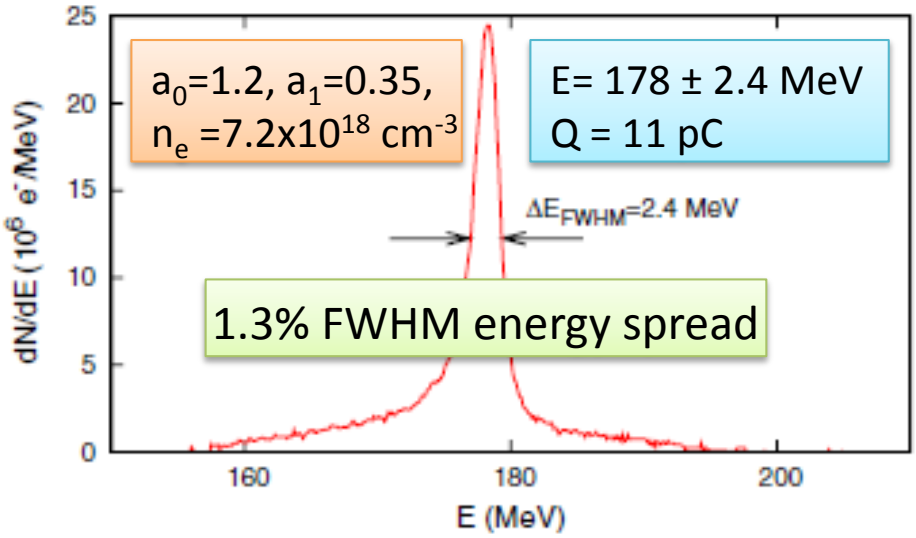
Colliding injection controls energy and its spread with stability as high as laser

J. Faure et al., Nature 444, 737, 2006

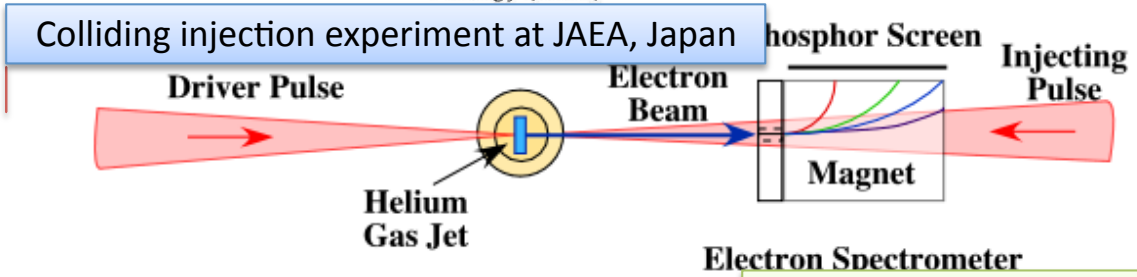
Colliding injection experiment at LOA, France



C. Rechatin et al., PRL 102, 164801 (2009)



Colliding injection experiment at JAEA, Japan

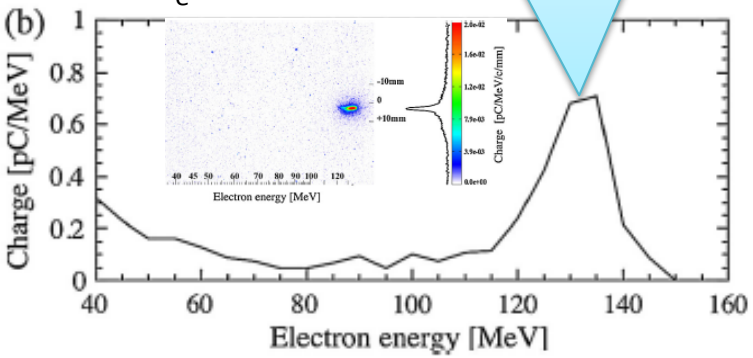


P= 10 TW (a_0 =1.2)
E=400 mJ ; τ=40 fs
w_0=34 μm
I=3x10^{18} W/cm^2

P=0.6 TW (a_1 =0.2)
E=30 mJ; τ=50 fs
w_0=50μm
I=8x10^{16} W/cm^2

Energy : 134MeV
Energy spread :11 MeV (3.5%)
Charge : 8.7 pC
Divergence: 4 mrad

n_e = 1×10^{19}cm^{-3}



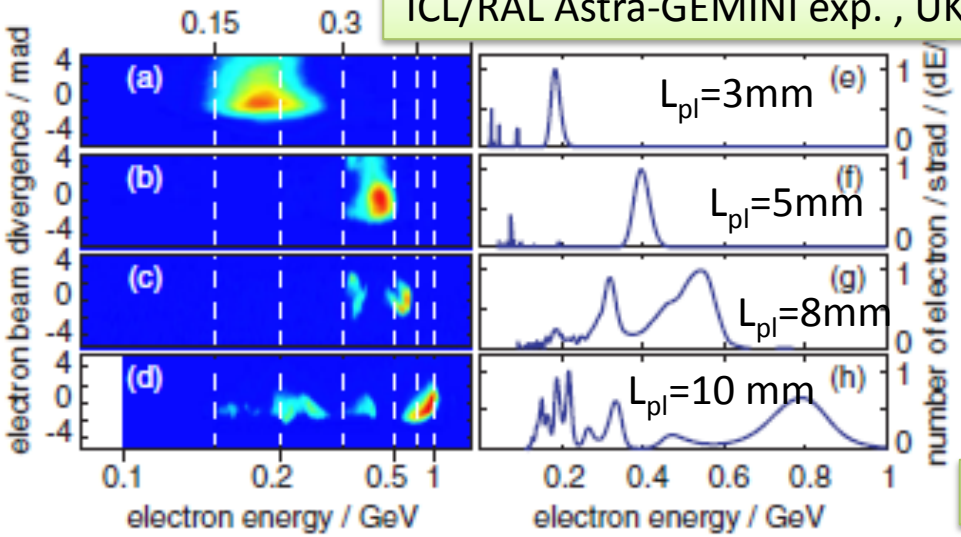
H. Kotaki, et al., Phys. Rev. Lett. ***103****, 194803 (2009).*

Self-guided LWFA in the bubble regime

High energy But less quality

180 TW, 55 fs, a_0 =3.9, n_e = 5.7x10^{18} cm^{-3}

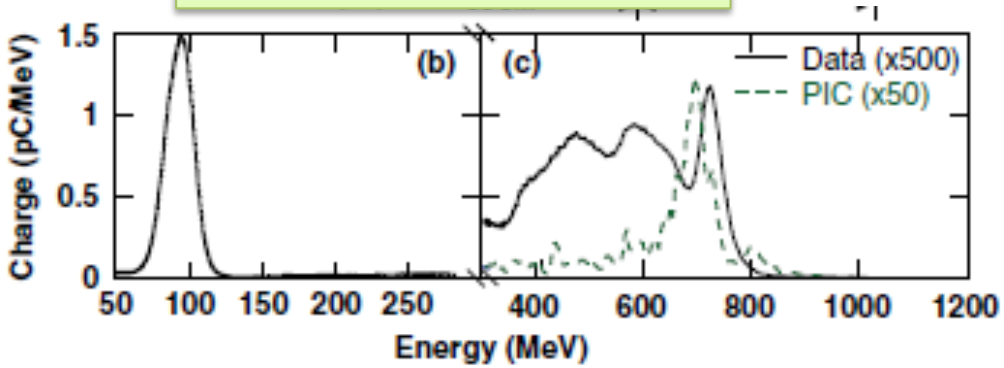
ICL/RAL Astra-GEMINI exp. , UK



S. Kneip et al., PRL 103, 035002 (2009)

65 TW, 60 fs, a_0 =2.8, n_e = 3x10^{18} cm^{-3}

UCLA/LLNL Jupiter exp., USA

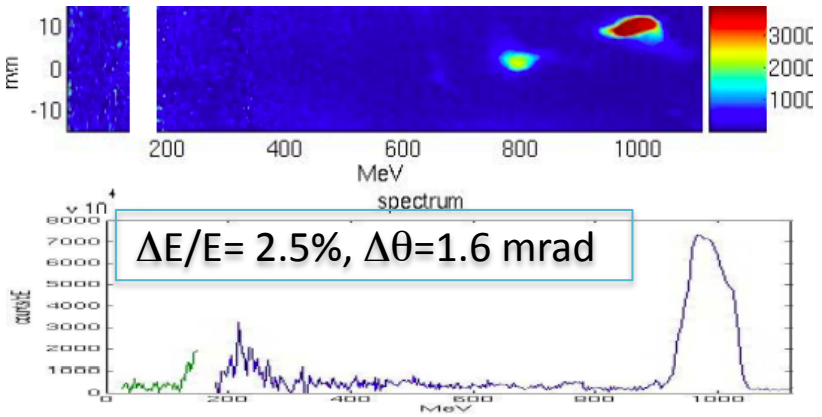


D. H. Froula et al., PRL 103, 215006 (2009)

Channel-guided LWFA in plasma channel

High-energy, high-quality But less charge

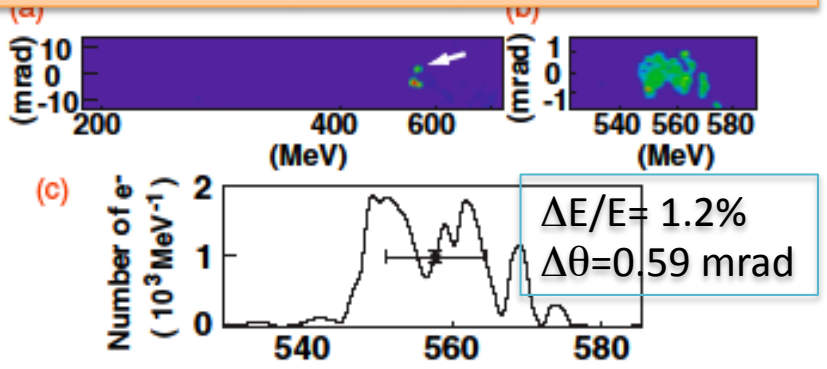
40 TW, 37 fs, a_0 =1.4, n_e = 4.3x10^{18} cm^{-3}



3.3 cm gas-fill capillary exp. at LBNL/Oxford, USA

W.P. Leemans et al., Nature Physics 2, 696 (2006)

24 TW, 27 fs, a_0 =1.7, n_e = 1.9x10^{18} cm^{-3}

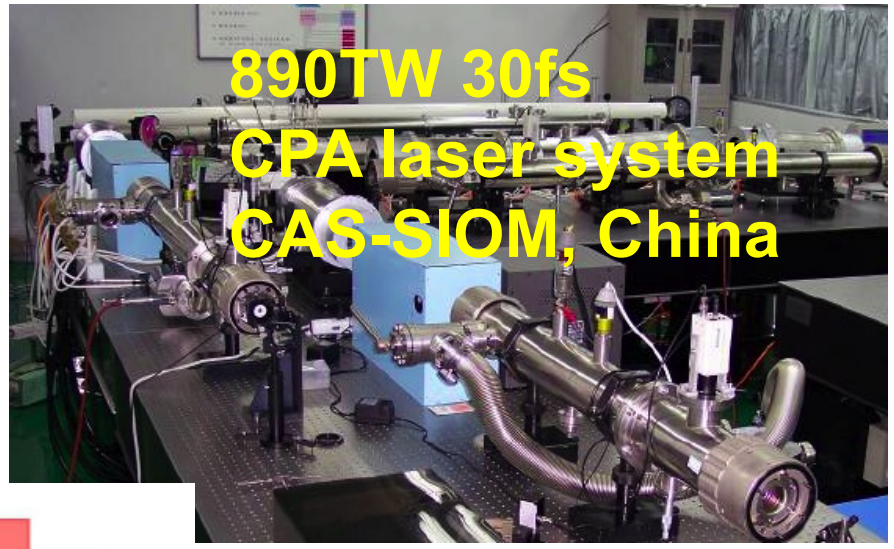


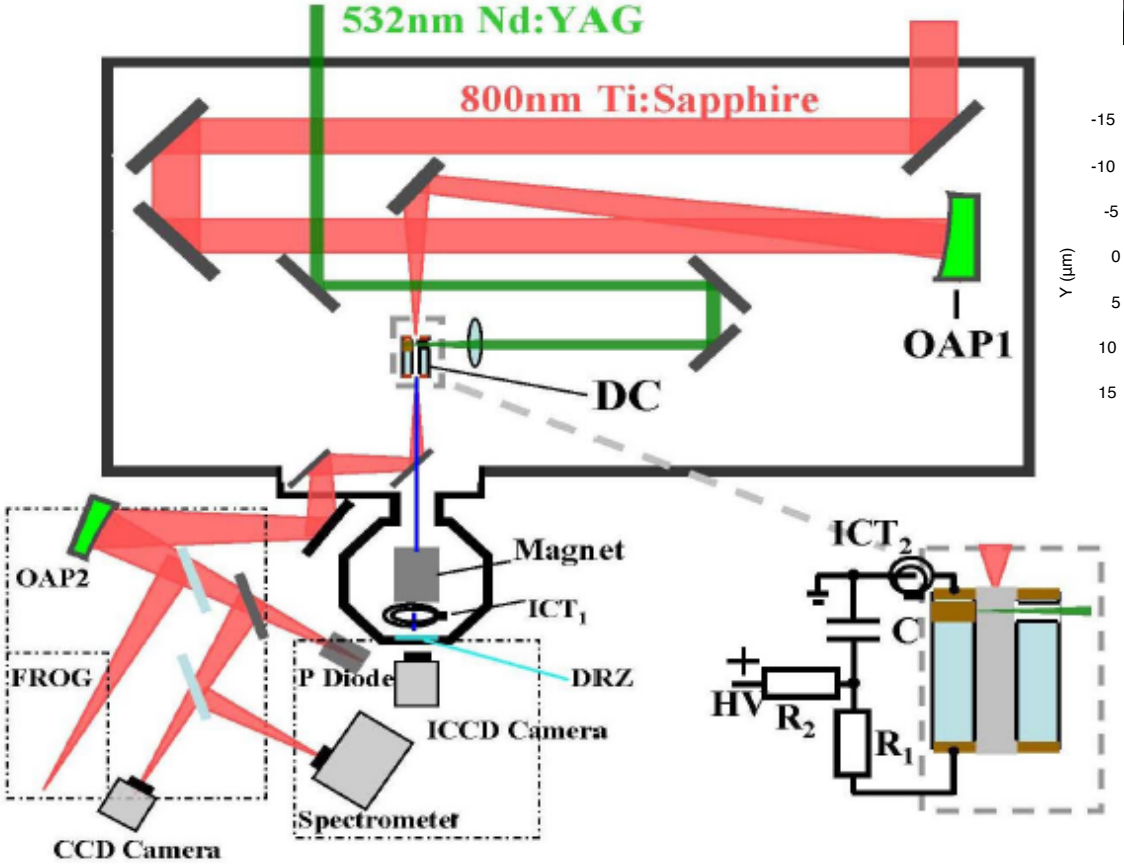
4 cm ablative capillary exp. at CAEP/KEK, China

Kameshima et al., Applied Physics Express 1, 066001 (2008)

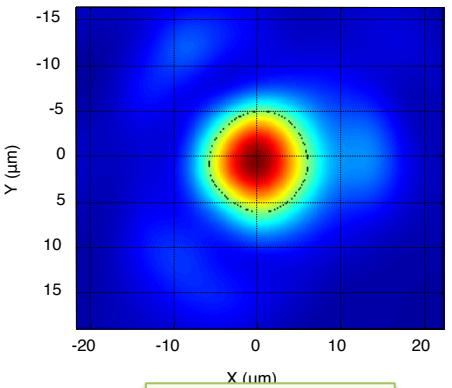
Laser plasma acceleration experiment with SIOM PW laser and KEK capillary plasma channel

SIOM-KEK collaboration

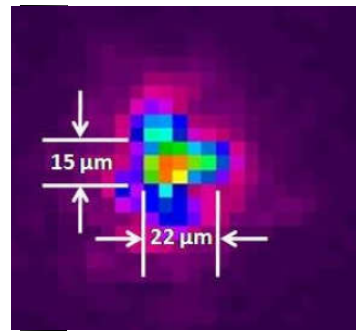




In vacuum



Guided



d_x =11 μm
d_y =12 μm
(FWHM)

d_x =22μm
d_y =15 μm
(FWHM)

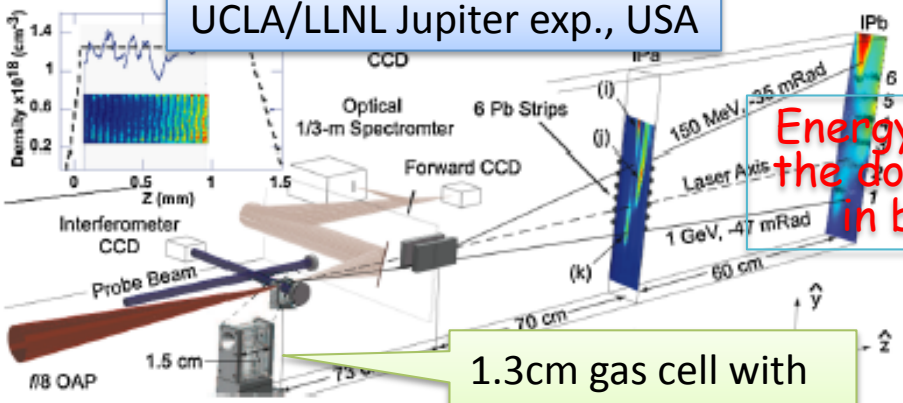
130 TW (6.5 J, 50fs)
on target

Setup with side-laser triggering ablative capillary driven by PW laser

Self-guided LWFA beyond 1 GeV

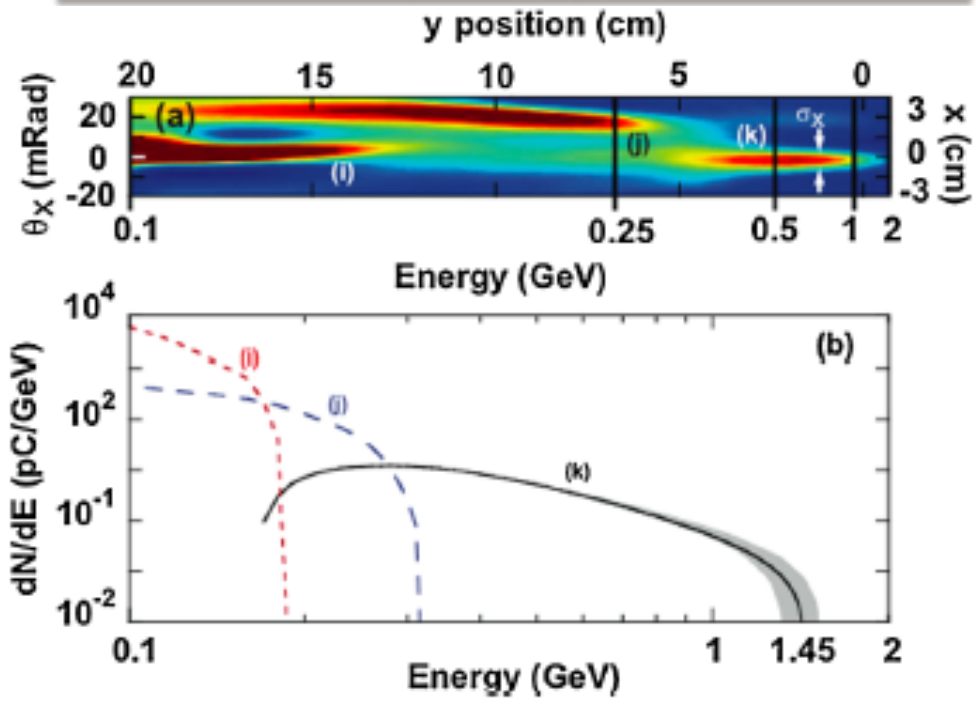
C. E. Clayton et al., PRL 105, 105003 (2010)

UCLA/LLNL Jupiter exp., USA



1.3cm gas cell with 97% He and 3% CO_2

110 TW 60 fs a_0 =3.8, n_e = 1.3 x 10^{18} cm^{-3}

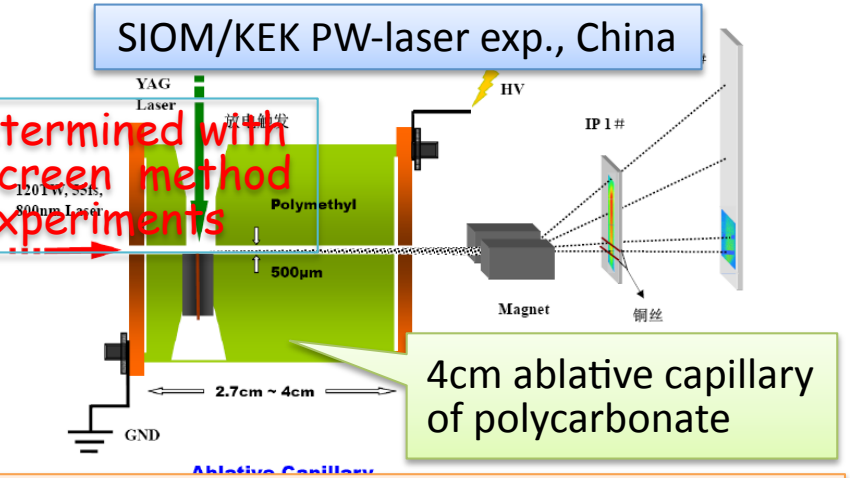


Capillary boosts LWFA up to near 2 GeV

J. S. Liu et al., CCAST-WL Worshop on Strong Field Laser Physics, Shanghai, Oct.10-29 (2010)

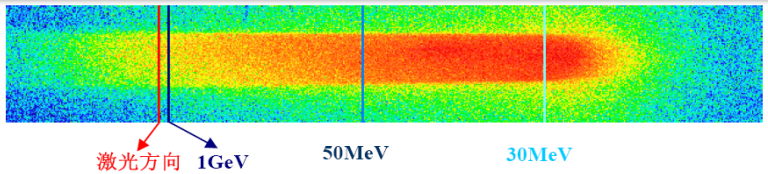
SIOM/KEK PW-laser exp., China

Energy is determined with the double screen method in both experiments

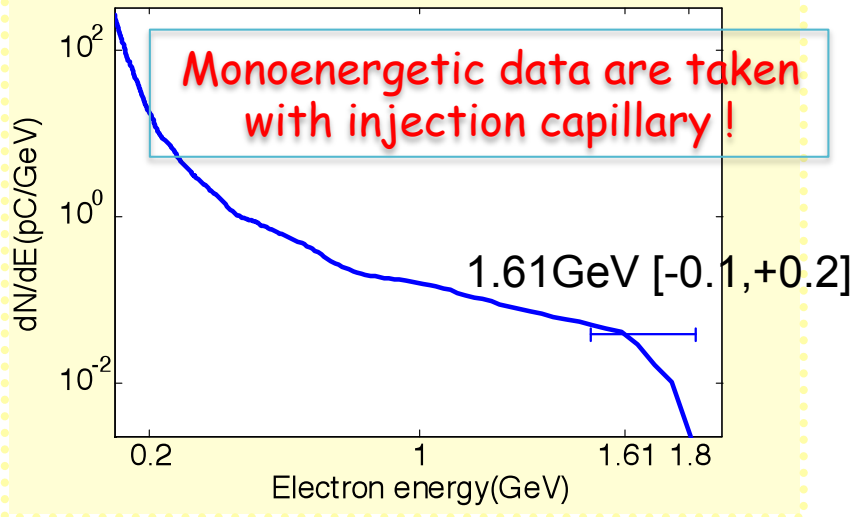


4cm ablative capillary of polycarbonate

72 TW 50 fs a_0 =2.9 n_e = 2.1x10^{18} cm^{-3}



Monoenergetic data are taken with injection capillary !



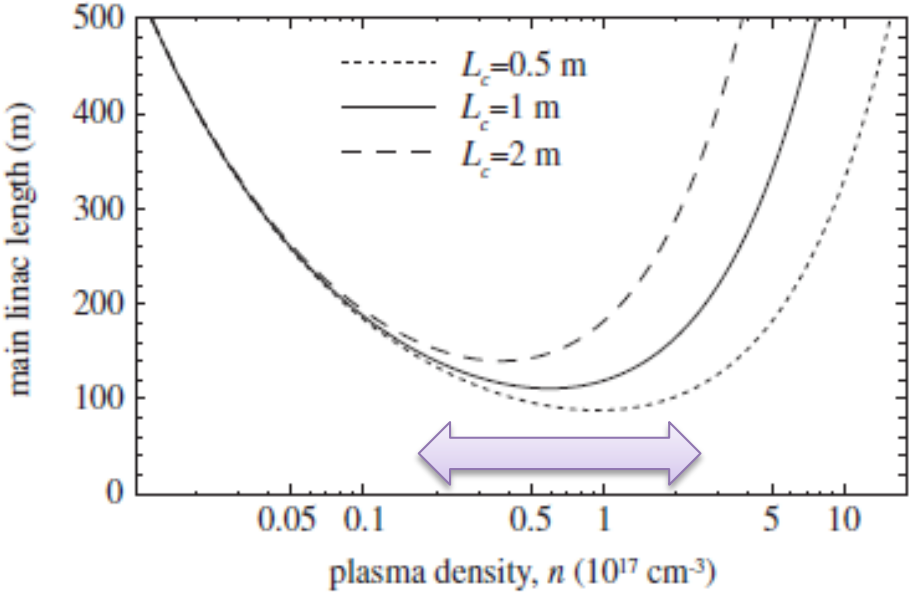
What is the optimum plasma density?

The electron plasma frequency: $\omega_p = \sqrt{\frac{4\pi e^2 n_0}{m_e}} = \frac{2\pi c}{\lambda_p}$

- Plasma electron density n_0 corresponds to frequency of RF cavity, which characterizes accelerator performance .
- Minimizing the overall length of LPA linac

$$L_{total} = \left[L_{stage} + L_c\right]\frac{E_b}{W_{stage}}$$

E_b : the final beam energy
W_{stage} : the energy gain in a single stage
L_{stage} : the single stage plasma length
L_c : the required coupling distance



C. B. Schroeder et al., PRST-AB 13, 101301 (2010)

$$W_{stage} \propto E_z L_d \propto n_0^{-1} \quad L_{stage} \approx L_{pd} \propto n_0^{-3/2}$$

For E_b =0.5 TeV, a_0 =1.5, coupling distance $L_c \lesssim$ 1m

The required operation plasma density ≈ 10^{17} cm^{-3}

- With minimization condition $L_c \sim L_{stage} \approx L_{pd}$

$$L_{total} \propto L_{pd} N_{stage} \propto n_0^{-1/2}$$

Selection of plasma density is not a big issue.

- Plasma density is continuously tunable over the broad range.
- Plasma accelerator structure is not so expensive.

Plasma density could be determined by beam quality and power requirement

Radiation damping effect

- Electrons accelerated by LPA undergo betatron oscillations due to strong focusing force
- Emission of synchrotron radiation results in a energy loss and radiation damping with its rate.

$$P_x \cong \frac{2e^2\gamma^2}{3m^2c^3}F_\perp^2 \qquad \nu_\gamma = \frac{P_s}{\gamma mc^2} = \frac{\tau_R\gamma}{m^2c^2}F_\perp^2$$

where $\tau_R = 2r_e/3c \cong 6.26\times10^{-24}$ s

$r_e = e^2/mc^2 = 2.818\times10^{-13}$ cm

$$F_\perp = -mc^2K^2x$$
$$K^2 = 2x_c^{-2}\left(e\phi_0/mc^2\right)$$

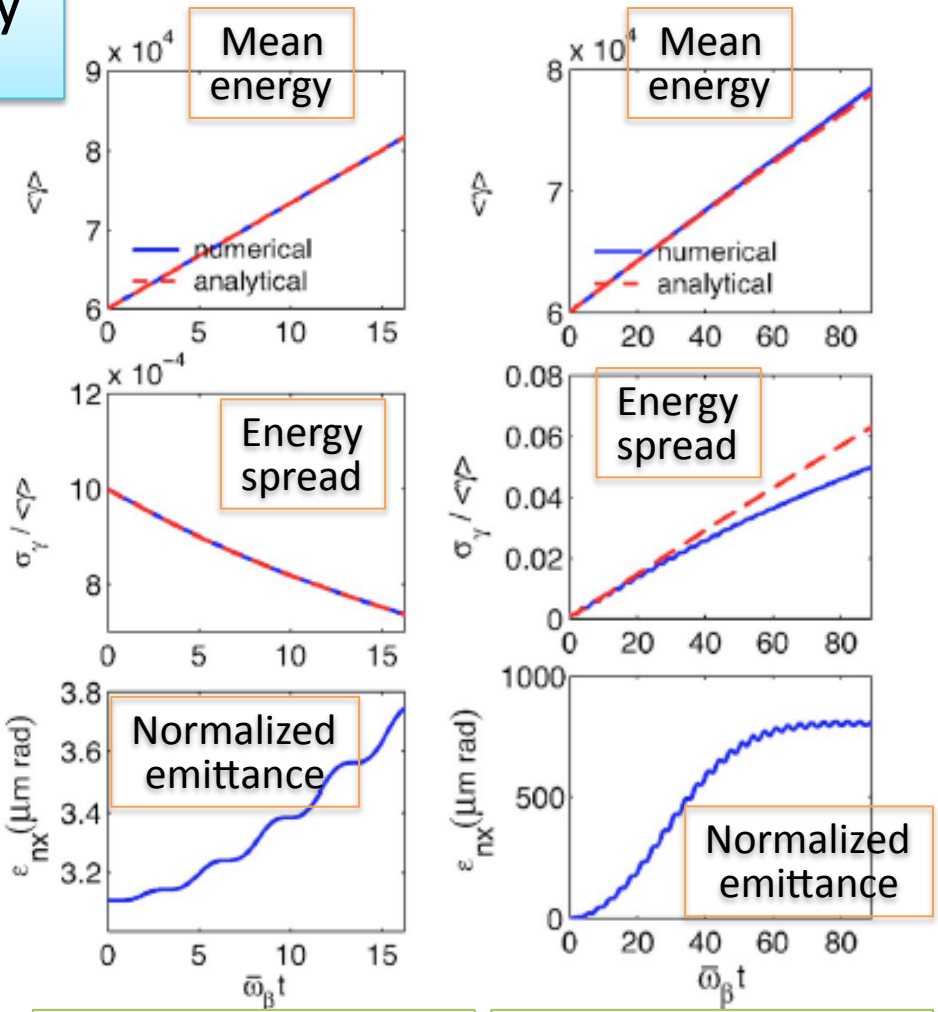
for the linear regime with potential ϕ_0, characteristic channel width x_c

$$K = k_p/\sqrt{2}$$

for the blowout (or bubble) regime

Power requirement for the linear collider

- Collision frequency: $f \propto N^{-2} \propto n_0$
  for a constant required luminosity
- Beam power: $P_b = f\,N E_b \propto n_0^{1/2}$
- Average laser power per stage: $P_{avg} \cong f\,U_L \sim f\cdot P_L\tau_L$
  $\propto n_0\cdot n_0^{-1}\cdot n_0^{-1/2} \propto n_0^{-1/2}$
- Total wall plug power $P_{wall} \propto N_{stage}P_{avg} \propto n_0^{1/2}$



30 GeV injection
30 cm plasma channel
E_z = 37 GV/m
n_0 = 10^{16} cm^{-3}

30 GeV injection
30 cm plasma channel
E_z = 37 GV/m
n_0 = 3x10^{17} cm^{-3}

P. Michel et al., PRE 74, 026501 (2006)

From points of high quality and power cost, choose plasma density of the order of 10^{16} cm^{-3}

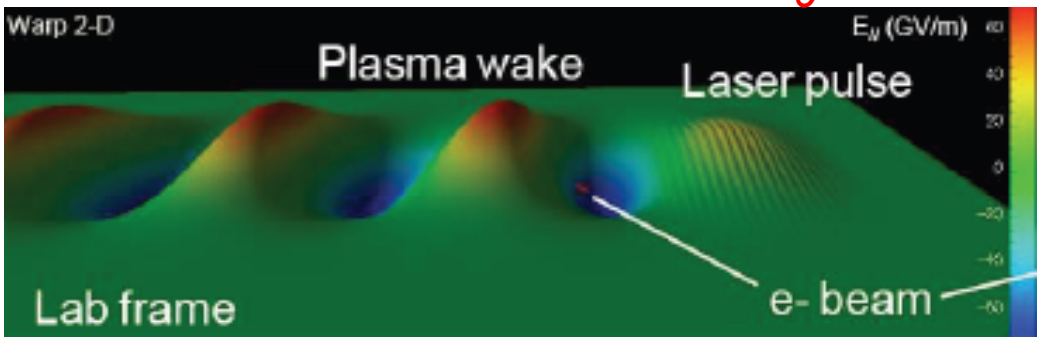
Linear wake or Nonlinear wake ?

Normalized vector potential of laser intensity

$$a_0 = \left(\frac{2e^2\lambda_0^2 I}{\pi m_e^2 c^5}\right)^{1/2} \cong 0.855\times10^{-9} I^{1/2}\left[\mathrm{W/cm^2}\right]\lambda_0[\mu\mathrm{m}]$$

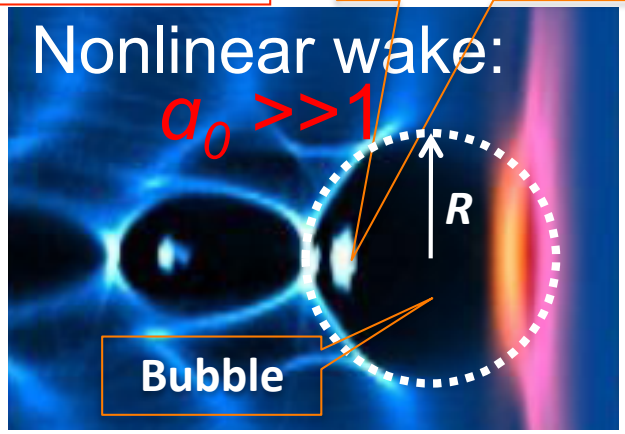
Self-injected electrons

Linear wake: $a_0 \lesssim 1$



C.G.R. Geddes,LPAW2009

Nonlinear wake: $a_0 >> 1$



W. Lu, PRST-AB 10, 061301 (2007)

$$\Delta W_{linear} \approx 1.3 mc^2 a_0^2 \frac{n_c}{n_p}$$

$$\Delta W_{linear}\left[\mathrm{GeV}\right] \approx 35 \frac{P\left[\mathrm{TW}\right]}{r_0^2\left[\mu\mathrm{m}\right]}\left(\frac{10^{18}}{n_p\left[\mathrm{cm^{-3}}\right]}\right)$$

for λ=0.8 μm

For $P = 1\,\mathrm{PW}, \tau_L = 130\,\mathrm{fs}, U_L = 130\,\mathrm{J}$

$r_0 = 172\,\mu\mathrm{m}, a_0 = 1, n_p = 1\times10^{17}\,\mathrm{cm^{-3}}$

$$\Delta W_{linear} \approx 12\ \mathrm{GeV\ at}\ L_{acc} = 1.8\ \mathrm{m}$$

Avoid self-injection of electrons

$$\Delta W \approx \frac{2}{3} mc^2 a_0 \frac{n_c}{n_p}$$

$$\Delta W\left[\mathrm{GeV}\right] \approx 0.36\left(P\left[\mathrm{TW}\right]\right)^{1/3}\left(\frac{10^{18}}{n_p\left[\mathrm{cm^{-3}}\right]}\right)^{2/3}$$

for λ=0.8 μm

For $P = 1\,\mathrm{PW}, \tau_L = 130\mathrm{fs}, U_L = 130\mathrm{J},$

$r_0 = 58\,\mu\mathrm{m}, a_0 = 3, n_p = 1\times10^{17}\,\mathrm{cm^{-3}}$

$$\Delta W_{linear} \approx 17\ \mathrm{GeV\ at}\ L_{acc} = 0.7\ \mathrm{m}$$

Allow self-injection of electrons

Design of 10 GeV acceleration stage in the quasi-linear regime

$$a_0^2 \sim 1$$

1) Acceleration wakefield

For $k_p\sigma_z = 2/3$ σ_z:laser pulse duration

$$E_z[\mathrm{GV/m}] \sim 0.3 \frac{a_0^2}{\sqrt{1+a_0^2/2}} \sqrt{\frac{n_0}{10^{14}[\mathrm{cm}^{-3}]}}$$

2) Acceleration length

Dephasing length: $L_d \cong \lambda_p \frac{\omega_0^2}{\omega_p^2} = \lambda_p \frac{n_c}{n_0}$

Pump depletion length:

$$k_p L_{pd} \cong \frac{8}{\sqrt{\pi}} \frac{\omega_0^2}{\omega_p^2} \frac{1}{a_0^2 k_p \sigma_z} \exp\left(\frac{k_p^2\sigma_z^2}{2}\right) = \frac{8.5}{a_0^2} \frac{n_c}{n_0}$$

3) Energy gain

$\Delta W \approx eE_z L_{acc}$

$$\Delta W \approx eE_z L_{etch} \approx 0.2 mc^2 \frac{a_0^2}{\sqrt{1+a_0^2/2}} \frac{n_c}{n_0}$$

$$\Delta W[\mathrm{GeV}] \approx 0.18 \frac{a_0^2}{\sqrt{1+a_0^2/2}} \left(\frac{10^{18}\,\mathrm{cm}^{-3}}{n_0}\right)\left(\frac{0.8\mu\mathrm{m}}{\lambda_0}\right)^2$$

Design of 10 GeV electron injector in the weakly nonlinear regime

$$a_0 \geq 2$$

For $k_p R \approx k_p r_L \approx 2\sqrt{a_0}$ *R:* Bubble radius, r_L:laser spot radius

$$E_{z\max} \sim \sqrt{a_0} \frac{mc\omega_p}{e} \approx 96[\mathrm{GV/m}] \sqrt{\frac{a_0 n_0}{10^{18}[\mathrm{cm}^{-3}]}}$$

Dephasing length:

$$k_p L_d \approx \frac{2}{3}\frac{\omega_0^2}{\omega_p^2} k_p R \approx \frac{4}{3}\sqrt{a_0}\frac{n_c}{n_0} \qquad L_d \approx \frac{2\sqrt{a_0}}{3\pi}\lambda_p \frac{n_c}{n_0}$$

Etching distance:

The laser etches back due to local pump depletion.

$$L_{etch} \cong \frac{\omega_0^2}{\omega_p^2} c\tau_L = c\tau_L \frac{n_c}{n_0}$$

$$L_{etch} \geq L_d \Rightarrow c\tau_L \geq \frac{2}{3}R \approx \frac{2\sqrt{a_0}}{3\pi}\lambda_p$$

$$\Delta W \approx eE_z L_d \approx \frac{4}{3} mc^2 a_0 \frac{n_c}{n_0}$$

$$\Delta W[\mathrm{GeV}] \approx 1.2 a_0 \left(\frac{10^{18}\,cm^{-3}}{n_0}\right)\left(\frac{0.8\mu\mathrm{m}}{\lambda_0}\right)^2$$

The quasi-linear regime

4) Spot size

To avoid bubble formation

$$\frac{k_p^2 r_L^2}{4} \geq \frac{a^2}{\sqrt{1+a^2/2}} \Rightarrow k_p r_L \geq 2 \quad \text{for } a_0 \sim 1$$

To avoid self-focusing

$$\frac{P}{P_c} = \frac{k_p^2 r_L^2 a_0^2}{32} \leq 1 \Rightarrow k_p r_L \leq 6 \quad \text{for } a_0 \sim 1$$

5) Power and energy requirement

$$P[\mathrm{TW}] = \frac{a_0^2}{30}\left(\frac{r_L}{1\mu\mathrm{m}}\right)^2\left(\frac{0.8\mu\mathrm{m}}{\lambda_0}\right)^2 \qquad E_L[\mathrm{J}] = P[\mathrm{TW}]\tau_L[\mathrm{ps}]$$

6) The maximum nunber of accelerated charge

For 100 % beam-loading efficiency with 100% energy spread,

$$N_{\max} \approx \left(\frac{n_0}{4\pi r_e}\right)^{1/2} \frac{eE_0}{mc\omega_p} A \qquad A \approx \pi / k_p^2$$

$$\approx \frac{1}{32}\left(\frac{1}{r_e^3 n_0}\right)^{1/2} \frac{a_0^2}{\sqrt{1+a_0^2/2}} k_p\sigma_z \exp\left(-\frac{k_p^2\sigma_z^2}{4}\right)$$

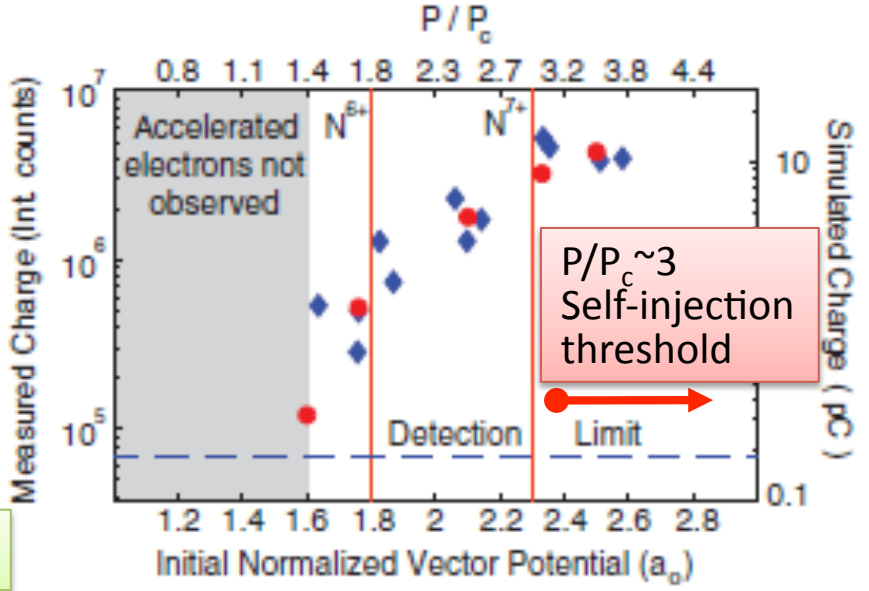
For $a_0 = 1, k_p\sigma_z = 2/3$

$$N_{\max} \approx 6.6\times10^9 \sqrt{\frac{10^{15}}{n_0[cm^{-3}]}} \qquad Q_{\max}[\mathrm{nC}] \approx \sqrt{\frac{10^{15}}{n_0[cm^{-3}]}}$$

The weakly nonlinear regime

$$k_p R \approx k_p r_L \approx 2\sqrt{a_0} \Rightarrow r_L = \frac{\lambda_p}{\pi}\sqrt{a_0}$$

Ionization induced injection needs $a_0 \gtrsim 2$



n_e ~ 1.4x10^{19}cm^{-3} ; He:N_2 9:1 gas mix

A. Pak et al., PRL 104.025003 (2010)

$$N_{\max} \approx \frac{8}{15 k_0 r_e}\sqrt{\frac{e^2 P}{m^2 c^5}} \approx 2.5\times10^9 \frac{\lambda_0[\mu\mathrm{m}]}{0.8}\sqrt{\frac{P[\mathrm{TW}]}{100}}$$

7) Plasma channel

$$n(r) = n_0 + \Delta n \frac{r^2}{r_{ch}^2}$$

- Matched radius:

$$r_M = \left(\frac{r_{ch}^2}{\pi r_e \Delta n} \right)^{1/4} \qquad r_e = e^2 / mc^2$$

- Channel depth:

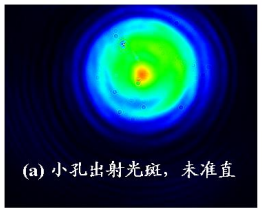
$$\Delta n = \frac{r_{ch}^2}{\pi r_e r_M^4} \qquad \frac{\Delta n}{n_0} = \frac{4}{k_p^2 r_M^2} \left(\frac{r_{ch}}{r_M} \right)^2$$

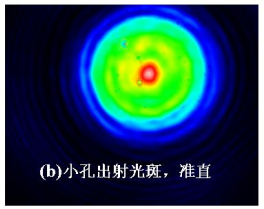
- Critical channel depth:

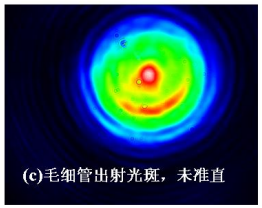
$$\Delta n_c = \frac{1}{\pi r_e r_L^2} \qquad \frac{\Delta n_c}{n_0} = \frac{4}{k_p^2 r_L^2}$$

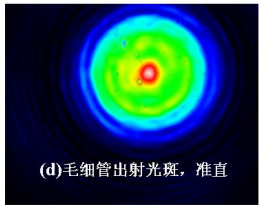
With $r_L = r_M$

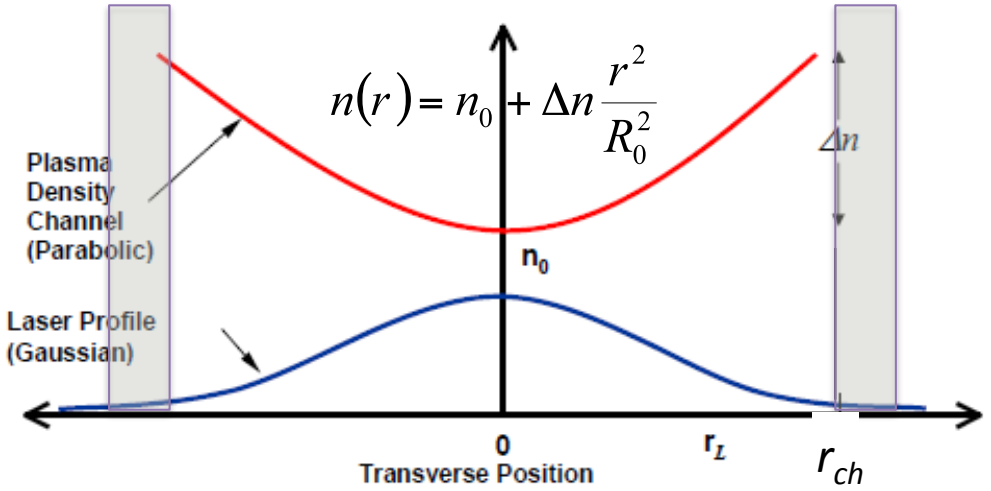
$$\frac{\Delta n}{n_0} = \frac{4}{k_p^2 r_L^2} \left(\frac{r_{ch}}{r_L} \right)^2$$









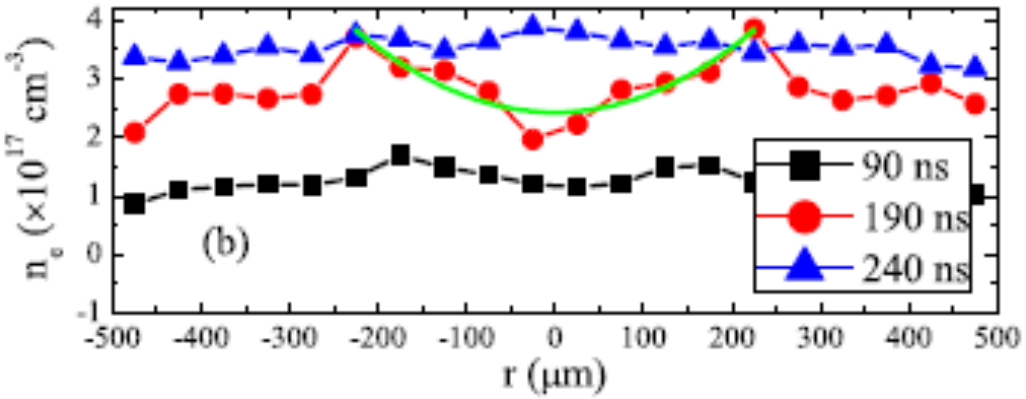


- Critical channel depth:

$$\frac{\Delta n_c}{n_0} = \frac{4}{k_p^2 r_L^2} \approx \frac{1}{a_0}$$

Ablative capillary with r_{ch} =0.5 mm in the range of 10^{17} cm^{-3}

M. Liu et al., Rev. Sci. Instr. 81, 036107 (2010)



Positron injector by ultraintense short laser pulse

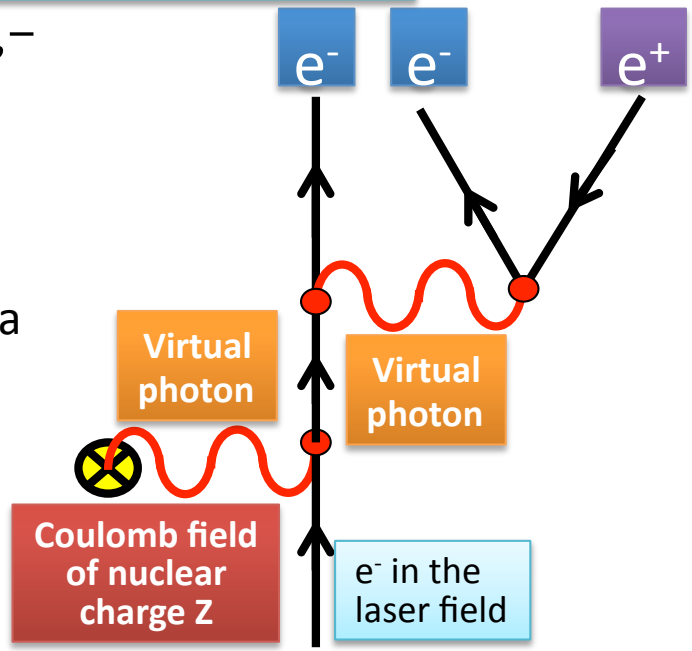
- Trident process in the nuclear field: $e + Z \rightarrow e' e^+ e^-$
- Threshold intensity for pair production

$$I_t = \frac{2.6\times10^{19}}{[\lambda_L(\mu\mathrm{m})]^2}\ \mathrm{W/cm^2} \quad \text{for} \quad E_i > 3m_e c^2$$

- The approximate cross section from H.J. Bhabha's formula

$$\sigma_T \cong 9.6\times10^{-4}(\alpha r_e Z)^2(\bar{\gamma}-3)^{3.6} \approx 9.6\times10^{-4}(\alpha r_e Z)^2\bar{\gamma}^4$$

H.J. Bhabha, Proc. R. Soc. 152, 559, 1935
Shearer, J.W. et al., Phys. Rev. A8, 1582, 1973



- Assuming the electron energy accelerated by laser radiation pressure as $\bar{\gamma} \approx \frac{1}{12} a_0^2 \frac{n_c}{n_0} >> 3$
- The yield of pair production *X. Q. Yan, 5th ASSS 2010*

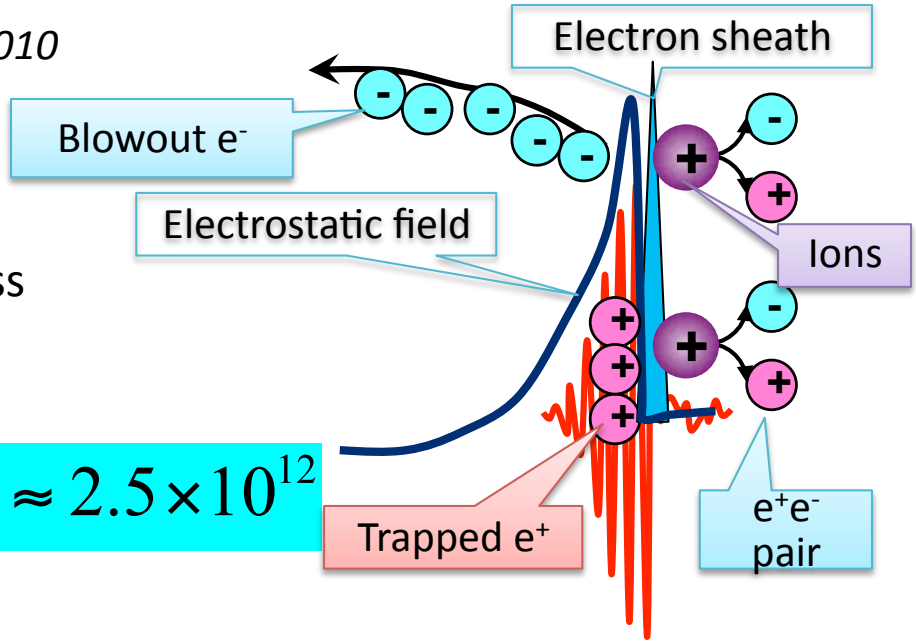
$$N_p \approx 5\times10^{-11} a_0^9 Z^3 \left(\frac{n_c}{n_0}\right)^2 \left(\frac{r_0}{\lambda}\right)^2 \left(\frac{\Delta}{\lambda}\right)^2$$

r_0 : the laser spot radius Δ : the plasma thickness

e.g.

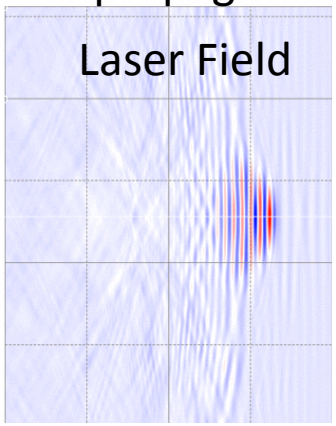
Z = 54 (Xe)
a_0 = 5.5 (I = 6x10^{19} W/cm^2)
n_0 = 5 x 10^{19} cm^{-3}
r_0 = 10 μm
Δ = 0.6 mm
λ = 0.8 μm

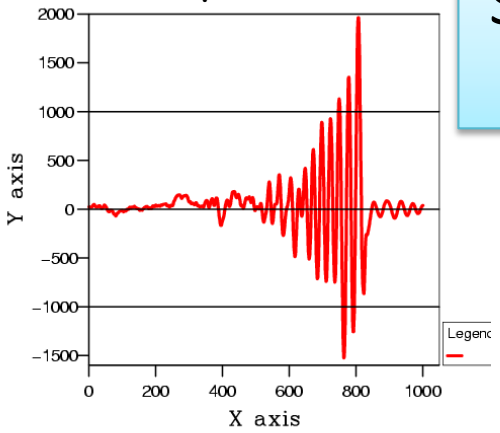
$$N_p \approx 2.5\times10^{12}$$

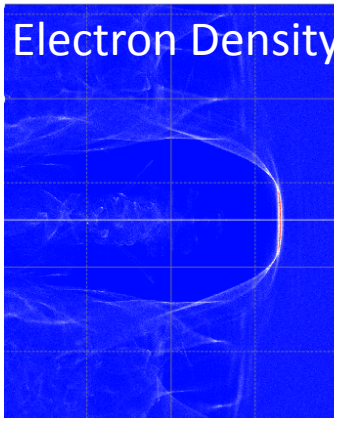


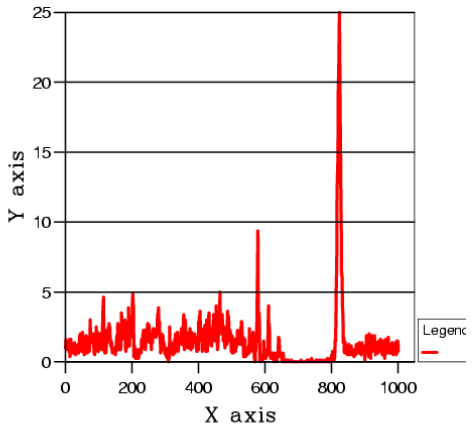
Solitary positive electrostatic field by asymmetric laser pulse

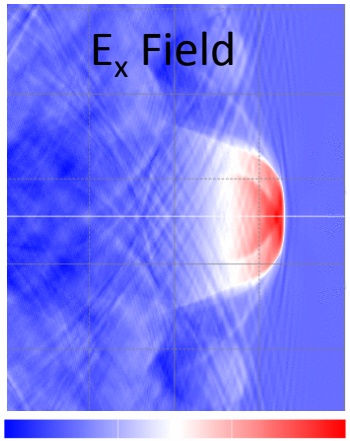
At propagation distance 256μm

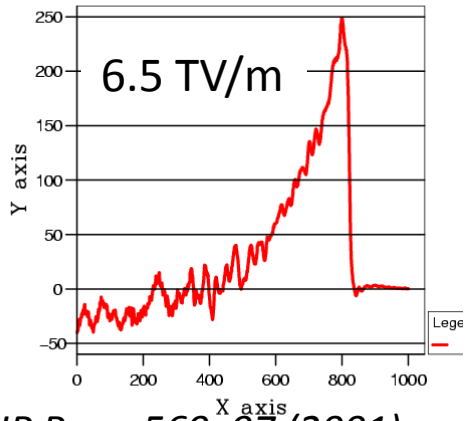












K. Nakajima et al., AIP Proc. 569, 97 (2001)

Peak power	P =100 TW
Pulse duration	τ_p =20 fs
Spot radius	r_0 = 10 μm
Intensity	I_0 = 6x10^{19} W/cm^2
	a_0 = 5.5
Plasma density	n_0 = 5x10^{19} cm^{-3}

$$n_e = \frac{n_0}{1-\beta_x} \approx \frac{n_0}{1-\beta_g} \Rightarrow \frac{n_e}{n_0} \approx \frac{1}{1-\beta_g}$$

$$\beta_g = \sqrt{1-\frac{n_0}{n_c}} \approx 0.986$$

$$n_e \approx 3.6\times10^{21}\,\mathrm{cm}^{-3}$$

As a result of strong self-focusing

$$E_{\max} \approx \sqrt{n_e\left[\mathrm{cm}^{-3}\right]}\,\mathrm{eV} \approx 6\ \mathrm{TV/m}$$

Pump depletion length ~ 0.6 mm

e^+ energy gain ~ 1.8 GeV

Design of multi-stage LWFA toward 100 GeV

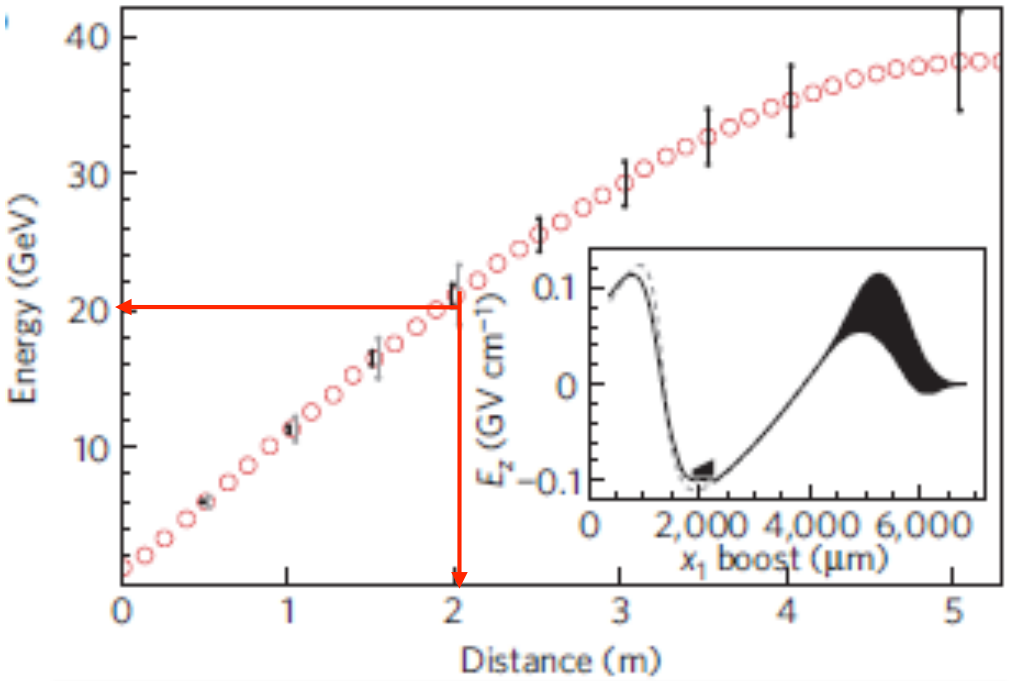
	Electron Injector	Positron Injector	10 GeV stage	100 GeV stage	Multi-stage 100 GeV	LBNL-BELLA 10 GeV
Energy gain ΔW [GeV]	10	1.8	10	100	10 x 10	10
Laser intensity a_0	2.0	5.5	1.0	2.0	1.0	1.4
Spot radius w_0 [μm]	31	10	64	80	64	90
Pulse duration τ_L [fs]	68	20	120	216	120	95
Peak power P [TW}	130	100	137	865	10 x 137	563
Pulse energy E_L [J]	9	2	16	187	10 x 16	53
Plasma density n_e [cm^{-3}]	2.4×10^{17}	5×10^{19}	2.8×10^{16}	2.4×10^{16}	2.8×10^{16}	1.0×10^{17}
Plasma length L_p [cm]	15	0.1	200	470	10 x 200	~100
Maximum charge Q [nC]	0.46	1	0.2	2		0.3

∗Stage energy gain of 10-100 GeV would be necessary for 1 – 10 TeV collider application

Comparison with 3D PIC simulation in the weakly nonlinear regime

3D PIC simulation:

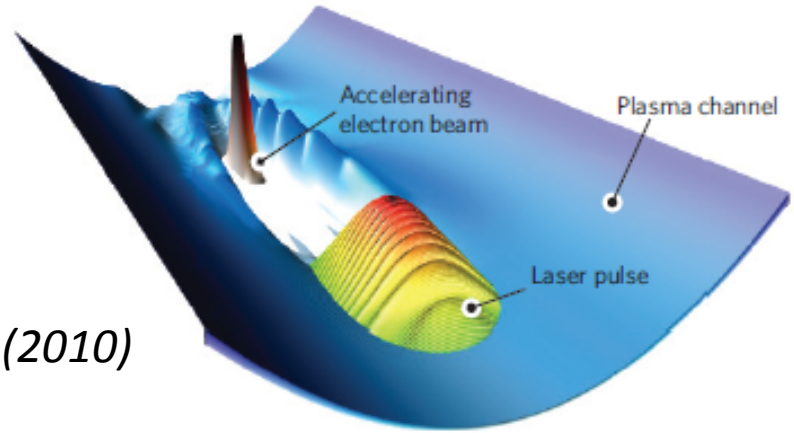
$$a_0 = 2, n_0 = 2.2\times10^{16}\,\mathrm{cm}^{-3}$$
$$\Rightarrow \bar{E}_z = 10\,\mathrm{GV/m}$$
$$\Delta W \approx 20\,\mathrm{GeV} \ \text{ in } L_{acc} = 2\,\mathrm{m}$$



Design:

$$a_0 = 1, n_0 = 2.8\times10^{16}\,\mathrm{cm}^{-3}$$
$$\Rightarrow \bar{E}_z = 5\,\mathrm{GV/m}$$
$$\Delta W \approx 10\,\mathrm{GeV} \ \text{ in } L_{acc} = 2\,\mathrm{m}$$

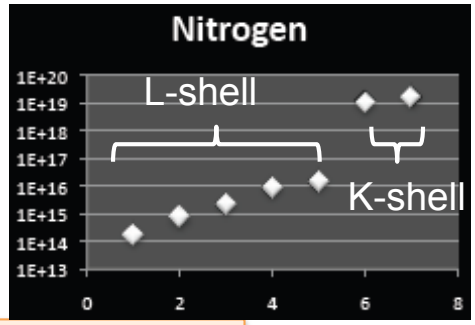
P = 1.4 PW, a_0=2.0, τ_L=160fs, w_0=100μm
n_e= 2.2x10^{16} cm^{-3} , L_{acc} = 528 cm



S. F. Martins et al., Nature Phys. 6, 311 (2010)

Electron injector example with RF discharge ignited by laser pulse

N_2 BSI threshold



An example: Ionization-induced Injection scheme

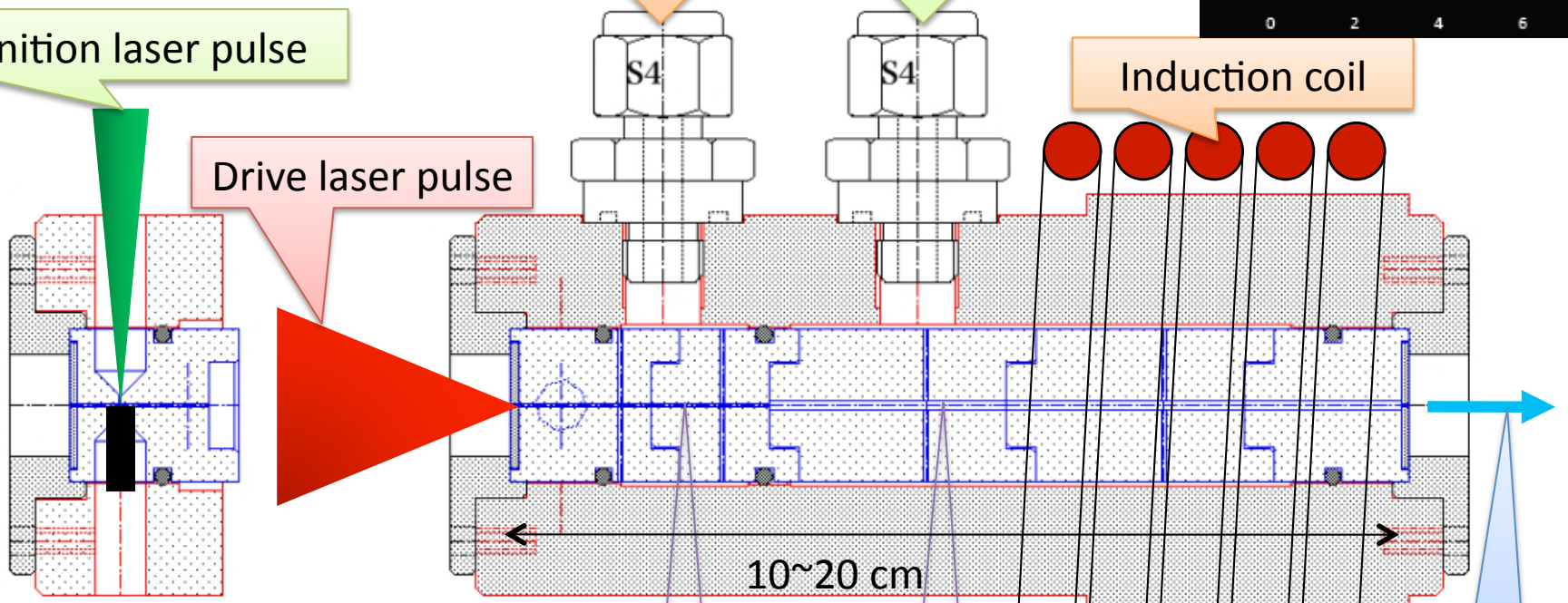
H_2+N_2 or Ar mixed gas

H_2 gas

Ignition laser pulse

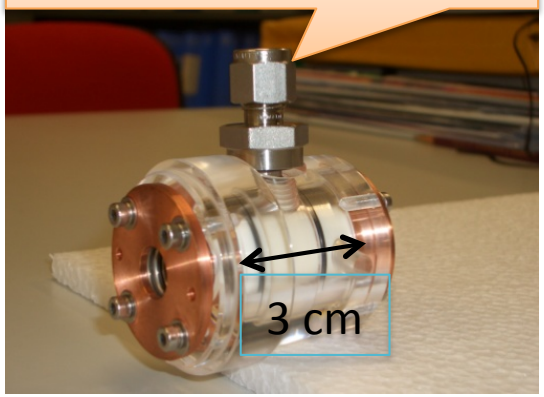
Drive laser pulse

Induction coil



Electron beam

Ceramic gas-fill capillary



Ceramic Capillary 0.5mmϕ

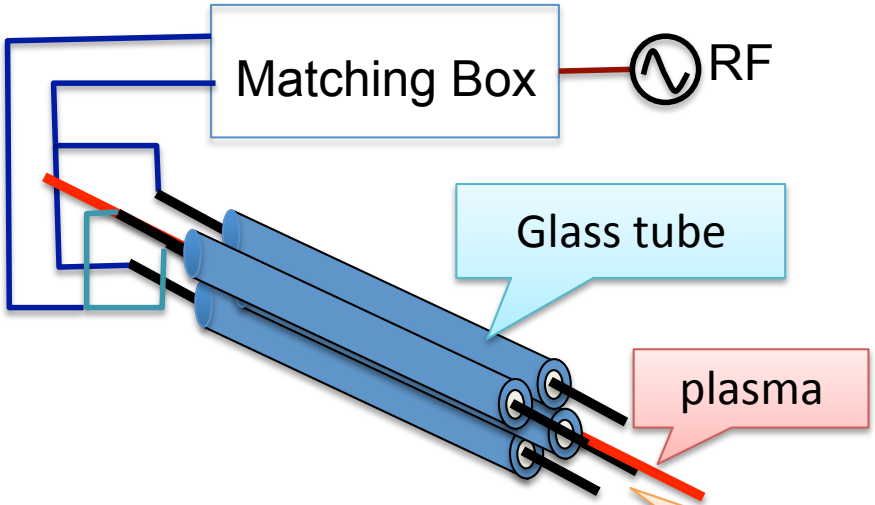
Ceramic Capillary 1mmϕ

RF power generator

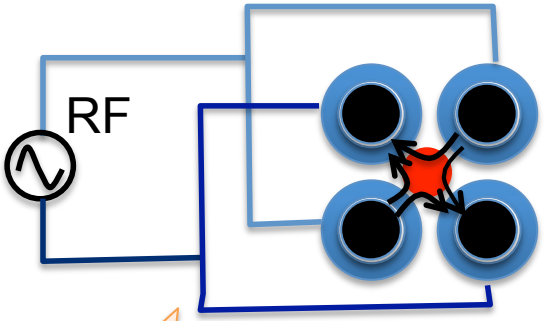
100 kHz operation is possible !

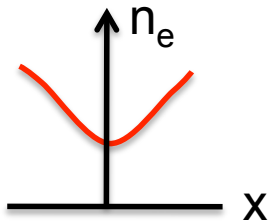
T. Shoji, Univ. Nagoya

Preliminary test of a long-range plasma channel generated by RF discharge



Capacitive (quadrupole field) discharge

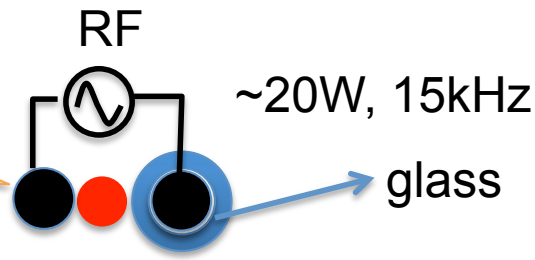


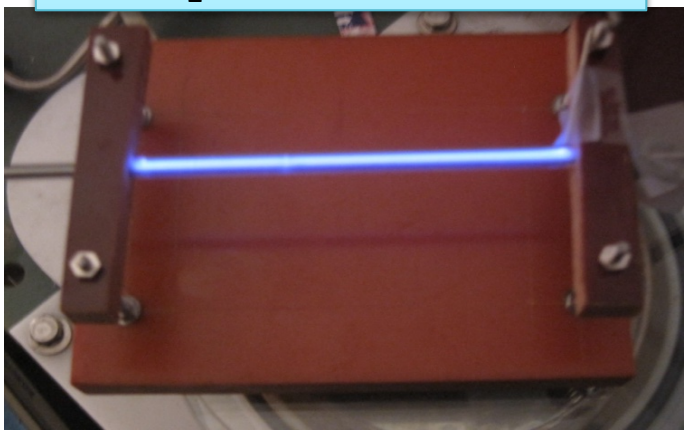


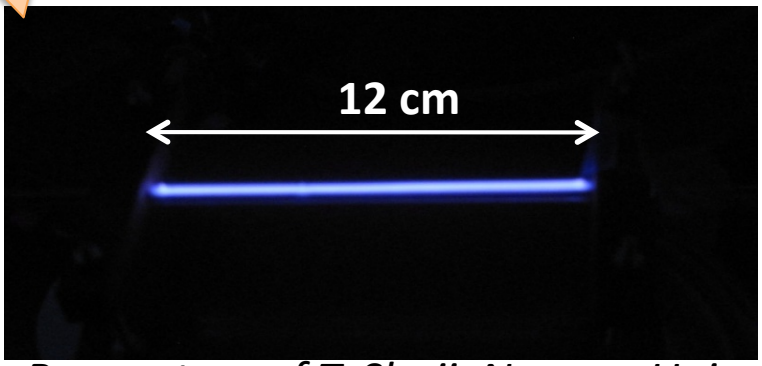
prediction

Test line plasma
Diameter: ~0.5mmϕ,
Length: 120 mm long
Gas: N_2 discharge at 1 atm

Plasma channel can be extended to ~100 m at 100 kHz rep rate







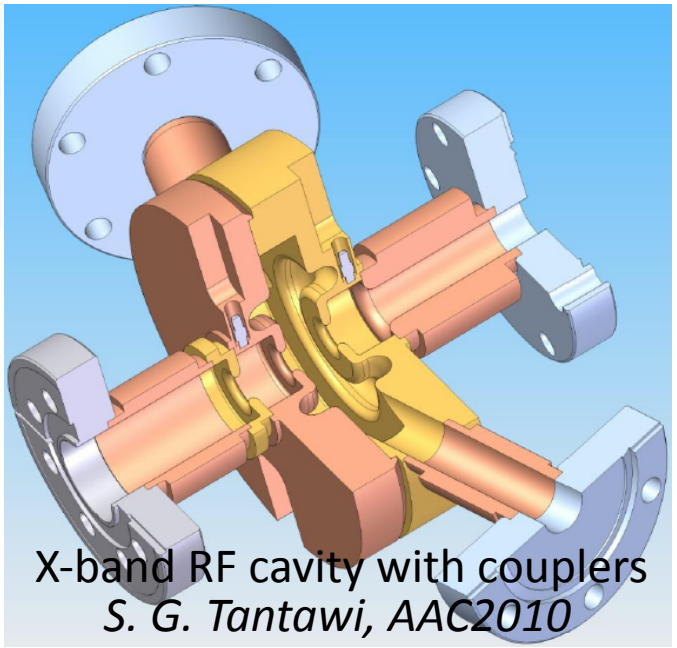
By courtesy of T. Shoji, Nagoya Univ.

Staging needs efficient coupling of ultraintense laser pulses at a rep rate of kHz like RF couplers for future linear collider applications

- Laser light is bent by a **curved plasma channel**

$$n(r) = n_0 + \Delta n \frac{r^2}{r_{ch}^2}$$

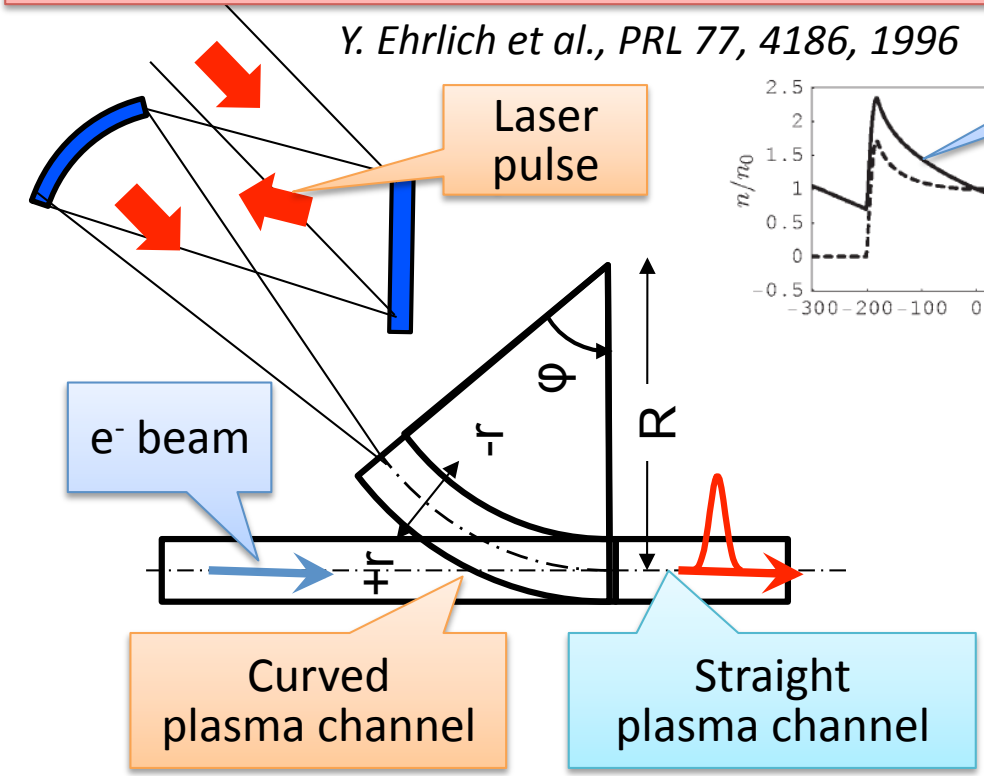
- Shift of equilibrium position $r_M = \frac{n_c}{\Delta n}\frac{r_{ch}^2}{R}$
- A minimum acceptable radius of curvature $R \geq \frac{n_c}{\Delta n} r_{ch}$

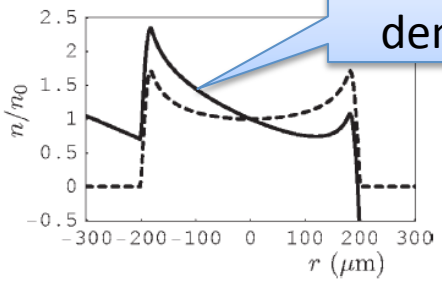


X-band RF cavity with couplers
S. G. Tantawi, AAC2010

- The first curved plasma channel experiment with 10 cm radius of curvature showed as high as 85% transmission of 50 μm spot radius for >10^{16} W/cm^2.

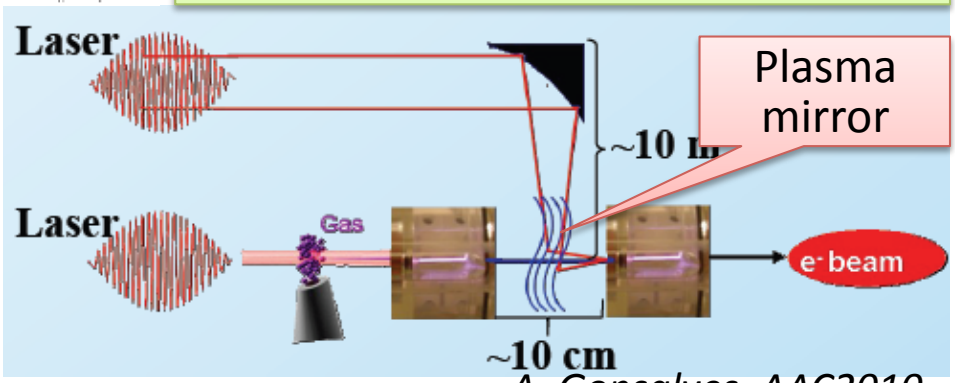
Y. Ehrlich et al., PRL 77, 4186, 1996





kHz operation possible ?

Plasma mirror in coupling: compact staging with liquid jet or thin foil producing critical density plasma

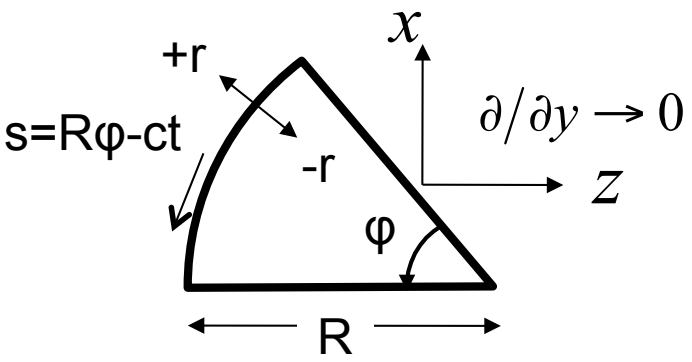


A. Gonsalves, AAC2010

Curved plasma channel coupler

A.J.W. Reitsma et al., POP 14, 053104 (2007) *A. Reitsma, LPAW2007*

Curved plasma channel



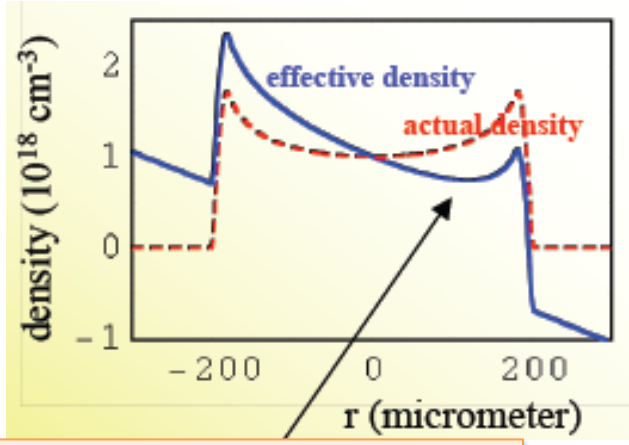
Geometry

Plasma density: $n(r) = n_0\left(1 + r^2/r_c^2\right)$

Paraxial approximation:

$$2cik_0\frac{\partial a}{\partial t} + c^2\frac{\partial^2 a}{\partial r^2} = \left(\frac{4\pi n_e e^2}{m\gamma_e} - 2c^2k_0^2\frac{r}{R}\right)a$$

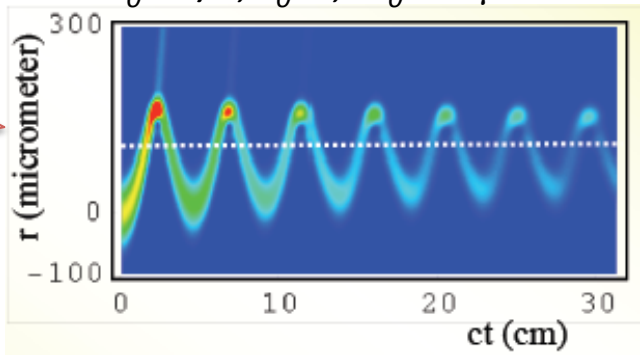
n_e, γ_e – plasma electron density and Lorentz factor $\gamma_e = \sqrt{1+|a|^2}$



Shift of equilibrium position from $r=0$ to $r_M=(\omega_0/\omega_{p0})^2 r_c^2/R$ should be small compared to channel radius: $r_c/R \ll (\omega_{p0}/\omega_0)^2$

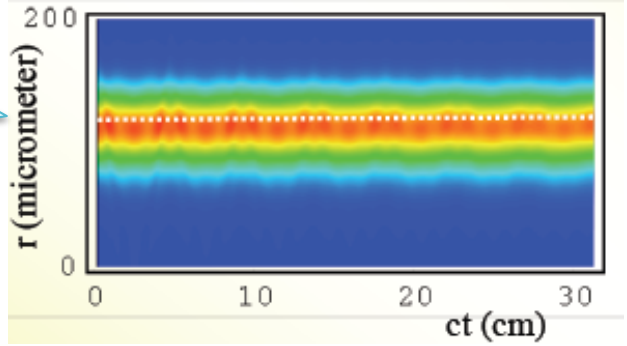
$a_0^2=1/2$, $r_0=0$, $w_0=43$ μm

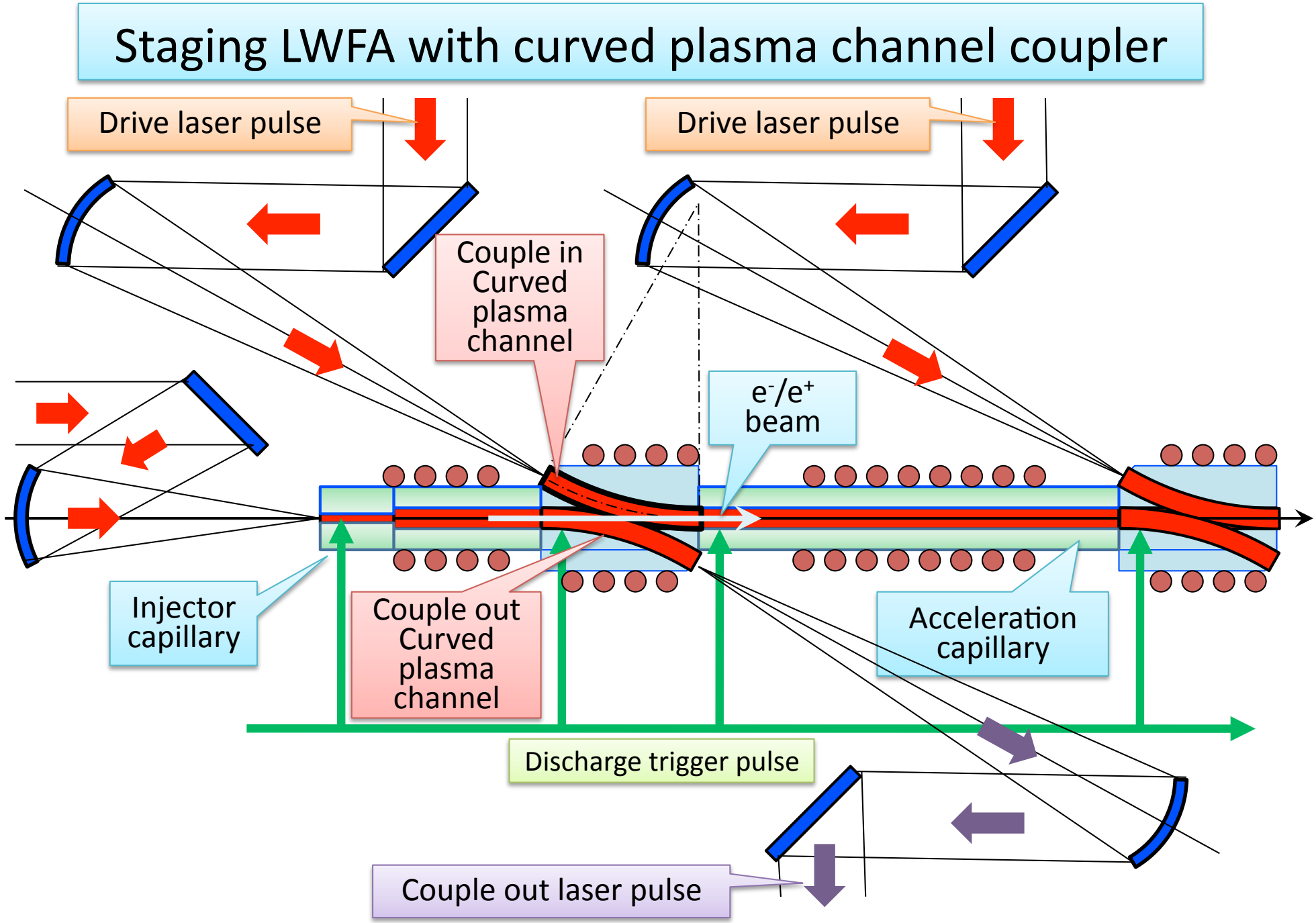
on-axis injection with a too-big spot size



$a_0^2=1/2$, $r_0=115$ μm, $w_0=30$ μm

off-axis injection with a spot size smaller than the matched spot




Staging LWFA with curved plasma channel coupler
Drive laser pulse
Drive laser pulse
Couple in Curved plasma channel
e-/e+ beam
Injector capillary
Couple out Curved plasma channel
Acceleration capillary
Discharge trigger pulse
Couple out laser pulse

Synchronization of two laser pulses will be controlled by frequency domain interferometry with fs resolution

Two pulses split in the time interval *T* can be observed as fringes in the frequency domain interferogram.

$$E_{tot}(t) = E_1(t) + E_2(t - T)$$

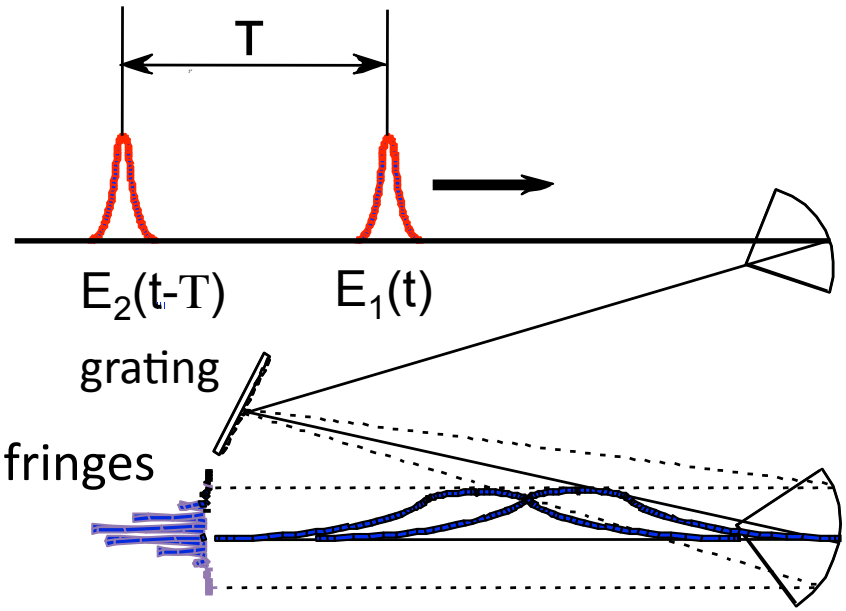
The power spectrum:

$$I_{tot}(\omega) = \frac{1}{2\pi}\left|\int_{-\infty}^{\infty} e^{-i\omega t}\left[E_1(t) + E_2(t-T)\right]dt\right|^2$$

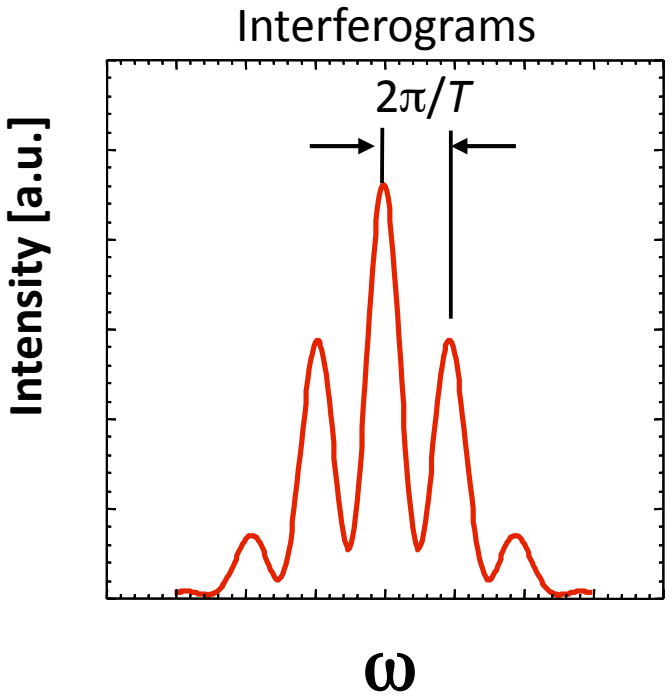
$$= \left|E_1(\omega) + E_2(\omega)e^{-i\omega T}\right|^2$$

Synchronization
$T \rightarrow 0$

For $E_1 = E_2$ $\quad I(\omega) = 2|E(\omega)|^2(1 + \cos\omega T)$

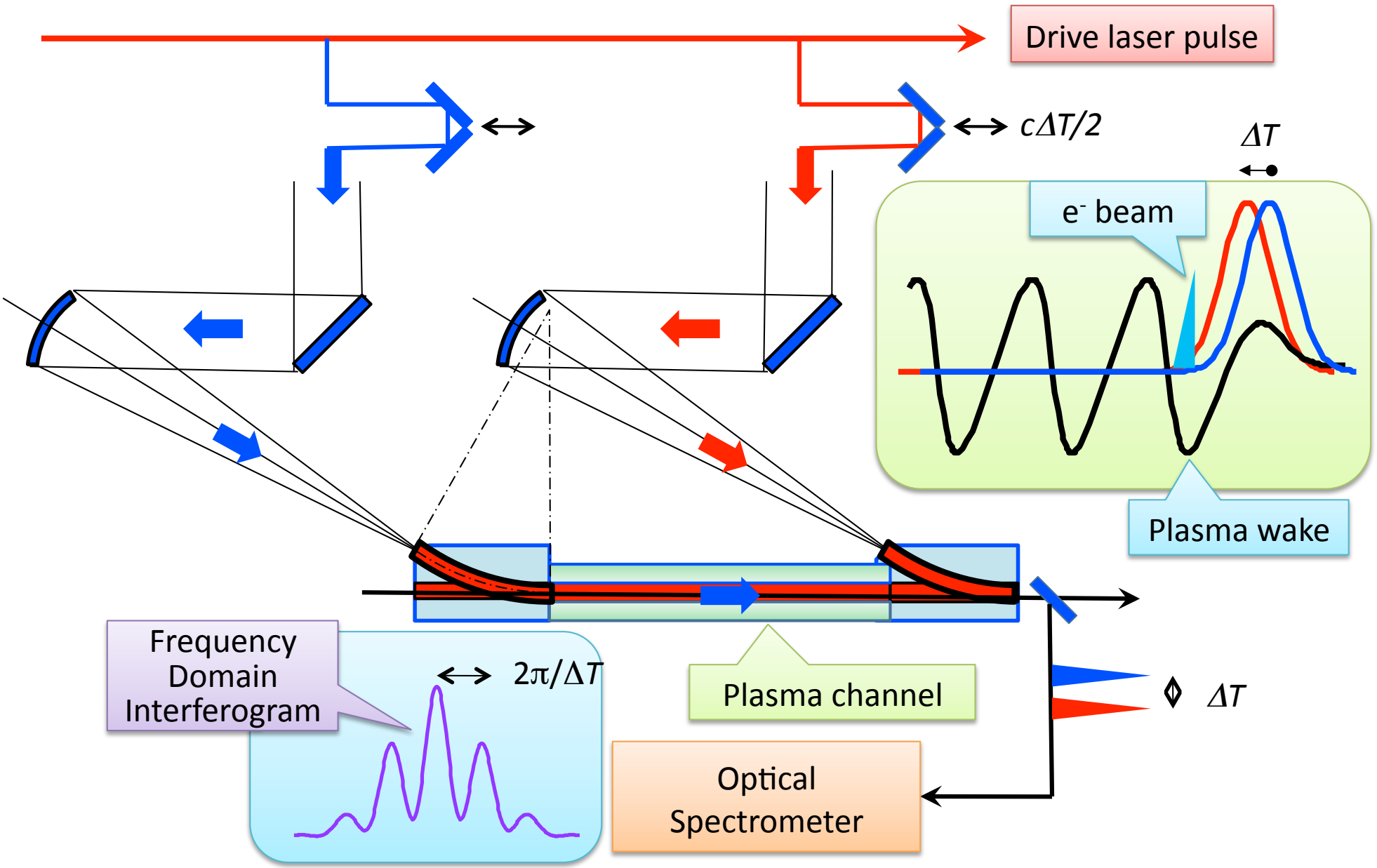


Czerny-Turner optical spectrometer



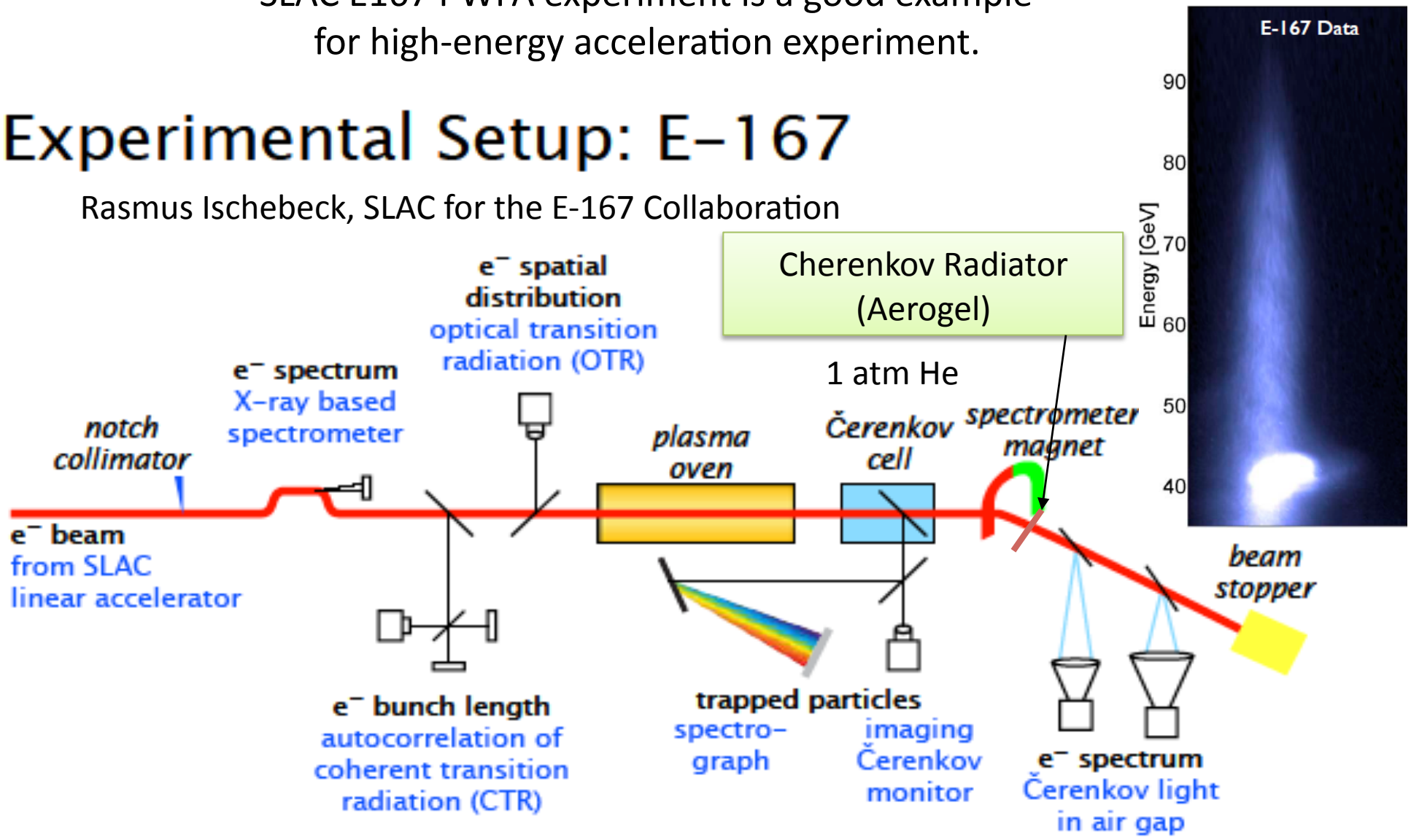
H. Kotaki et al., Phy. Plasmas 9, 1392, 2002

Adjustment of staging phase in fs resolution

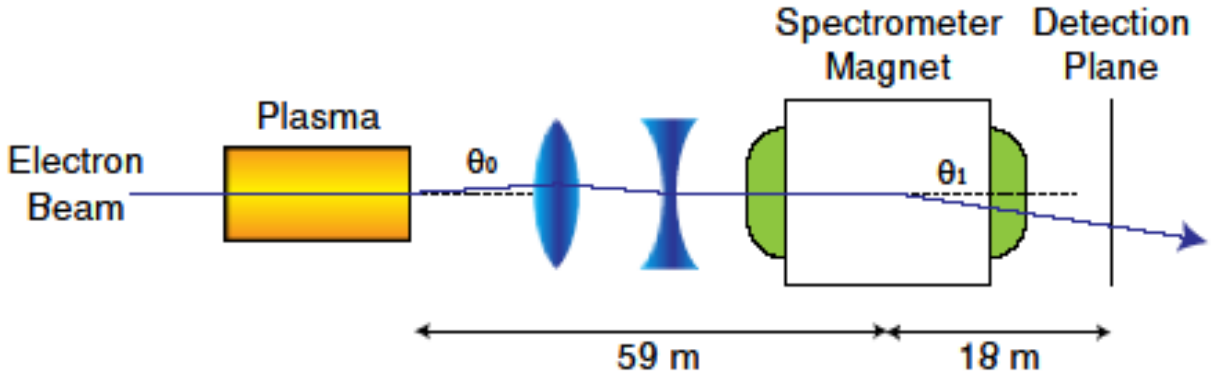


How to measure 100 GeV beam

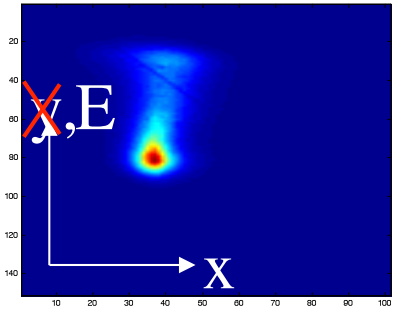
SLAC E167 PWFA experiment is a good example
for high-energy acceleration experiment.



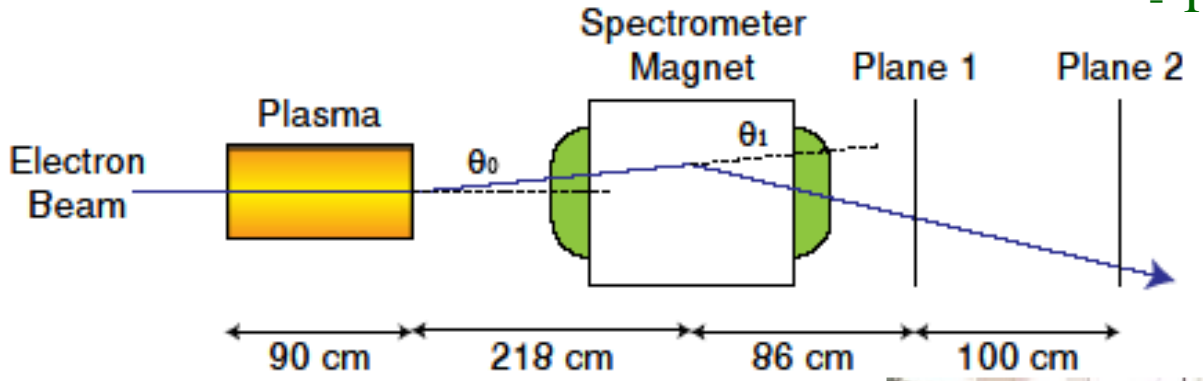
Imaging Spectrometer



E-162:



Two-Plane Spectrometer



- Spatial resolution ≈100 μm
- Energy resolution ≈30 MeV
- Time resolution: ≈1 ps

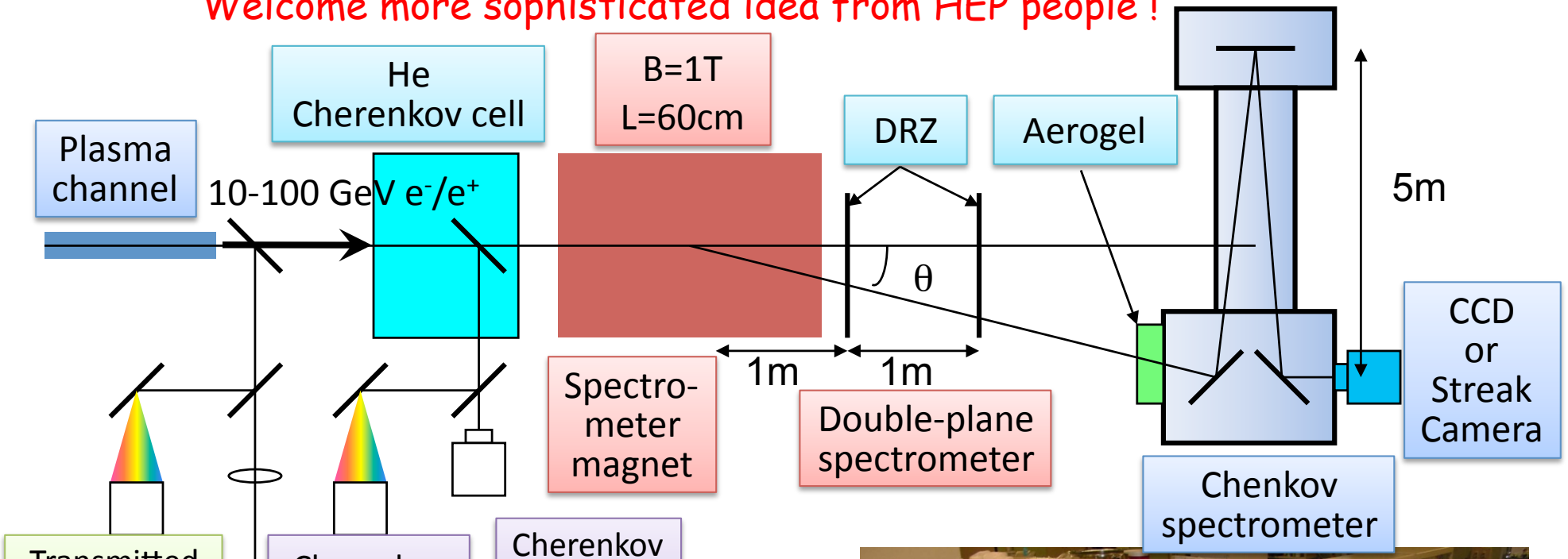
Rasmus Ischebeck, Energy Doubling of 42 GeV Electrons. AAC 2006

Spectrometer magnet

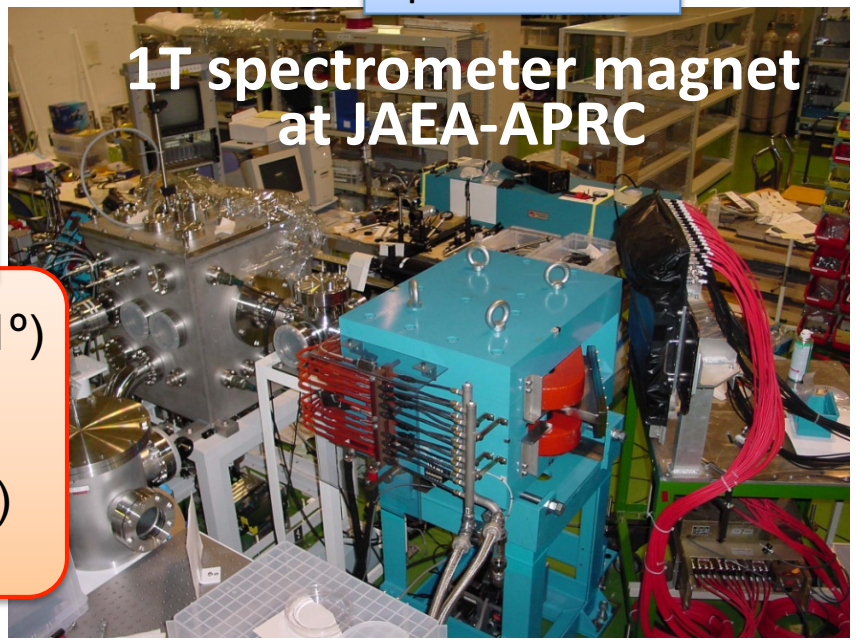
Rasmus Ischebeck, SLAC
for the E-167 Collaboration

A design of 10-100 GeV beam diagnostics

Welcome more sophisticated idea from HEP people !

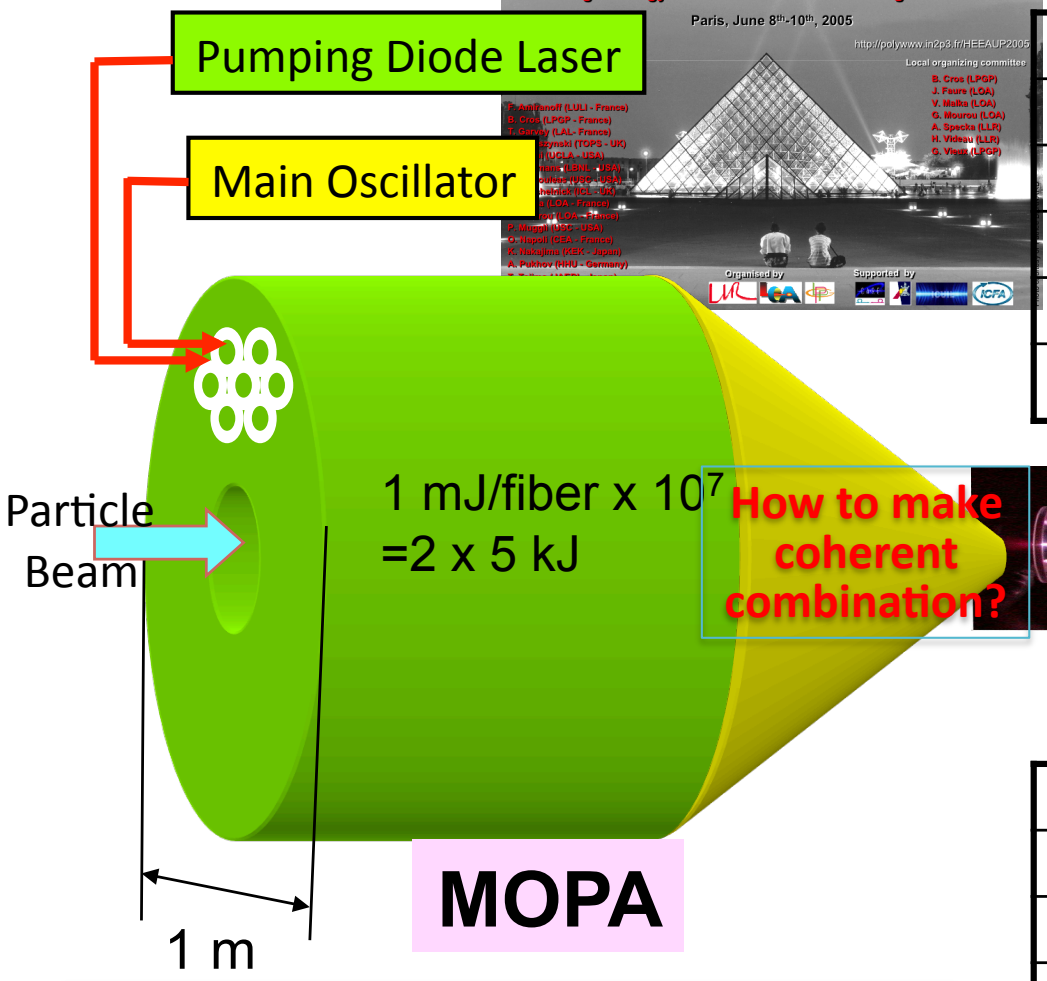


Particle energy	Deflection Angle (θ)
100 GeV	1.8 mrad (0.1°)
10 GeV	18 mrad (1°)
1 GeV	180 mrad (10°)



150MW average power laser for LWFA collider

suggested by G. Mourou, HEEAUP2005, Paris



How to make coherent combination?

Cost

Fiber lasers: \$10/W x 150MW =\$1.5G

Plasma accelerator: negligible

Power requirement for 3 TeV CLIC with luminosity 10^{35} $cm^{-2}s^{-1}$

Number of charge/bunch	$4x10^9$
Beam energy/bunch	0.96 kJ
Number of bunches/pulse	154
Linac repetition rate	100 Hz
Beam power/beam	14.8 MW
Total AC power	**410 MW**

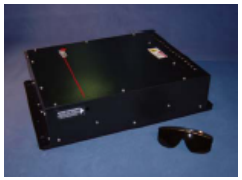
Power requirement for 3 TeV LWFA collider

Wakefield acceleration efficiency	20%
Laser energy/pulse	5 kJ
Peak power of 100 fs laser pulse	50 PW
Repetition rate of LWFA linac	15 kHz
Average driving power for two LWFA	150 MW
Total AC power of fiber lasers with 50%	**300 MW**

Pulse Train Resonant Laser-Plasma Accelerator

Resonant LPA scheme mitigates requirement of a single ultra-intense laser pulse

Yb fiber power-amplifier or fiber laser pumped parametric amplifier array



N-pulse train with power *P* optimal spacing equal to the plasma wavelength resonantly excite the plasma wave amplitude comparable to a single pulse with power *N*×*P* in the linear regime.

All-fiber oscillator

Fiber stretcher

Fiber pre-amplifier

Grating compressor

100fs, 1TW/pulse x 100 pulses at kHz rep rate

e^-/e^+ bunch

Drive laser pulse train

Linear plasma wave

Accelerating wakefield E_z by 1TW, 100fs 100 pulses

NOT necessary coherent combination !

=

Accelerating wakefield E_z by a 100TW, 100fs single pulse

With kHz~MHz rep rate TW drive lasers, RLPA shortcuts to the collider application

K. Nakajima,PRA, 45,1149 (1992)
"Plasma-wave resonator for particle-beam acceleration"

Summary

- GeV-range high-quality, controllable and stable electron injectors are available in the state-of-art LPA technology.
- 100 GeV high-quality e^-/e^+ LPA experiment will be carried out with the multi-staging of LWFA operated in the linear regime at plasma density in the order of 10^{-16} cm^{-3} as well as the e^-/e^+ injector in the nonlinear regime.
- Meter-scale Long plasma channels necessary for staging will be generated with RF discharge at kHz-rep rate.
- Curved plasma channel will be used for coupling drive laser pulse in/out the stage at kHz-rep rate.
- Synchronization of stage-to-stage laser pulses will be adjusted by the frequency domain interferometry with fs resolution.
- 10-100 GeV high-resolution spectrometer should be developed.
- RLPA may be useful for future fiber laser-based LWFA operated at kHz-rep rate.
- LPA community is ready for 100 GeV acceleration and kHz-LWFA with required lasers such as APOLLON and kHz-TW fiber lasers.