Chaires internationales de recherche Blaise Pascal

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The Eighth Blaise Pascal Lecture
Wednesday, July 7, 2010
Ecole Polytechnique

A Practical View toward Laser Accelerator/Collider

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Acknowledgments for Collaboration and advice: G. Mourou, D. Habs, C. Barty, J. Fuchs, C. Labaune, P. Mora, P. Chomaz, D. Payne, H. Videau, P. Martin, V. Malka, , F. Krausz, T. Esirkepov, S. Bulanov, M. Kando, W. Sandner, M. Gross, K. Homma, A. Suzuki, M. Teshima, X. Q. Yan, B. Cros, J. Chambaret, W. Leemans, E. Esarey, R. Assmann, R. Heuer, A. Caldwell, S. Karsch, F. Gruener, M. Zepf, M. Somekh, E. Desurvire, D. Normand, J. Nilsson, W. Chou, F. Takasaki, M. Nozaki, K. Yokoya, J. Urakawa

The Second Blaise Pascal Lecture
Ecole Polytechnique
11/18/09

Laser Electron Acceleration and its Future

Toshi Tajima
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Acknowledgments for Advice and Collaboration: G. Mourou, V. Malka, J. Fuchs, C. Labaune, H. Videaux, P. Mora, F. Krausz, D. Habs, S. Karsch, L. Veisz, F. Gruener, T. Esirkepov, M. Kando, K. Nakajima, A. Chao, A. Suzuki, F. Takasaki, S. Bulanov, A. Giullietti, W. Leemans, T. Raubenheimer, A. Ogata, A. Caldwell, P. Chen, Y. Kato, M. Downer, M. Tigner, H.C. Wu, K. Kondo, S. Kawanishi, M. Hegelich, P. Shukla, S. Chattopadyay, K. Yokoya、S. Cheshkov

Conclusions (from my seminar on May 18, 2010)

- Laser electron acceleration: experimentally well established; its unique properties getting known
- Laser has come around to match the condition set 30 years ago; Still some ways to go to realize the dream (such as ELI)
- GeV electrons; 10 GeV soon; 100GeV considered;

  TeV laser collider contemplated; PeV ?
- Beam control: greater attention necessary
- **Other applications**: already beginning, soon to flourish : radiolysis, intraoperative therapy, bunch decelerator, nuclear detection, compact FEL source, compact radiation sources, ultrafast diagnosis,…)
- Need to establish a center which carries laser acceleration science proof-of-principle experiments at collider level energies, as well as incubates collider-fit laser driver technology

Relativistic nonlinearity under intense laser

Plasma free of binding potential , but its electron responses:

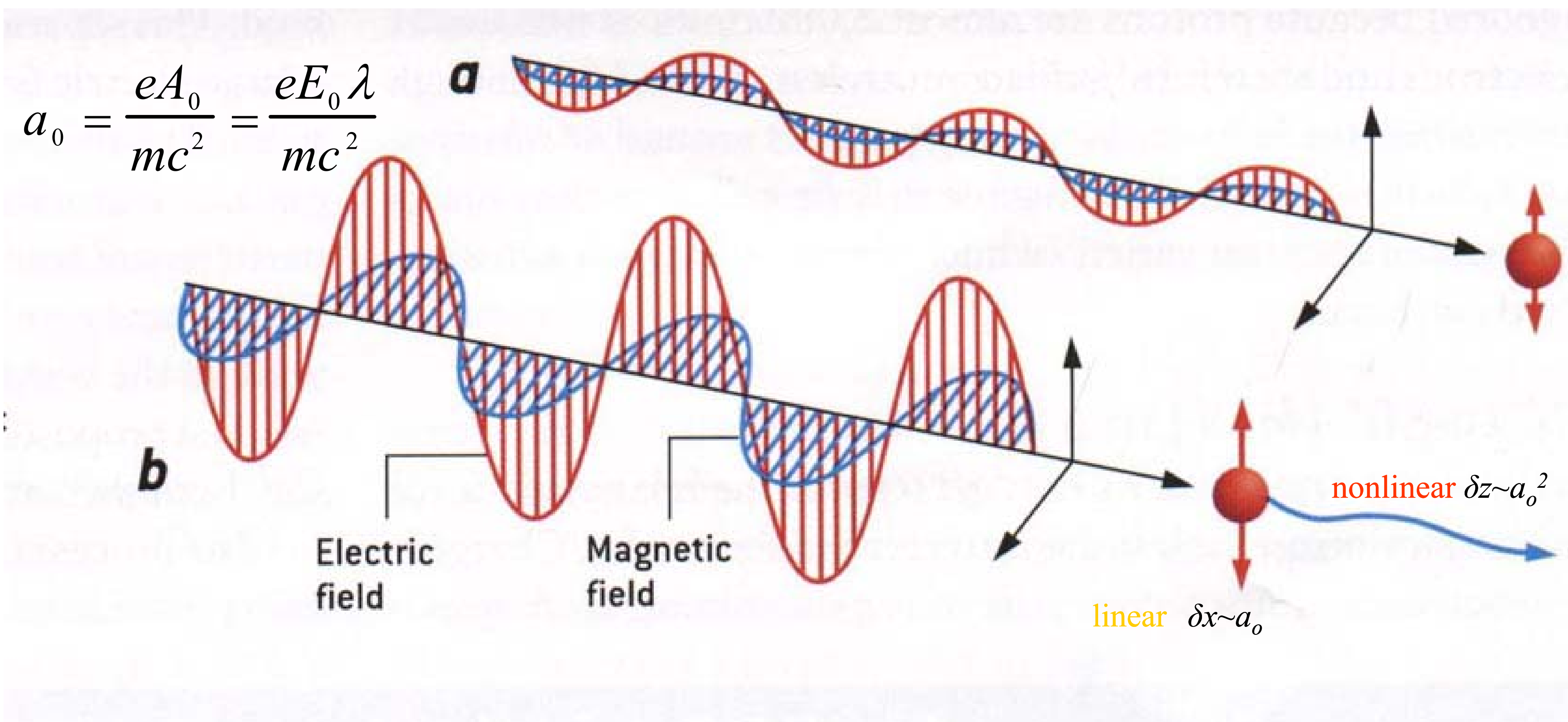
a) Classical optics : $v<<c$,

$a_0<<1$: δx only

b) Relativistic optics: $v\sim c$

$a_0>>1$: $\delta z >> \delta x$

$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2}$$



Wakefield : <u>Nonlinearity</u>-driven, <u>Collective</u>

<u>Collective</u> phenomenon = all particles in medium participate

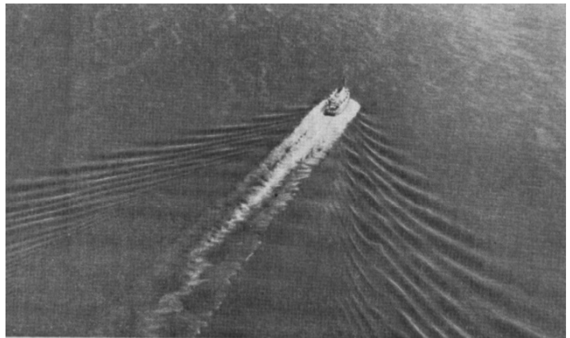
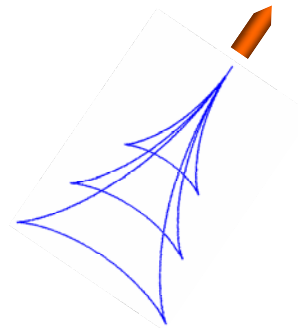


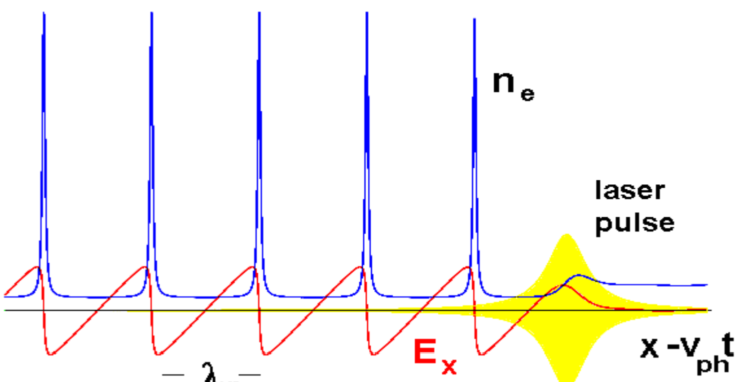
Рис. 71. Наблюдаемая картина корабельных волн. [Любезно предоставлено Aerofilms Ltd.]

Kelvin wake



<u>Nonlinearities</u> of plasma and water waves

No wave breaks and wake **peaks** at v≈c



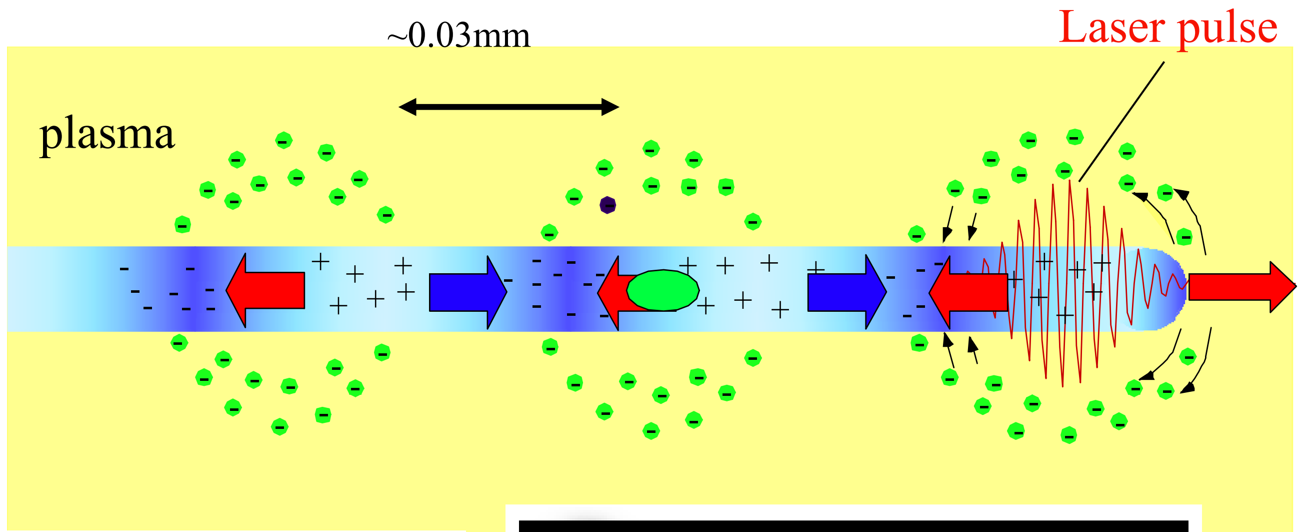
(Wave-head *hard* to overtake trough.
→ density cusp singularity)

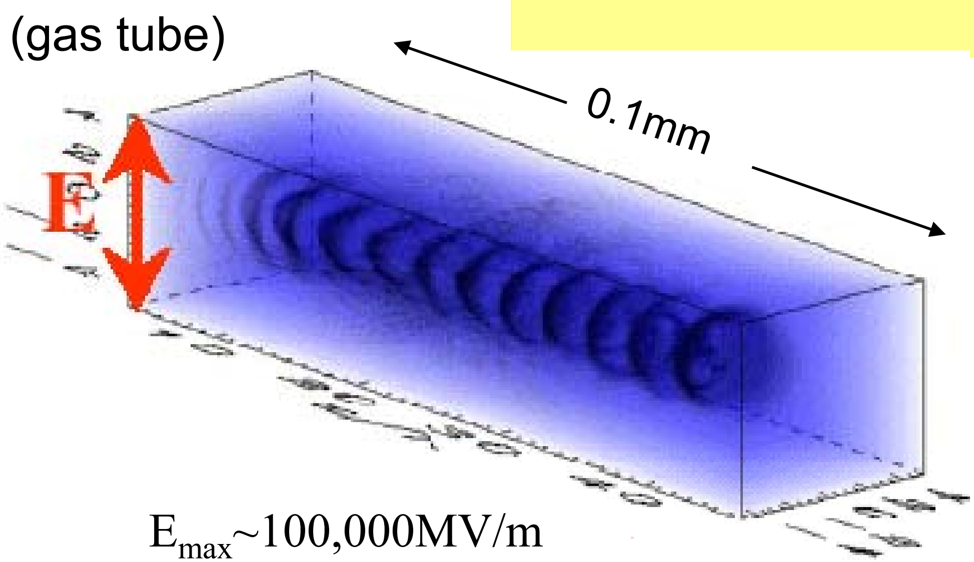
Wave **breaks** at v<c

(Wave-head overtakes trough)

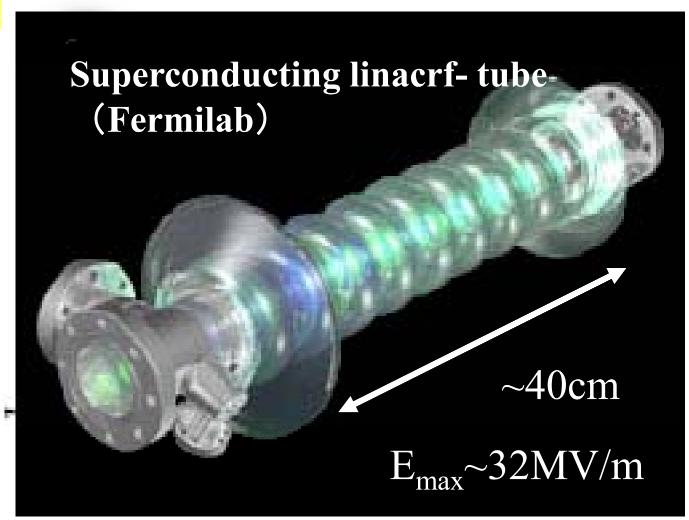
Thousand-fold Compactification

Laser Wakefield Acceleration (LWFA): $10^{3\text{-}4}$ fold gradient

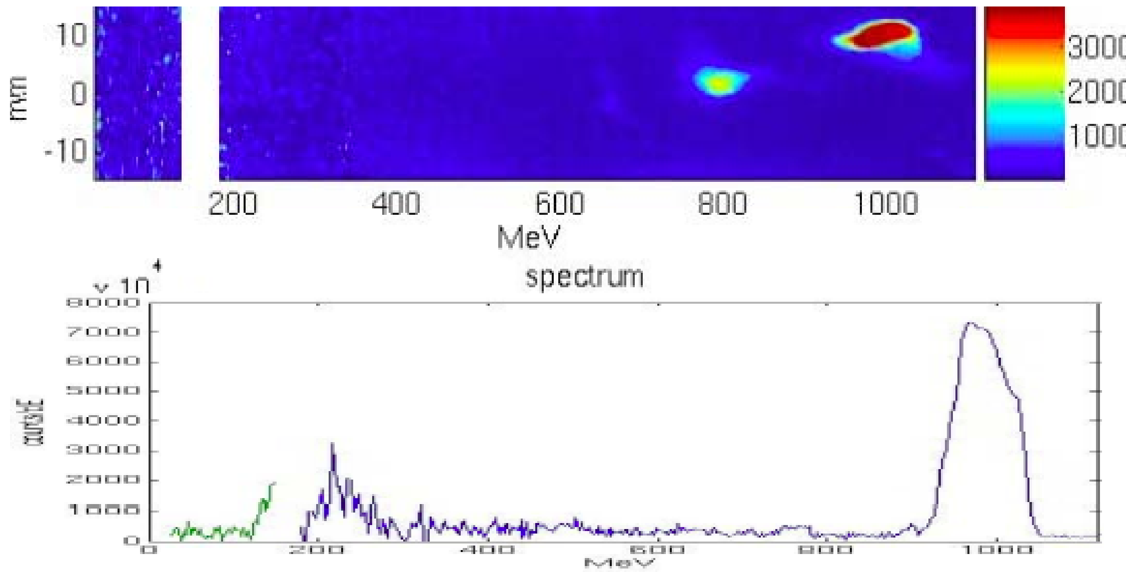


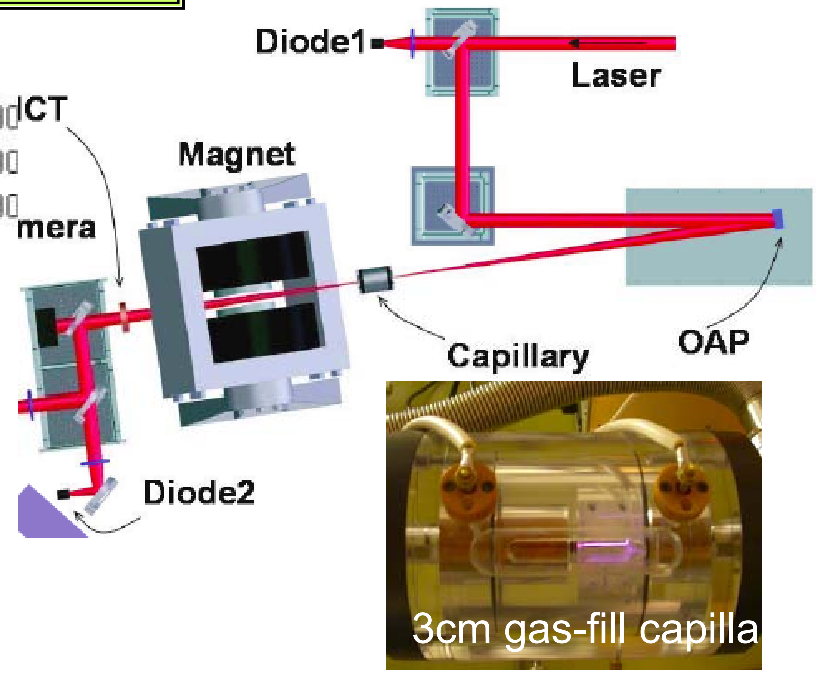


E_{max}~100,000MV/m

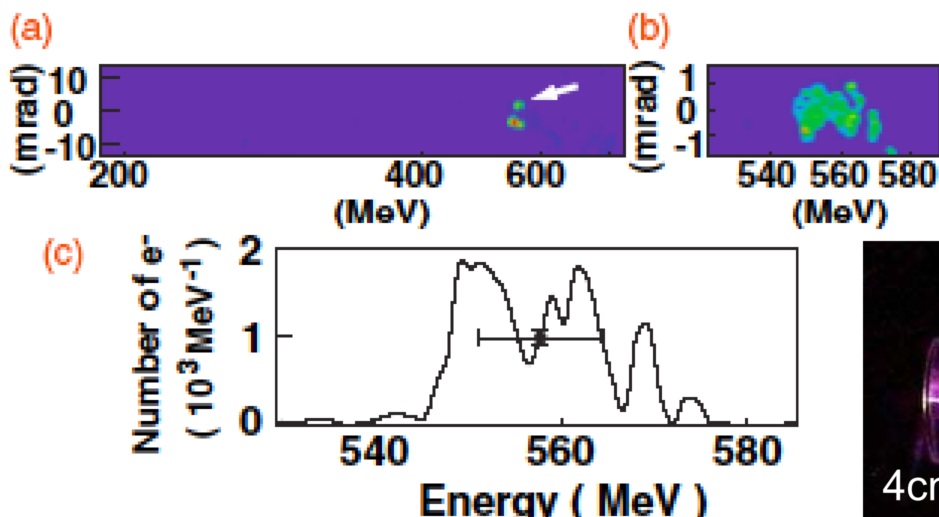


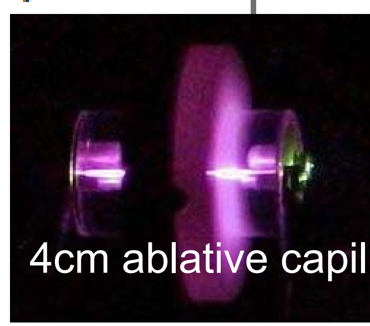
1 GeV capillary accelerator experiment at LBNL/Oxford U.





0.56 GeV capillary accelerator experiment at CAEP/KEK





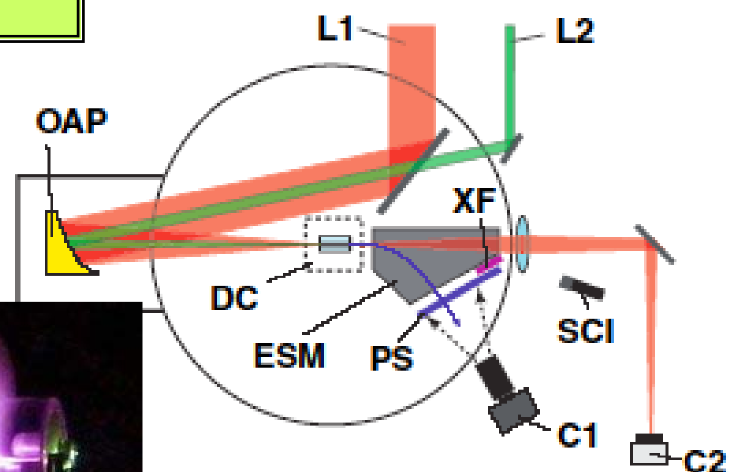
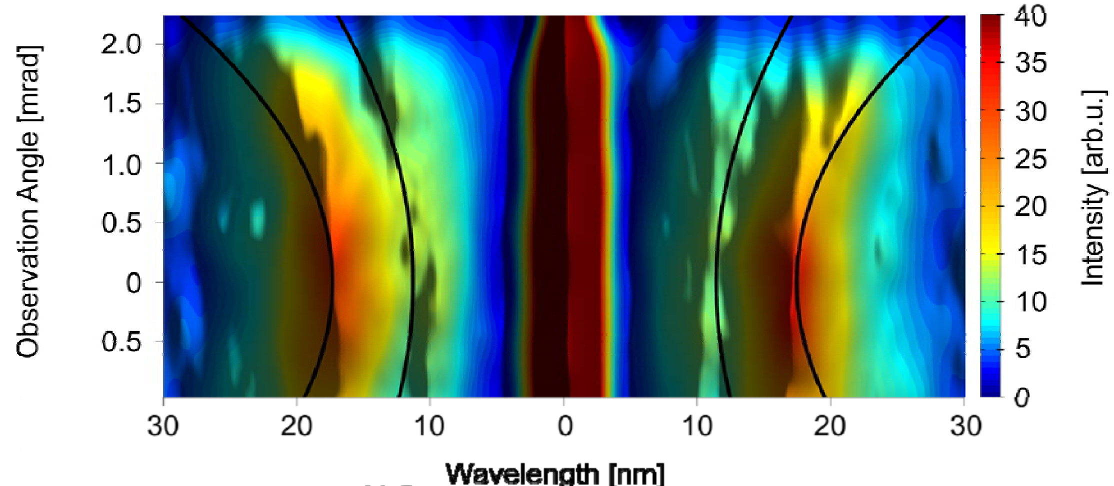
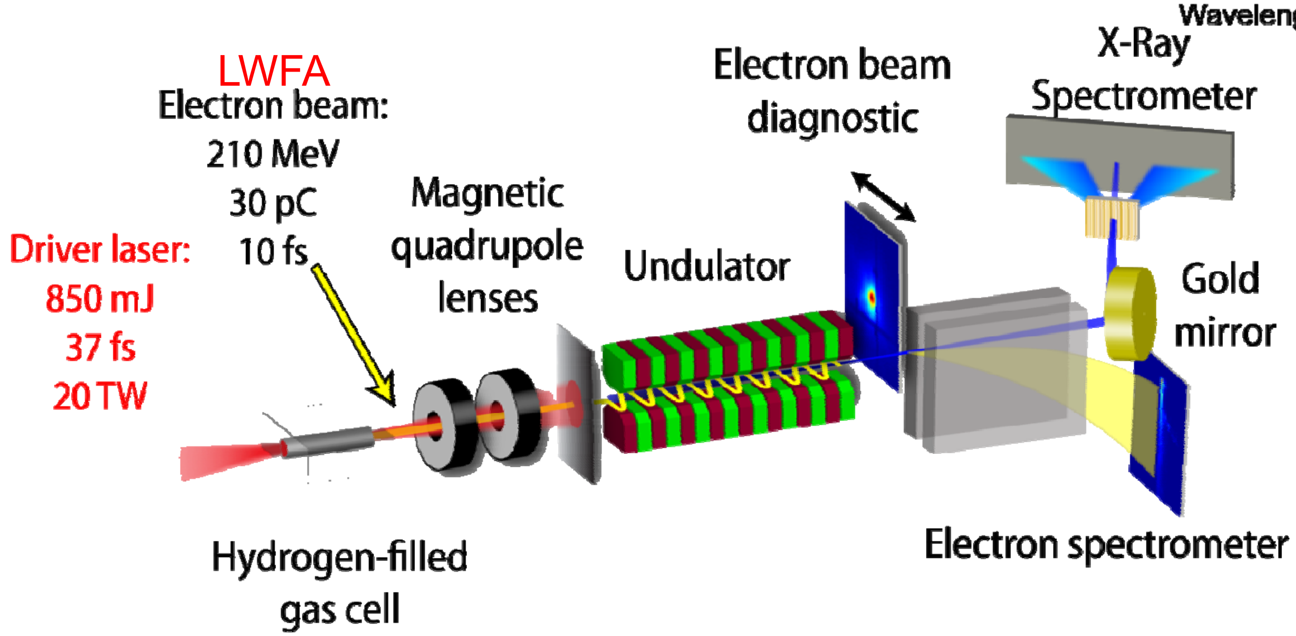


Table-top Brilliant Undulator X-ray Radiation from LWFA

(F. Gruener, S. Karsch, et al., Nature Phys., 2009)

<u>Observed</u> undulator radiation spectrum





Toward Coherent Control of Wakefields:

Frequency-domain Holography

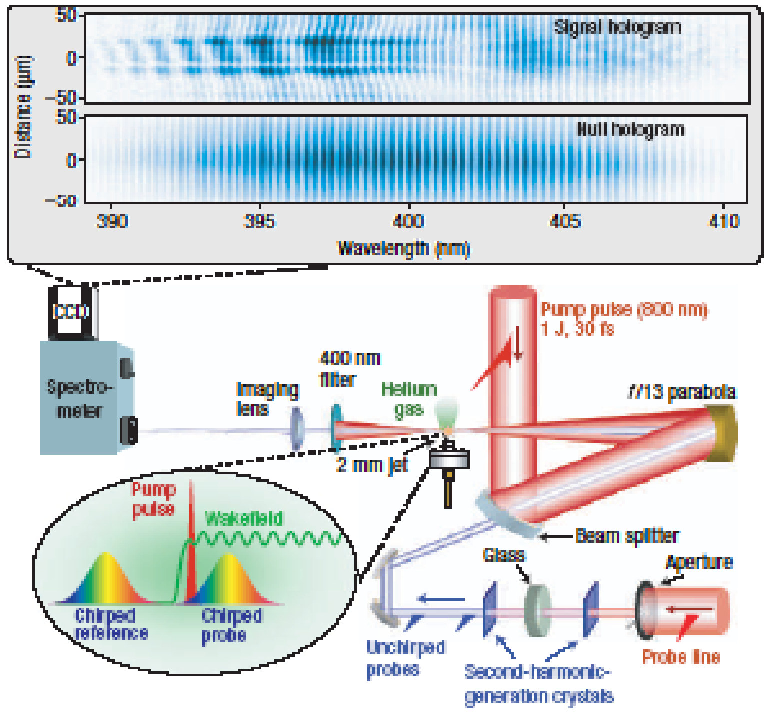


Figure 1 Experimental setup for FDH of laser wakefields. An *f*/13 parabola focuses an intense 30 fs pump pulse into a jet of helium gas, creating a plasma and laser wakefield. Two chirped, frequency-doubled 1 ps pulses, temporally synchronized and co-propagating with the pump, take holographic snapshots of the ionization front and wake. Phase alterations imposed on the trailing probe by these plasma disturbances are encoded in an FD interferogram, shown at the top with (upper) and without (lower) a pump, recorded by a charge-coupled-device camera at the detection plane of an imaging spectrometer. The wake structure is recovered by Fourier-transforming this data.

(Matlis et al.,2006)

M.Downer (UTexas)

Snapshot of wakefields:

phase sensitive instantaneous single-shot detection

LETTERS

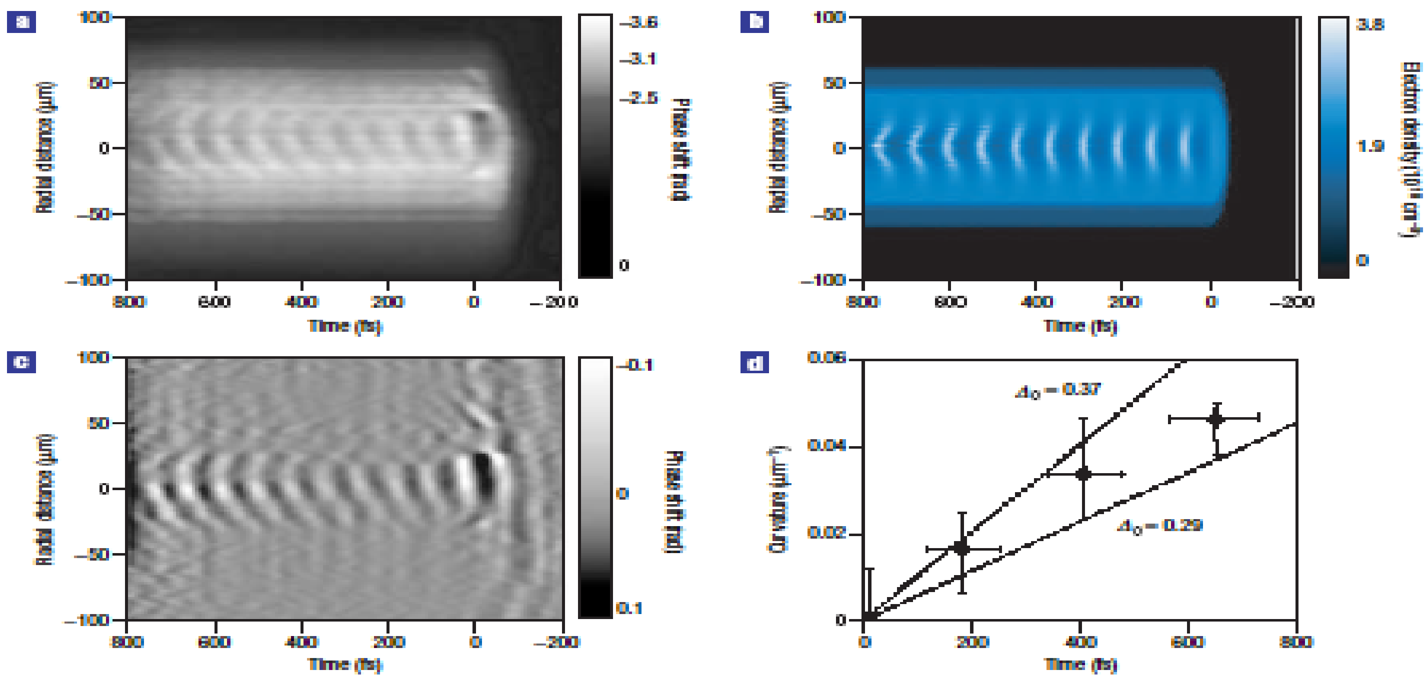
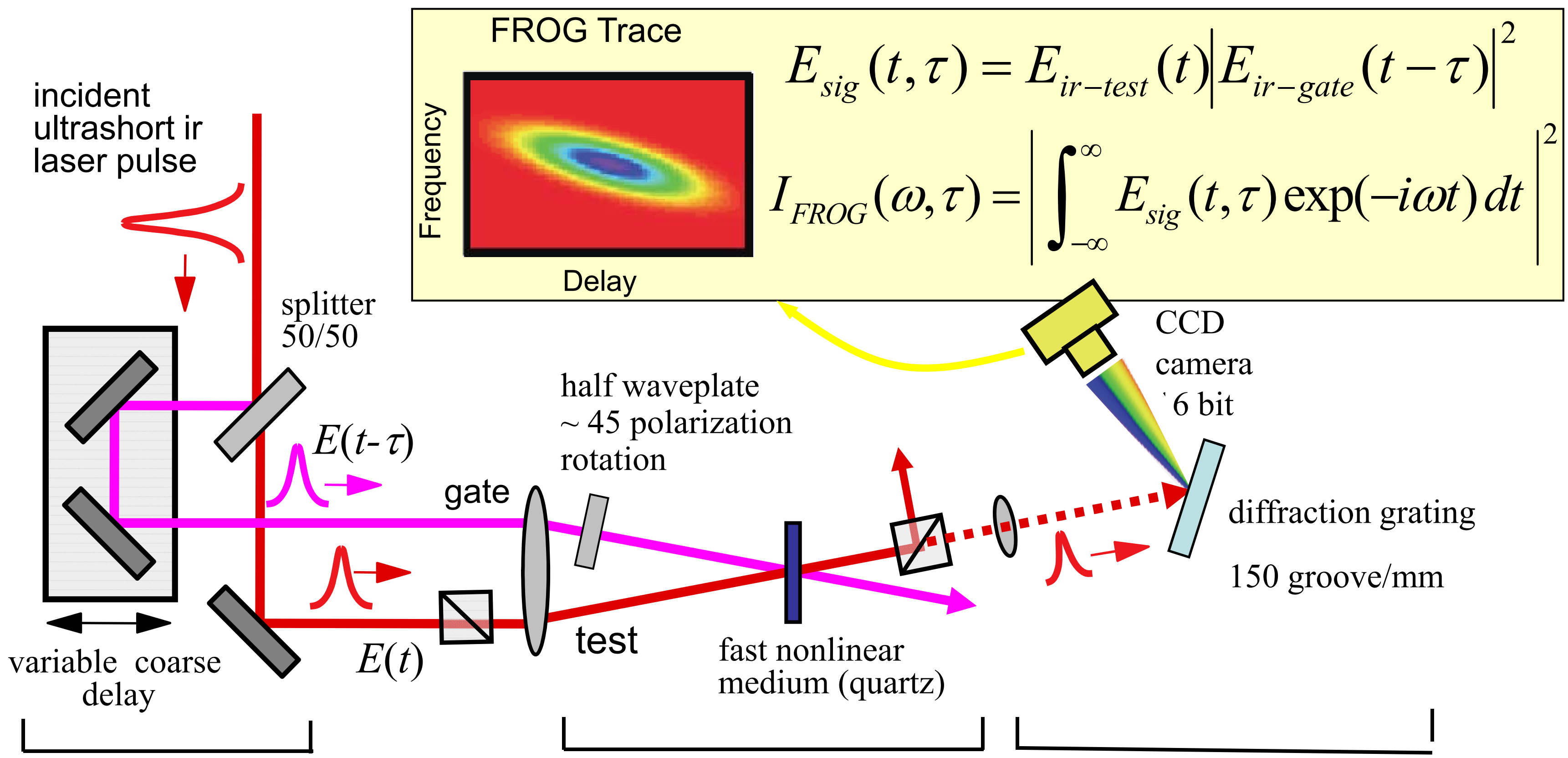


Figure 3 Strongly driven wake with curved wavefronts. a, Probe phase profile $\Delta\phi_{pr}(r,\xi)$ for an ~30 TW pump, $n_e^{max} = 2.2 \times 10^{18}$ cm^{-3} in the He^{2+} region. **b**, Simulated density profile $n_e(r,\xi)$ near the jet centre. **c**, Same data as in **a**, with the background $\bar{n}_e$ subtracted to highlight the wake. **d**, Evolution of the reciprocal radius of wavefront curvature behind the pump (data points), compared with calculated evolution (dashed lines) for indicated wake potential amplitudes. Each data point (except at $\xi = 0$) averages over three adjacent periods. The horizontal error bars extend over the three periods averaged, and the vertical error bars extend over the range of fitted curvature values averaged.

(Matlis et al, 2006)

Polarization-Gated (PG) FROG: Single Pulse Dynamics a Finesse Approach



$$E_{sig}(t,\tau) = E_{ir-test}(t)\left|E_{ir-gate}(t-\tau)\right|^2$$

$$I_{FROG}(\omega,\tau) = \left|\int_{-\infty}^{\infty} E_{sig}(t,\tau)\exp(-i\omega t)\,dt\right|^2$$

gate beam generation

the pulse to be measured
is split into a replica pair and
one replica pulse
(the 'gate') is delayed with a
polarization rotation ~ 45°

Kerr effect polarization gating

the two pulses are coincident
In an isotropic medium, Kerr-induced
birefringence by the
gate pulse yields an autocorrelation

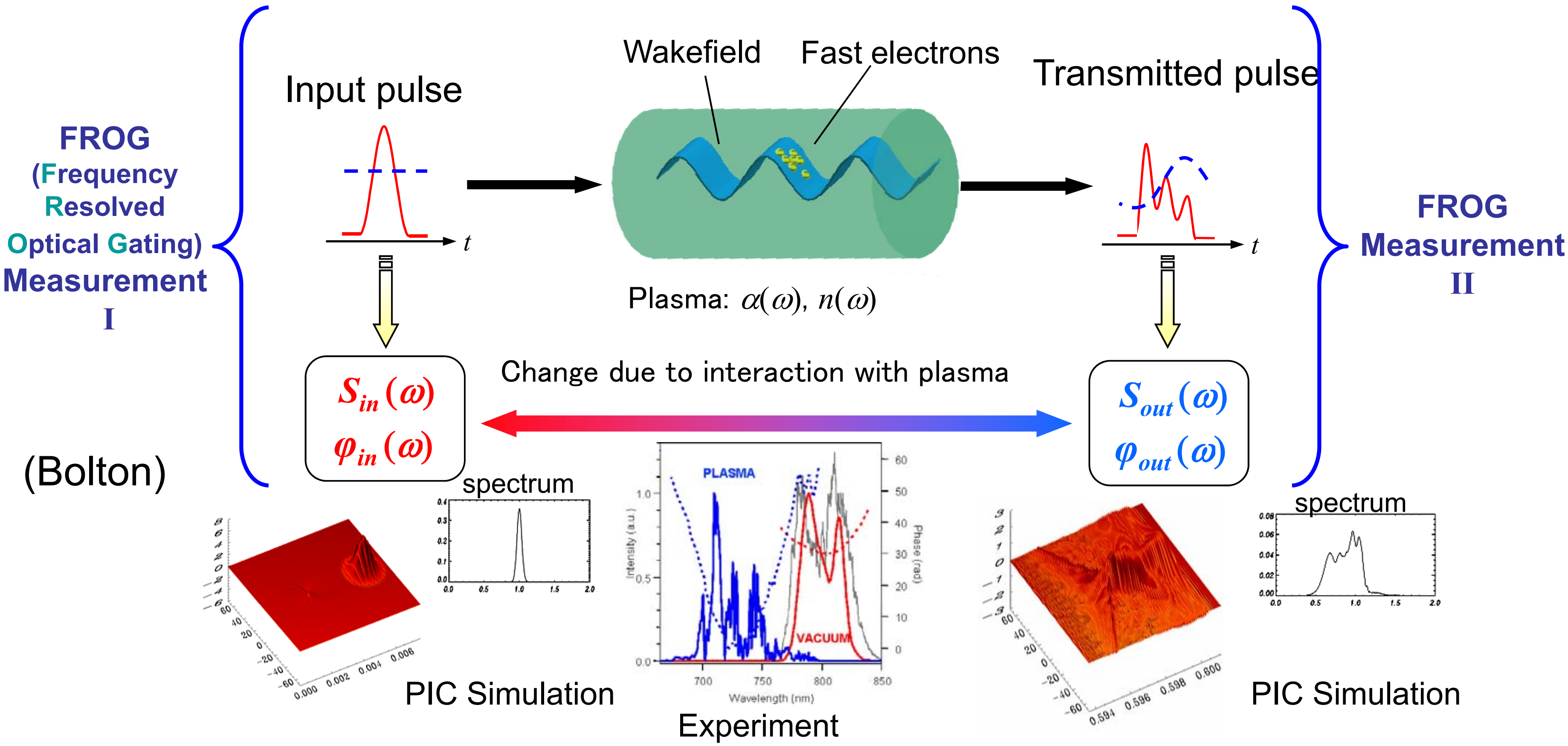
imaging and spectral dispersion

grating provides spectral
resolution for a 2D FROG
trace

P.Bolton + Y. Fukuda

Single Shot Phase-Preserved fs Metrology of the Laser system and Laser-Plasma Interaction

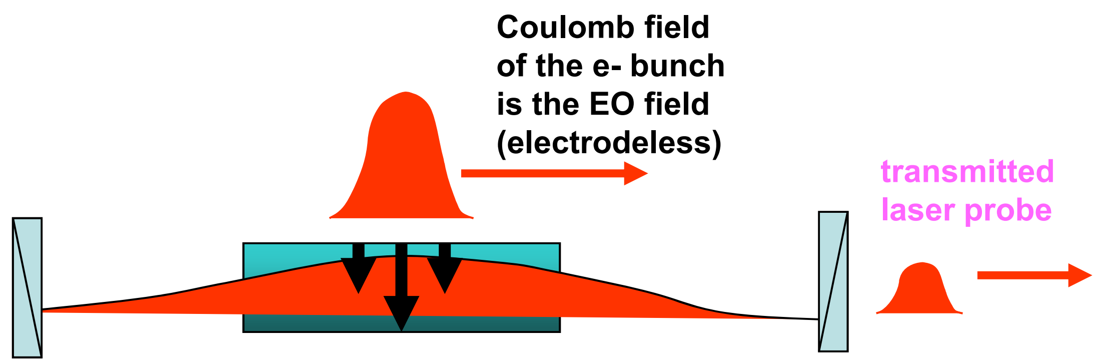
Laser pulse spectrum modified in plasma;
Dynamical information of ultrafast interaction 'encoded' onto the laser waveform
Extract spectrum and phase of the transmitted laser pulse.
Feed back info to laser by simple feedback, neural net, genetic algorithm,….



Another Finesse Single-shot Diagnosis: Electro-Optical Method

- can be noninvasive
- important for future accelerators
- all-optical:
  - optical controls in ideal laser setting
  - can apply optics sophistication
- jitterless (probe synchronized with laser driver)
- ultrafast – single bunch profile (~ 100 fsec)
- high repetition rate – multi-bunch timing jitter
- potential for feedback and beam (facility) control

Electrodeless Case

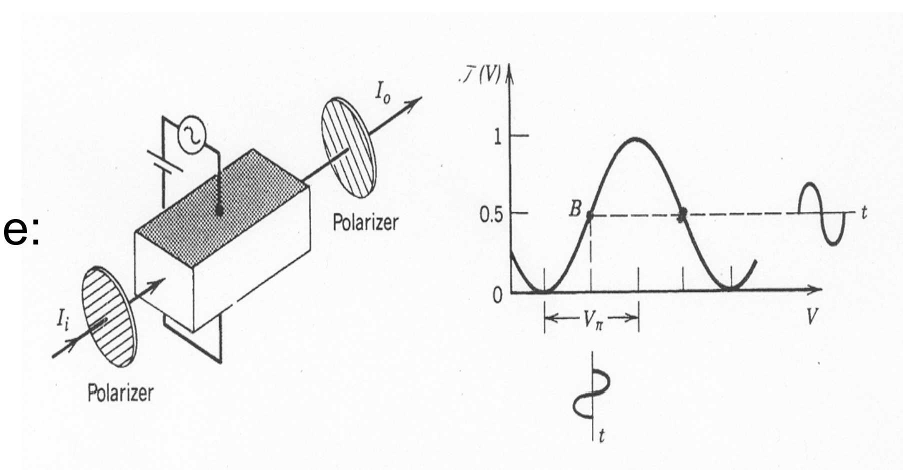


overlapping (coincident) portion of the laser probe pulse experiences the phase retardation in transit across the crystal

Use reference 'pi' field instead of 'pi' voltage:

$$transmission, T(E) \propto \sin^2\left(\frac{\varphi_o}{2} - \frac{\pi}{2}\frac{E}{E_\pi}\right)$$

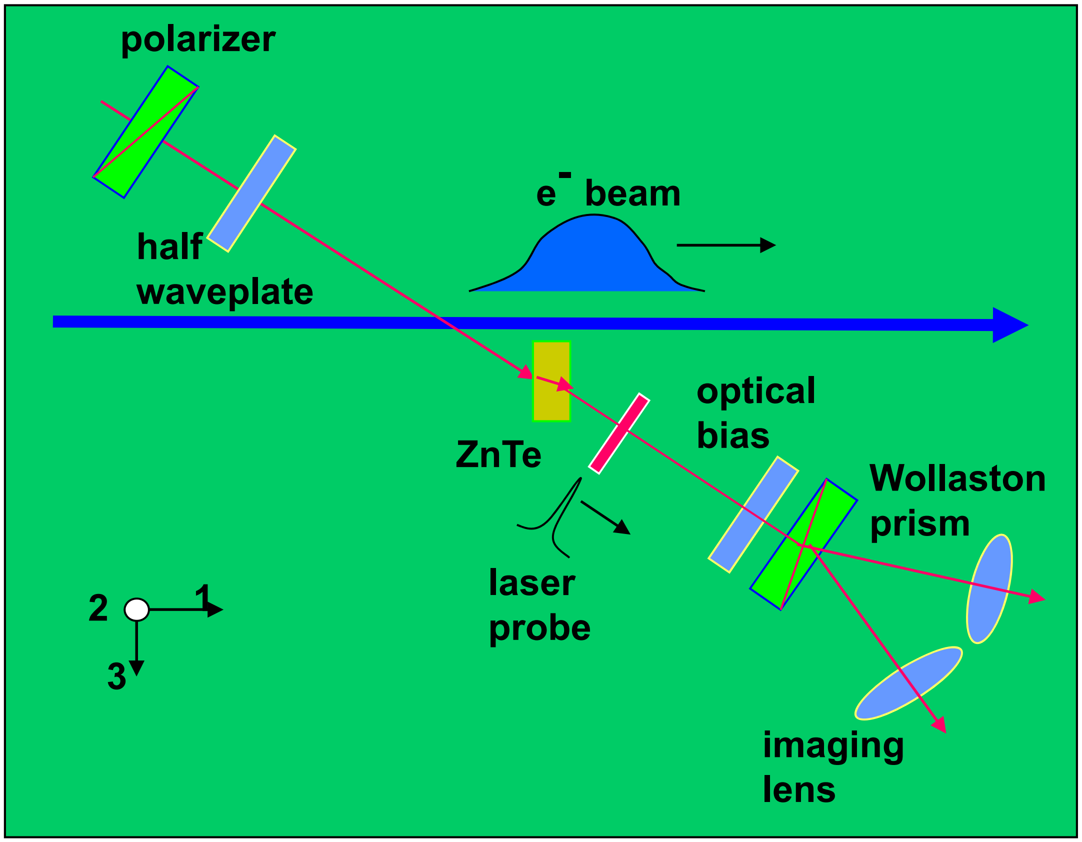
$$\Rightarrow want\_low\_E_\pi$$



P.Bolton

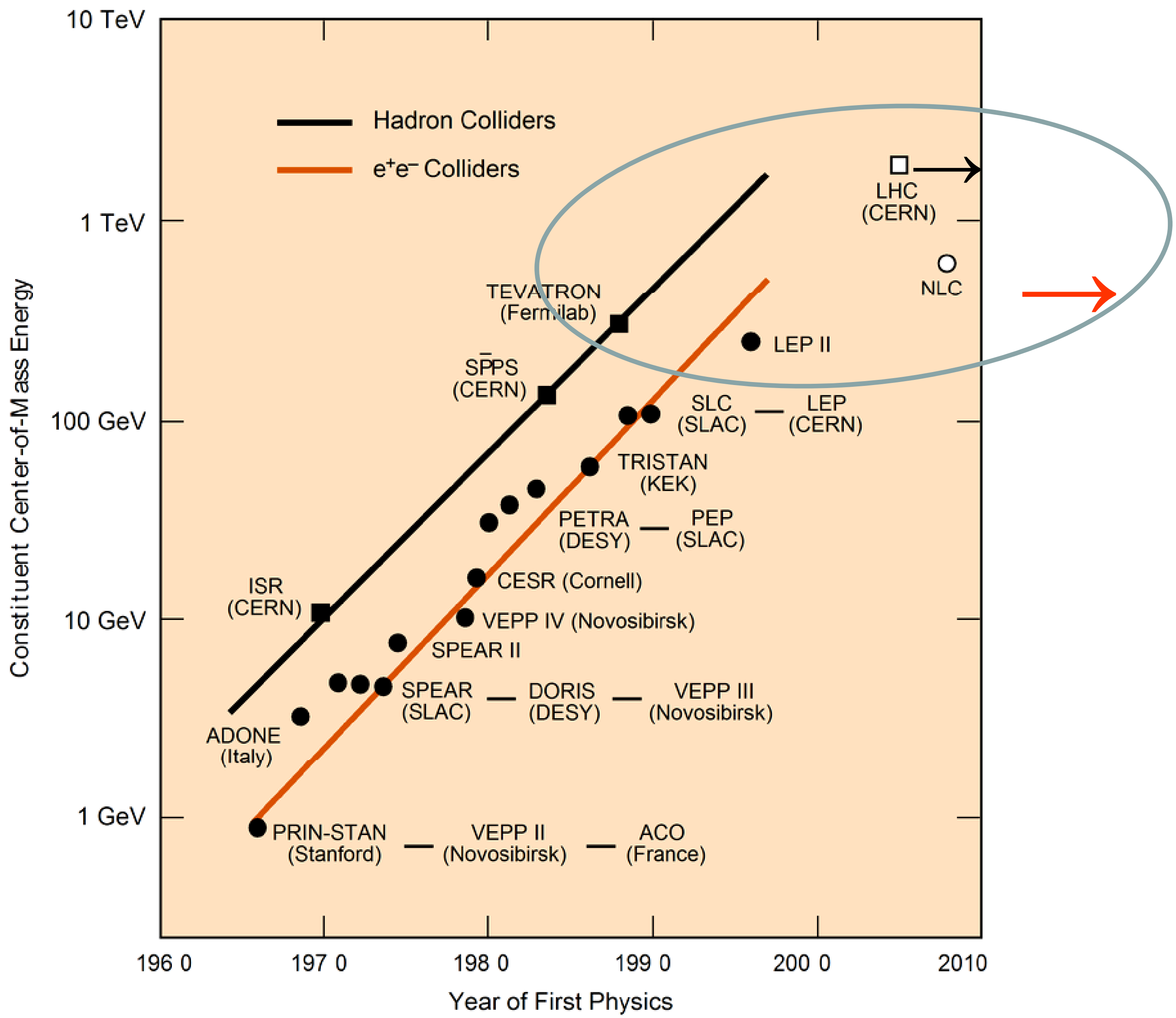
EO Example: Spatial-Temporal Transcription with Pockels Effect

- require ultrashort probe and thinnest possible EO crystal
- optional horizontal line focus of probe at crystal



P.Bolton

Livingston Chart and Recent Saturation

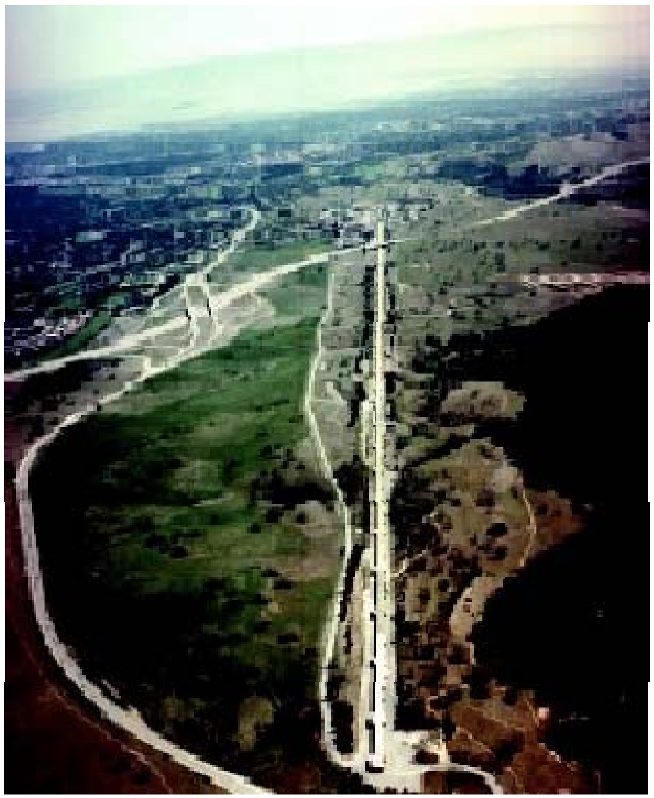


(Suzuki, 2009)

(http://tesla.desy.de/~rasmus/media/Accelerator%20physics/slides/Livingston%20Plot%202.html)

World Lab goal =
Put *SLAC* on a football field

Initiatives considered, emerging: *French; CERN; KEK; LBL*



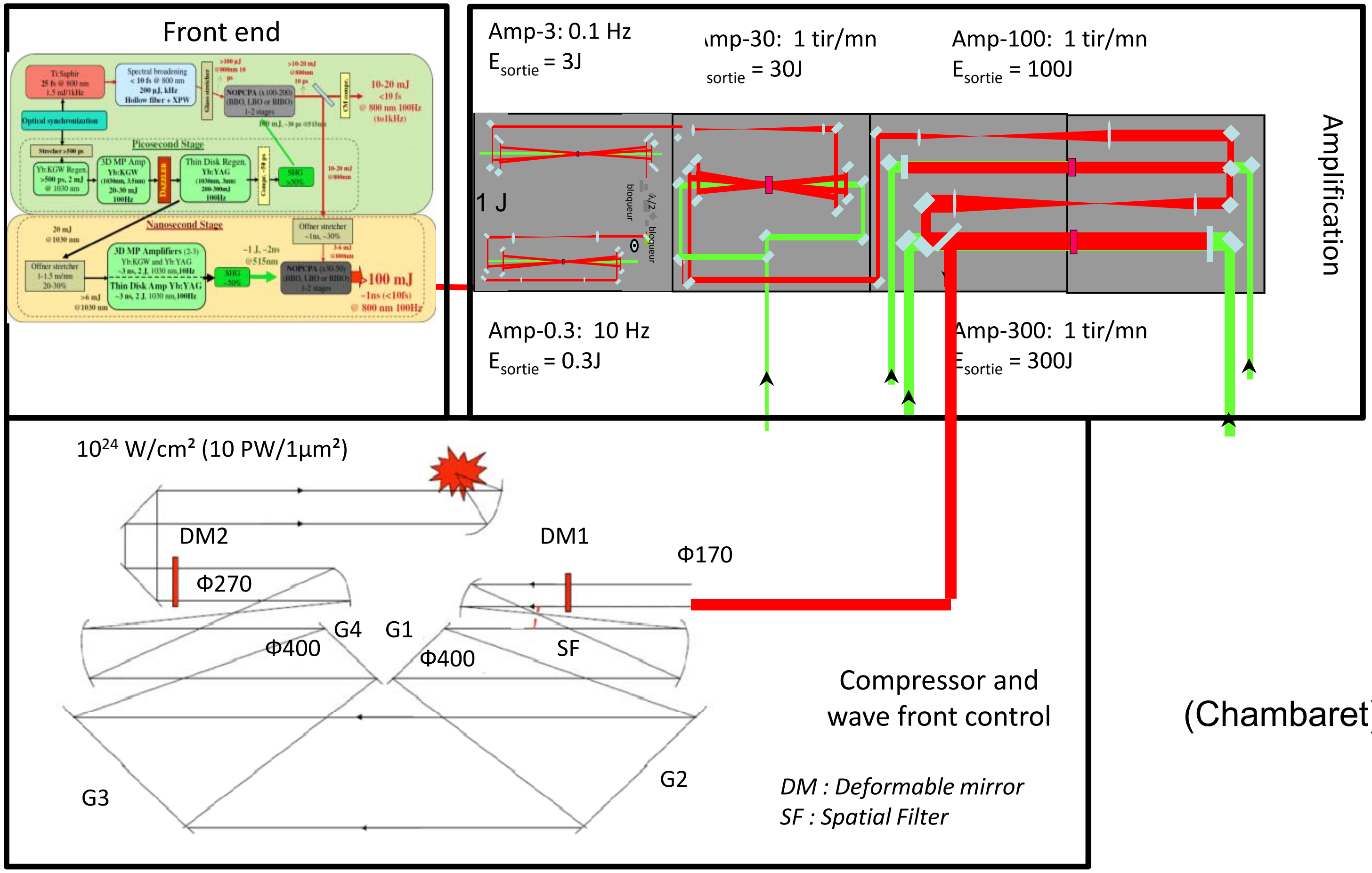
→

Laser acceleration =

- no material breakdown (→ 3/4 orders higher gradient); however:
- 3 orders finer accuracy, and 2 orders more efficient laser needed

SLAC's 2 mile linac (50GeV)

Apollon as a driver for 100GeV



(Chambaret)

150J Apollon split into 10 beams, driving 10 of 10GeV stages

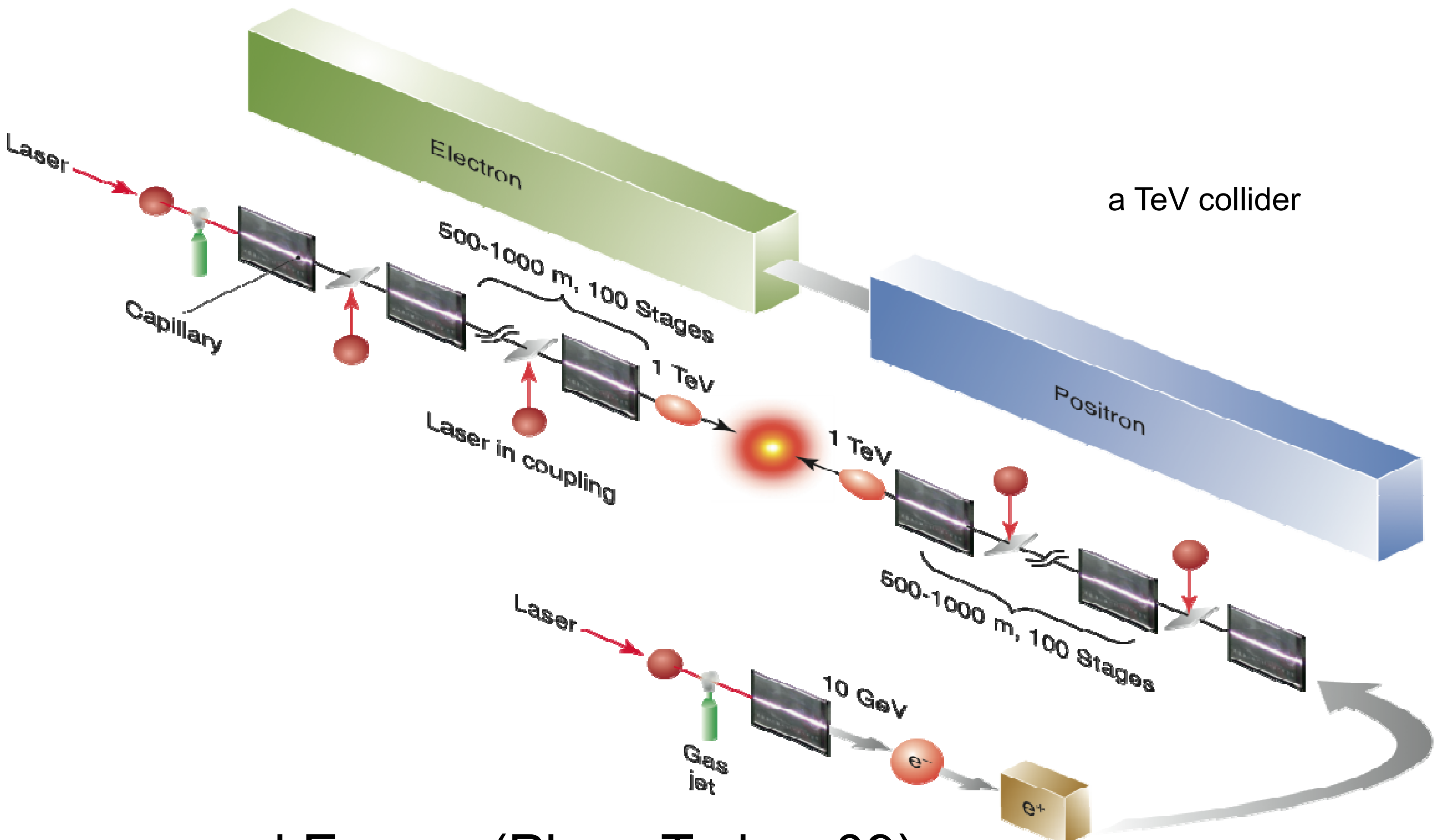
Key issues of future colliders

(T. Raubenheimer, SLAC, 2008)

Beam Acceleration

* Largest cost driver for a linear collider is the acceleration
  - ILC geometric gradient is ~20 MV/m → 50km for 1 TeV
* Size of facility is costly → higher acceleration gradients
  - High gradient acceleration requires high peak power and structures that can sustain high fields
    - Beams and lasers can be generated with high peak power
    - Dielectrics and plasmas can withstand high fields
* Many paths towards high gradient acceleration
  - High gradient microwave acceleration } ~100 MV/m
  - Acceleration with laser driven structures } ~1 GV/m
  - Acceleration with beam driven structures } ~1 GV/m
  - Acceleration with laser driven plasmas } ~10 GV/m
  - Acceleration with beam driven plasmas } ~10 GV/m

Laser driven collider concept



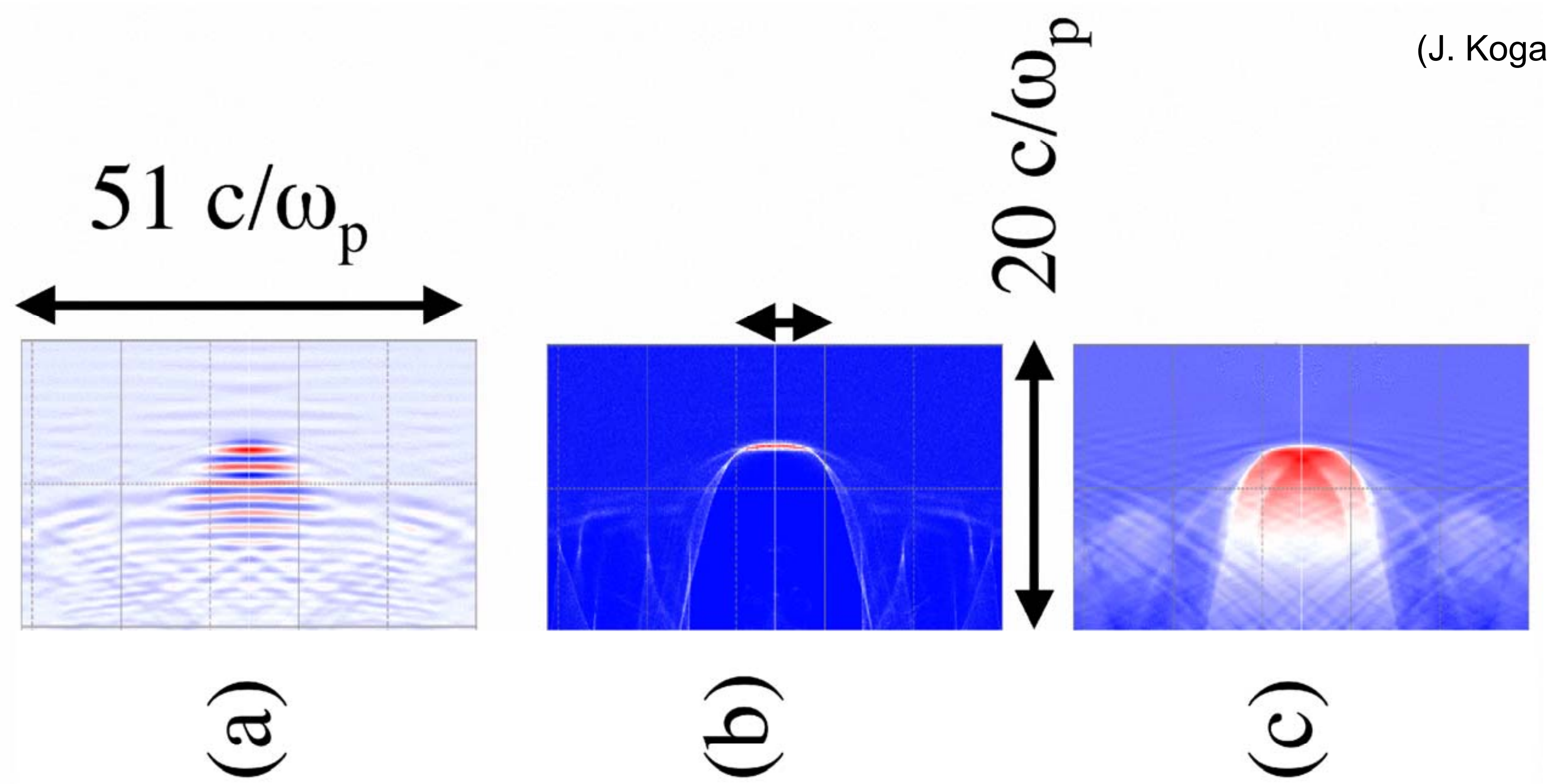
a TeV collider

Leemans and Esarey (Phys. Today, 09)

ICFA-ICUIL Joint Task Force on Laser Acceleration(Darmstadt,10)

Wakefield in Stable 1D Regime

(J. Koga)



Laser fields

Electron density

wakefield

ICUIL – ICFA joint effort

Toshi Tajima (ICUIL chair) aims to promote relationship between ICUIL and ICFA:

- Common interest in laser driven acceleration
- Contacted Suzuki and Wagner: invited Tajma to speak at ICFA meeting (Oct., 2008)
- Leemans appointed in November 2008 to lay groundwork for joint standing committee actvities
- ICFA endorsed initiation of joint efforts on February 13, 2009
- Joint Task Force formed (2009)

(from Leemans)

Proposed activity

- Joint workshop on laser technology for future colliders
  - Planning underway by Barty, Leemans and Sandner
  - Convene international panel of experts on laser technology
  - Create a comprehensive survey of the requirements for laser based light and particle sources with emphasis on sources that can advance light and particle science AND require lasers beyond the state of the art or state of current use.
  - Identify future laser system requirements
    - Identify key technological bottlenecks
  - From projected system requirements, provide visions for technology paths forward to reach survey goals and outline required laser technology R&D steps that must be undertaken
    - Write technical report

(Leemans)

Suggestions to ICFA-ICUIL JTF

- Science efforts by US, Europe, Asia mounting to extend the laser technology toward HEP accelerators
- Technology efforts still lacking in developing suited laser technology(ies) for HEP accelerators
- Technologies: emerging and credible for these
- ICFA-ICUIL collaboration: important guide of direction
- Lead lab(s) necessary to lead and do work on this initiative
- World Test Facility (‘World Lab’)?
- Other applications important (light sources, medical, nuclear waste management, fusion, defense, etc.)

(Tajima; April 10, 2010)

ICFA-ICUIL Joint Task Force
on laser acceleration (Darmstadt, 2010)

W. Leemans, Chair

Case	1 TeV	10 TeV (Scenario I)	10 TeV (Scenario II)
Energy per beam (TeV)	0.5	5	5
Luminosity (10^{34} $cm^{-2}s^{-1}$)	1.2	71.4	71.4
Electrons per bunch ($\times 10^9$)	4	4	1.3
Bunch repetition rate (kHz)	13	17	170
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	700	200	200
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	700	200	200
β^* (mm)	0.2	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	12	2	2
Vertical beam size at IP σ^*_y (nm)	12	2	2
Luminosity enhancement factor	1.04	1.35	1.2
Bunch length σ_z (μm)	1	1	1
Beamstrahlung parameter Υ	148	8980	2800
Beamstrahlung photons per electron n_γ	1.68	3.67	2.4
Beamstrahlung energy loss δ_E (%)	30.4	48	32
Accelerating gradient (GV/m)	10	10	10
Average beam power (MW)	4.2	54	170
Wall plug to beam efficiency (%)	10	10	10
One linac length (km)	0.1	1.0	0.3

Collider subgroup
List of parameters
(W. Chou)

Table 1
Collider parameters

JTF Report #2

Case	1 TeV	10 TeV (Scenario I)	10 TeV (Scenario II)
Wavelength (μm)	1	1	1
Pulse energy/stage (J)	32	32	1
Pulse length (fs)	56	56	18
Repetition rate (kHz)	13	17	170
Peak power (TW)	240	240	24
Average laser power/stage (MW)	0.42	0.54	0.17
Energy gain/stage (GeV)	10	10	1
Stage length [LPA + in-coupling] (m)	2	2	0.06
Number of stages (one linac)	50	500	5000
Total laser power (MW)	42	540	1700
Total wall power (MW)	84	1080	3400
Laser to beam efficiency (%) [laser to wake 50% + wake to beam 40%]	20	20	20
Wall plug to laser efficiency (%)	50	50	50
Laser spot rms radius (μm)	69	69	22
Laser intensity (W/cm^2)	3×10^{18}	3×10^{18}	3×10^{18}
Laser strength parameter a_0	1.5	1.5	1.5
Plasma density (cm^{-3}), with tapering	10^{17}	10^{17}	10^{18}
Plasma wavelength (μm)	105	105	33

Collider subgroup
List of parameters
(W. Chou)

Table 2
Laser parameters

JTF Report #3: Comparison of Choices

Accelerator	Beam	Beam energy (GeV)	Beam power (MW)	Efficiency AC to beam	Note on AC power
PSI Cyclotron	H+	0.59	1.3	0.18	RF + magnets
SNS Linac	H^-	0.92	1.0	0.07	RF + cryo + cooling
TESLA (23.4 MV/m)	e^+/e^-	250 × 2	23	0.24	RF + cryo + cooling
ILC (31.5 MV/m)	e^+/e^-	250 × 2	21	0.16	RF + cryo + cooling
CLIC	e^+/e^-	1500 × 2	29.4	0.09	RF + cooling
LPA	e^+/e^-	500 × 2	8.4	0.10	Laser + plasma

CLIC based on TBA (Two-Beam Acceleration)

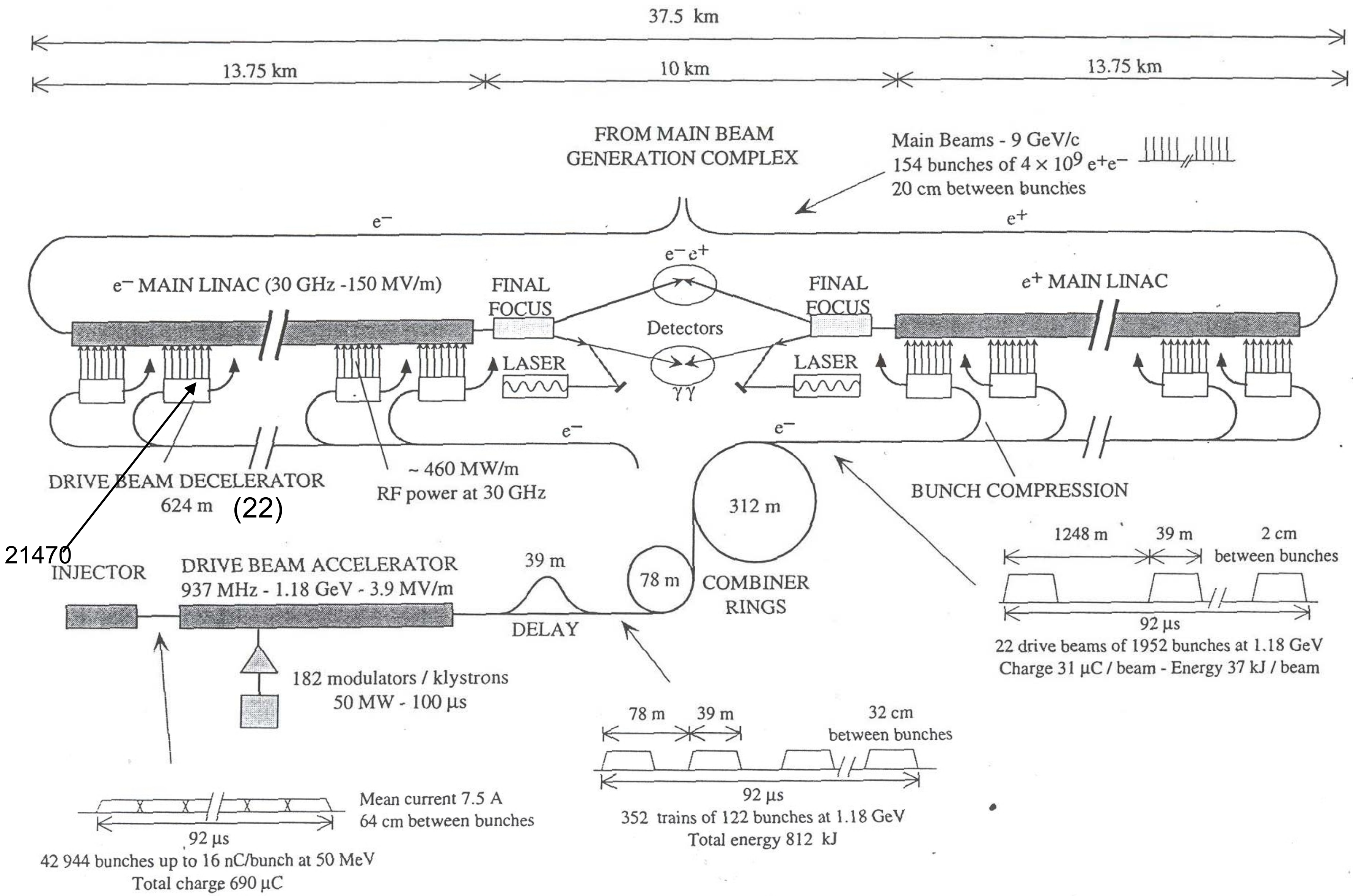


Fig. A.1: Overall layout of the CLIC complex at 3 TeV centre of mass.

PETS Power Extraction and Transfer structures)

Table 1.3: Main-beam and main-linac parameters for CLIC at 3 TeV c.m.

Main-beam parameters at IP		
Luminosity (with pinch)	L	$10.0 \times 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$
Luminosity (in 1% of energy)	$L_{1\%}$	$3.0 \times 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$
Beamstrahlung mom. spread	δ_B	31%
Beamstrahlung parameter	Υ	8.1
Number of photons/electron	N_γ	2.3
Number of particles/bunch	N_b	$4.0 \times 10^9 e^\pm$
Number of bunches/pulse	k_b	154
Bunch spacing	Δ_b	20 cm
	Δt_b	0.666 ns
Transverse emittances	$\gamma\varepsilon_{x/y}$	680/20 nm·rad
Beta functions	$\beta_{x/y}$	8/0.15 mm
r.m.s. beam size (no pinch)	$\sigma_{x/y}$	43/1 nm
Bunch length	σ_z	30 μm
Enhancement factor	H_D	2.24
Beam power per beam	P_b	14.8 MW
Main-linac parameters		
Centre-of-mass energy	E_{CM}	3 TeV
Linac repetition rate	f_{rep}	100 Hz (15kHz)
RF frequency of linac	$\omega/2\pi$	30 GHz
Acceleration field (loaded)	G_a	150 MV/m
Energy overhead		8%
Active length per linac	L_A	10.74 km
Total two-linac length	L_{tot}	27.5 km
RF power at structure input	P_{st}	229 MW
RF pulse duration	Δt_p	102 ns
Number of drive-beams/linac	N_D	22
Number of structures per linac		21 470
AC-to-RF efficiency	η_{RF}^{AC}	40.3%
RF-to-beam efficiency	η_b^{RF}	24.4%
AC-to-beam efficiency	η_b^{AC}	9.8%
AC power for RF production	P_{AC}	300 MW

CLIC Characteristics

Energy of each electron pulse
E_p= 1.5TeVx4 10^9electronsx1.6$10^{-19}$C =1kJ
E_p=1kJ

Energy of each Pulse
E_{op} = [Efficiency(20%)]$^{-1}$x E_p(1kJ)
E_{op}=5kJ

Peak Power P_p= E_{op}(5kJ)/.1ps
P_p= 50PW

Average Power for two beams
P_{AV}=2xE_{op} (5kJ)xRep.RateN(15kHz)
P_{AV}=150MW

(Mourou)

Efficiencies
CLIC vs. Laser-Plasma

	CLIC	Laser Plasma (Fiber-based)
AC to RF/Laser	40%	40%
RF/Laser to beam	24%	20%
AC to beam	9.6%	8%

(Mourou)

The bottleneck in high-power lasers is
the average power !

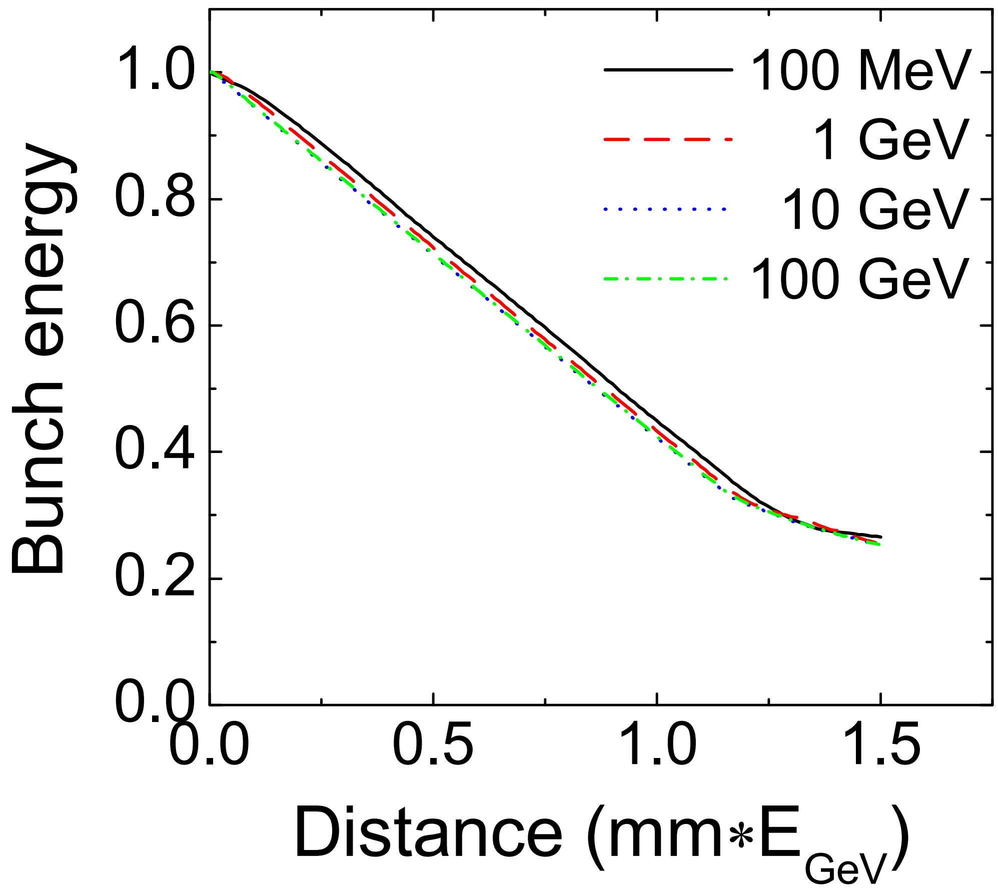
„Beyond Petawatt means Kilowatt“

W. Sandner (2010)

Laserlab
Europe

Collective deceleration over mm

Results of computer simulation



isomorphic, regardless of energies

(Wu et al, 2009)

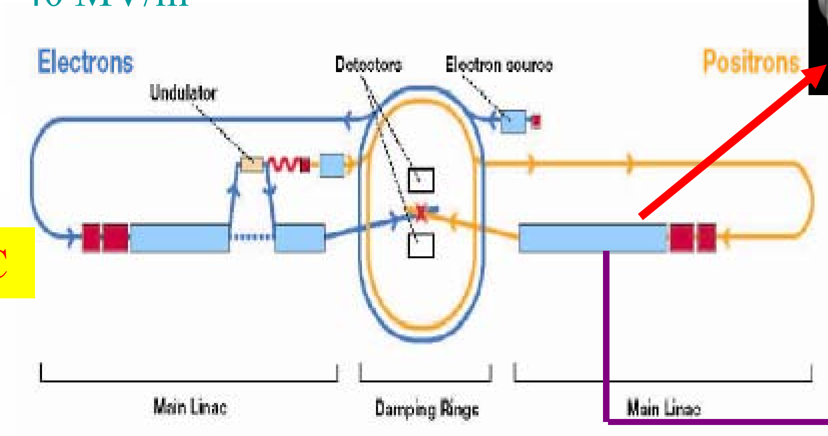
Accelerator

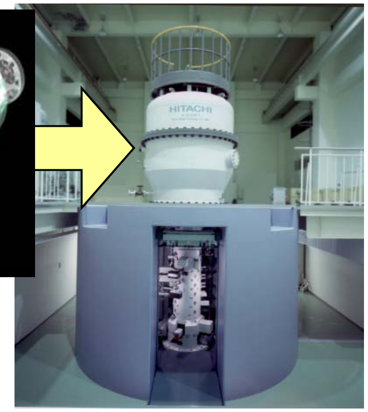
Evolution of Accelerators and their Possibilities (Suzuki,2008)

2020s

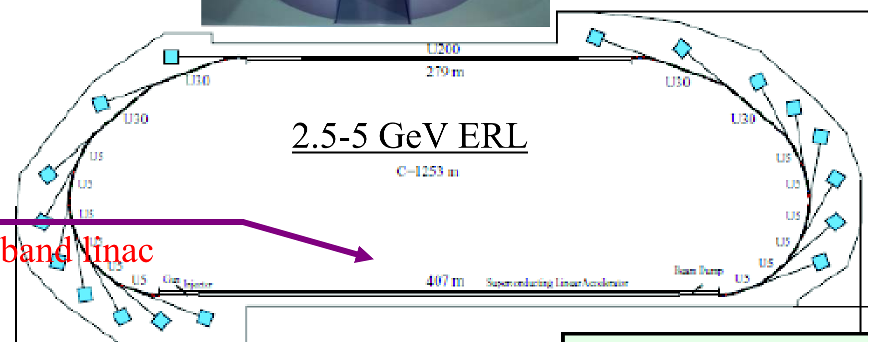
ILC

E=40 MV/m





Ultra-High Voltage STEM with Superconducting RF cavity

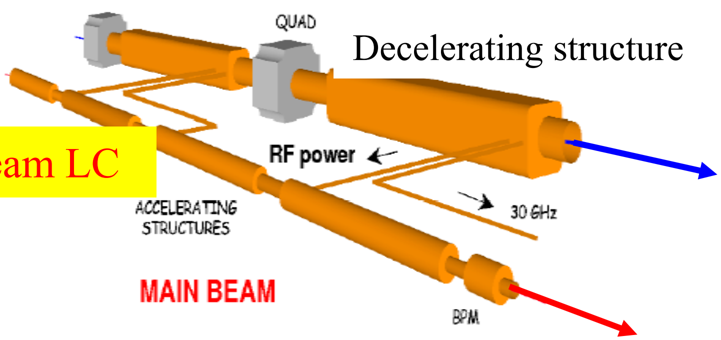


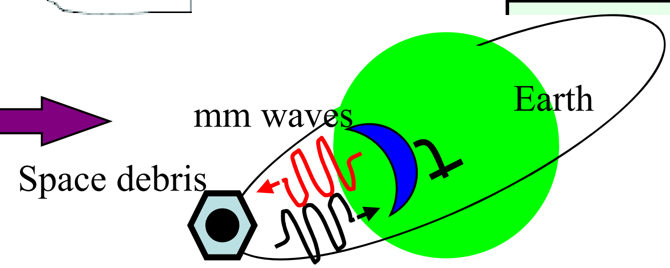
Superconducting L-band linac

2030s

Two-beam LC

E=200 MV/m





Earth-based space debris radar

2040s

Laser-plasma LC

E=10 GV/m

10cm-10GeV Plasma Channel Accelerator

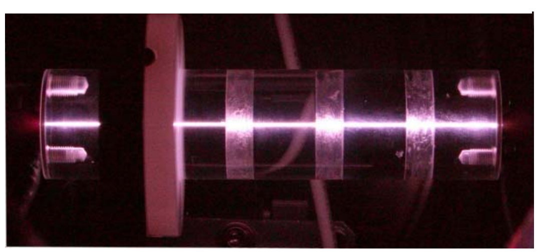


Table-top high energy accelerator

A. Suzuki (KEK)

1000 times higher energy

1 PeV=10^{15} eV

"New paradigm"

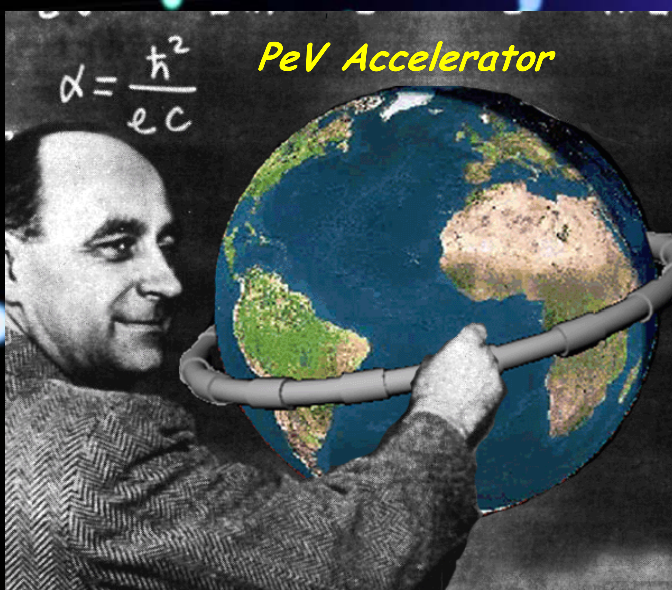
Leptogenesis

SUSY breaking

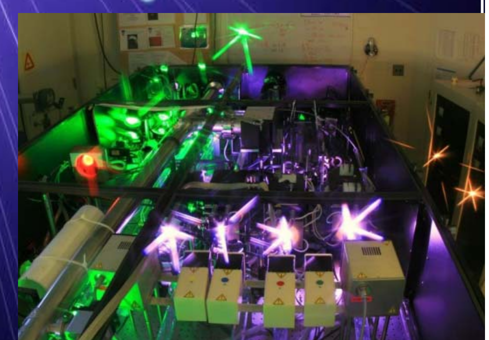
Extra dimension
Dark matter
Supersymmetry

1 TeV=10^{12} eV

"Standard model"
Higgs
Quarks
Leptons



***Laser* Acceleration Technology**



Coherent Amplifying Network

G. Mourou (2005)

- Basic concept
- Measuring the Phase
- Controlling the phase
- Phase modulator

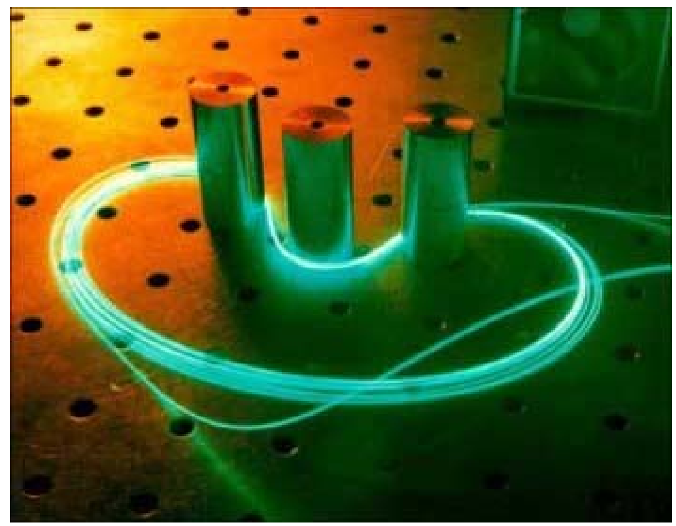
Gérard A. MOUROU
ENSTA – Ecole Polytechnique – CNRS
Almantas Galvanauskas
University of Michigan

CAN, Coherent Amplifying Network

Patrick Georges IOGS
Jean-Pierre Huignard Thale
Arnaud Couairon
Cécile Belanger Thalès
Jerôme Primot

Fiber vs. Bulk lasers

- High Gain fiber amplifiers allow ~ 40% total plug-to-optical output efficiency
- Single mode fiber amplifier have reached multi-kW optical power.
- large bandwidth (100fs)
- immune against thermo-optical problems
- excellent beam quality
- efficient, diode-pumped operation
- high single pass gain
- They can be mass-produced at low cost.



(G. Mourou)

Properties of rare-earth-doped fibers

Why Ytterbium?

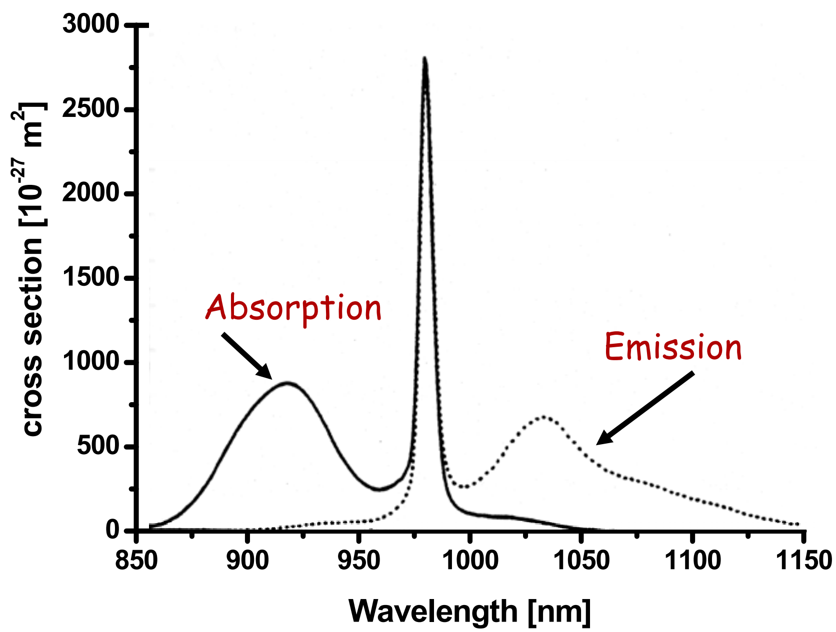
simple energy levels → no ESA

broad emission bandwidth (~40 nm)

broad absorption band overlaps with diode wavelengths

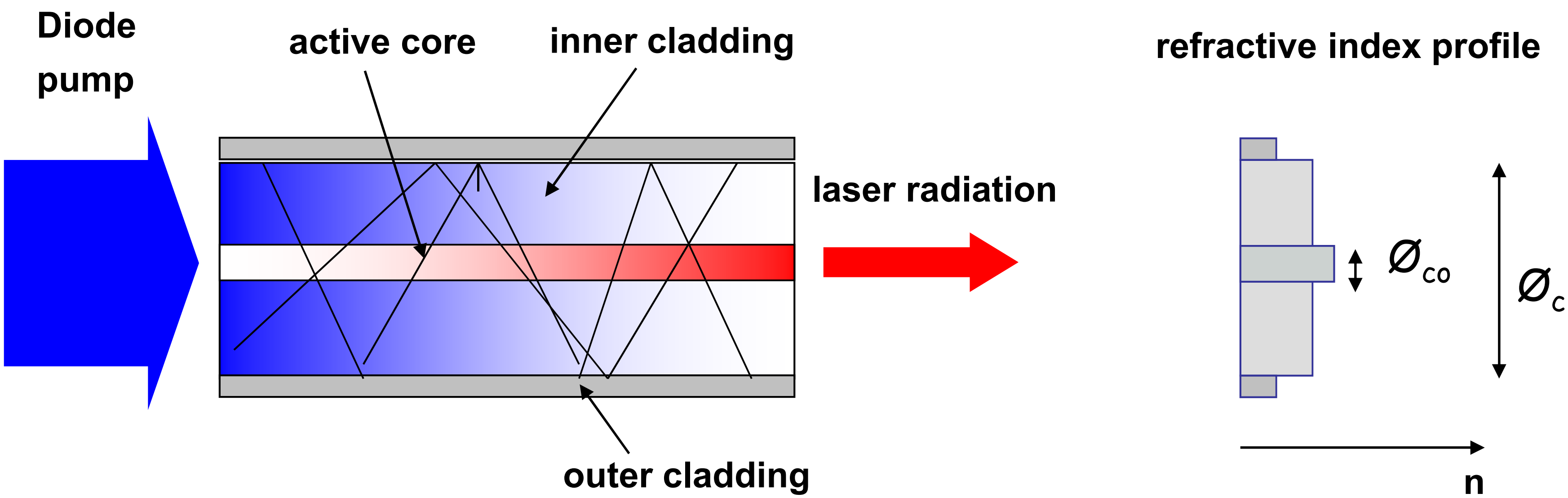
small quantum defect → optical-to-optical efficiency >80%

huge saturation fluence, long fluorescence lifetime



(Mourou)

→ Fiber laser



Single mode $Ø_{co}$~10λ

(Mourou)

Fiber Laser Technology

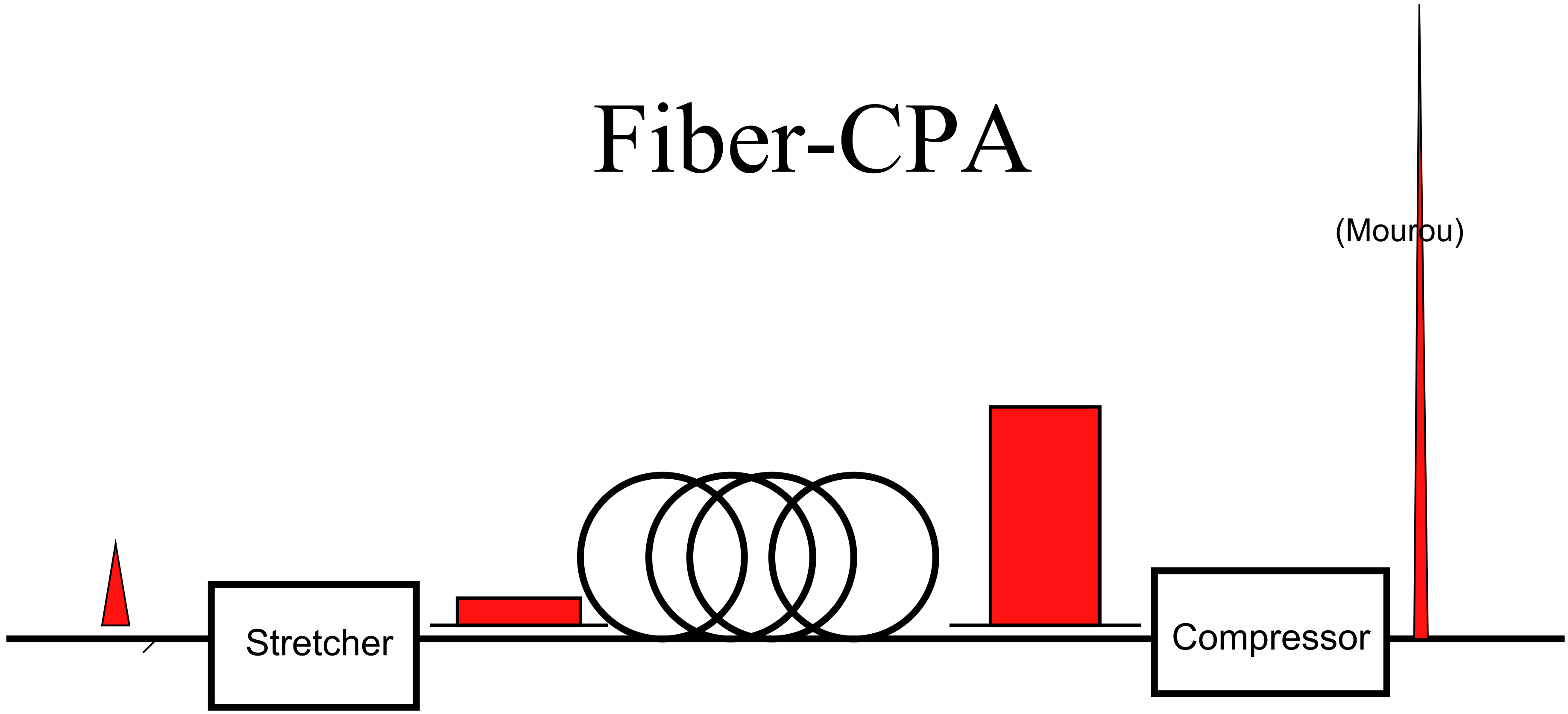
(Mourou)

- Practical technology:
  - Robust
  - Efficient, up to 40% electrical-to-optical
  - Compact
  - Extremely Reliable
- Uniquely high powers:
  - Single-mode 1 - 2 kW achieved, 5 - 10 kW range feasible
  - >10 kW multi-mode (combined fibers) demonstrated

Main Challenge:

Can Fiber lasers provide enough energy for laser plasma generation?

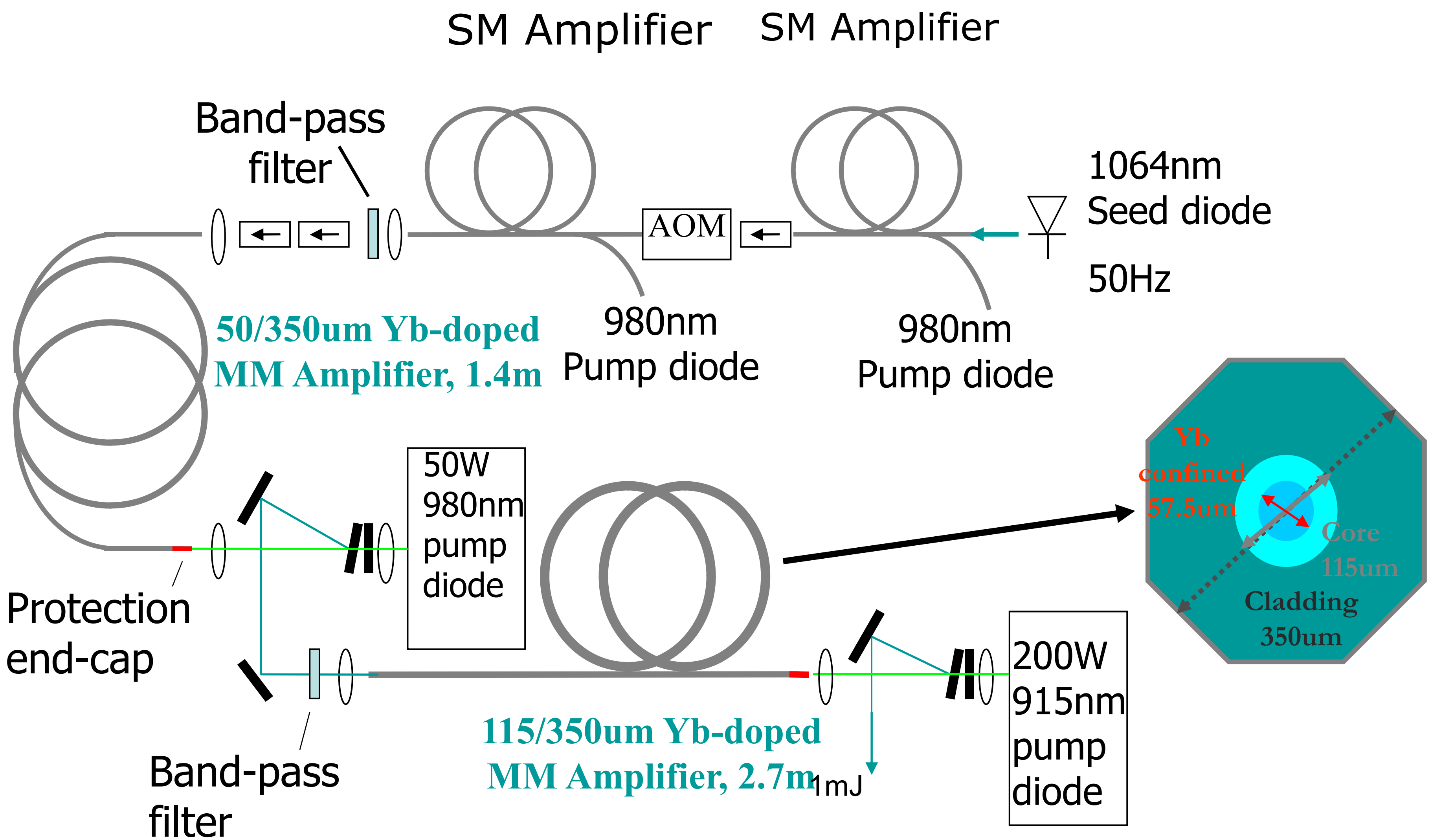
Fiber-CPA



A. Galvanauskas, Z. Sartania, and M. Bischoff," Millijoule femtosecond fiber-CPA system, " in *Advanced Solid-State Lasers,* Seattle, WA, January 28-31, 2001 postdealinepaper PD3.

M. L. Stock and G. Mourou, "Chirped Pulse Amplification in an Erbium-Doped Fiber
Oscillator/Erbium-Doped Fiber Amplifier System," *Opt. Commun.* 106, 249-252 (1994).
D. Strickland and G. Mourou "Compression of Amplified Chirped Optical Pulses. "*Opt. Commun.*, vol. 56, pp. 219-221, 1985.

mJ Fiber Laser Driver



(Mourou)

Energy per Fiber

The Yb: glass has a saturation fluence of ~ 50J/cm^2.

For stretched Pulses the dielectric breakdown ~100J/cm^2.

A single mode fiber (core size of $10\text{–}20\mu\mu$) could provide

E_{fiber}= Area x 100J/cm^2= 1mJ/fiber

E_{fiber}= 1mJ/fiber

Number of fibers N pour 2x 5kJ = 10kJ/1mJ

$N=10^7$

To produce 150MW of average power each fiber will need to produce 15W/fiber which is an easy requirement.

At a predicted cost of $10/W. The cost of the diodes would amount to 1.5G$.

(Mourou)

Single Mode 1XN Splitters

view catalog

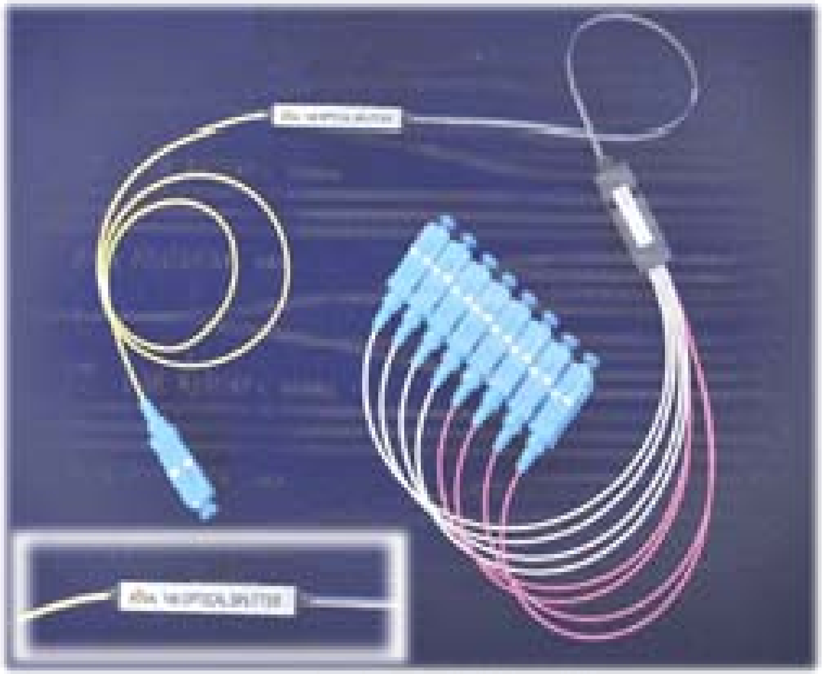
Single Mode 1×N Splitters divide uniformly optical signals from input ports to multiple outputs. Splitters can also be operated in the reverse direction to combine multiple wavelengths into one.

Features

- Single mode
- Up to 32 outputs standard
- Available in 1×N configurations

Applications

- Fiber optic equipments & systems
- CATV networks
- Data communications
- Passive optical networks
  (ATM, WDM, Ethernet...)

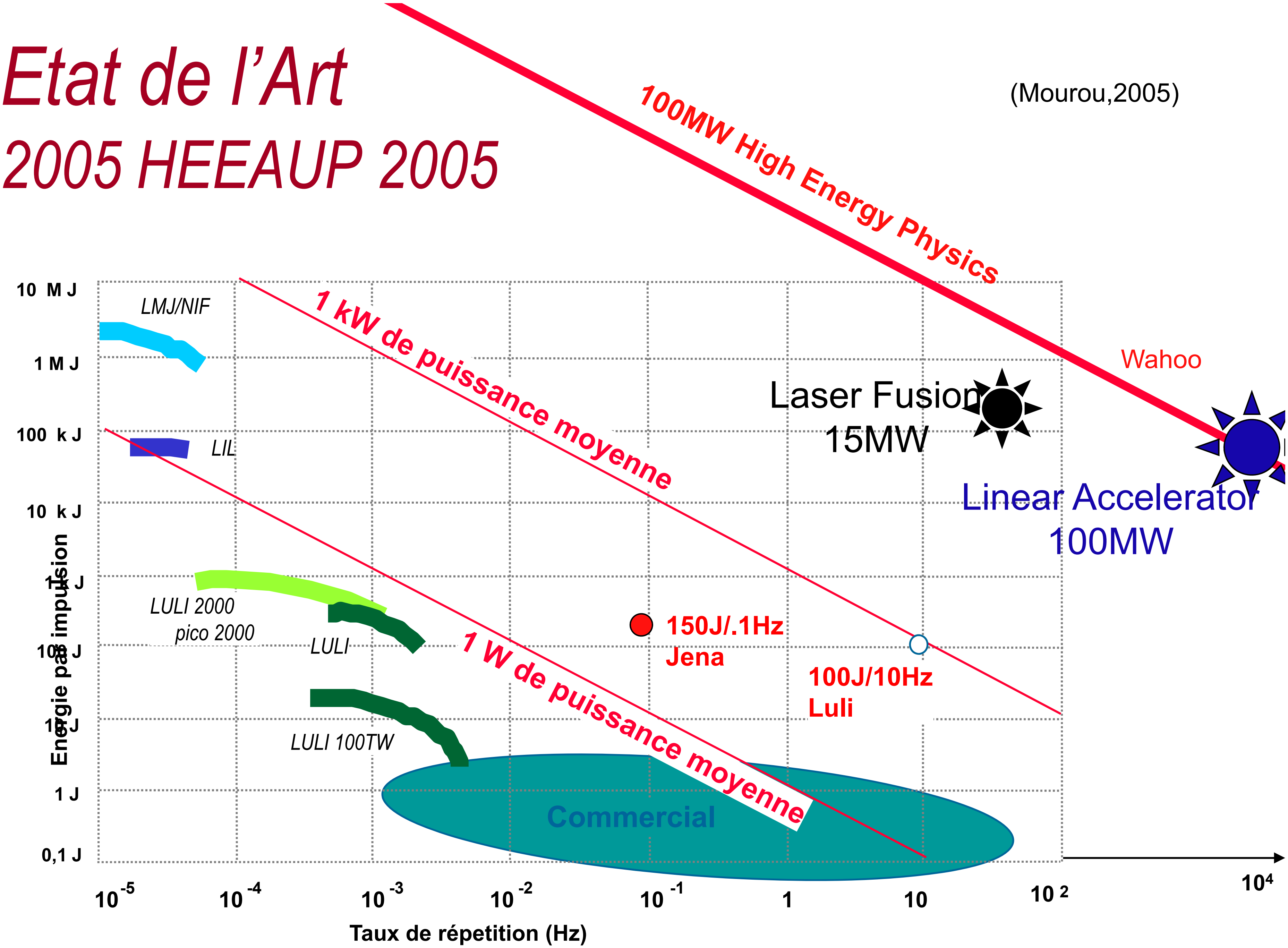


<1x16 Splitter with SC connectors>

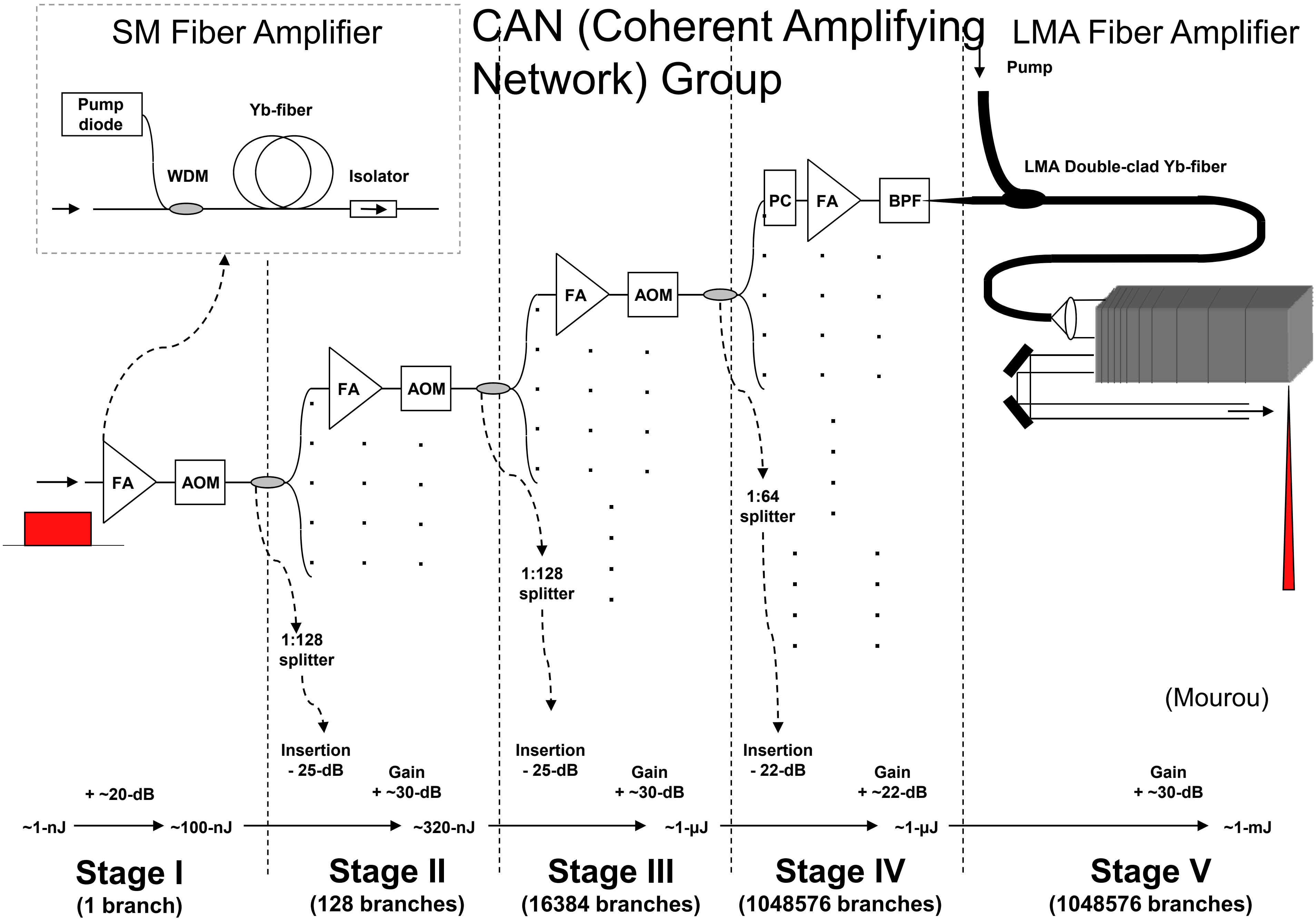
(mourou)

Etat de l'Art
2005 HEEAUP 2005

(Mourou,2005)

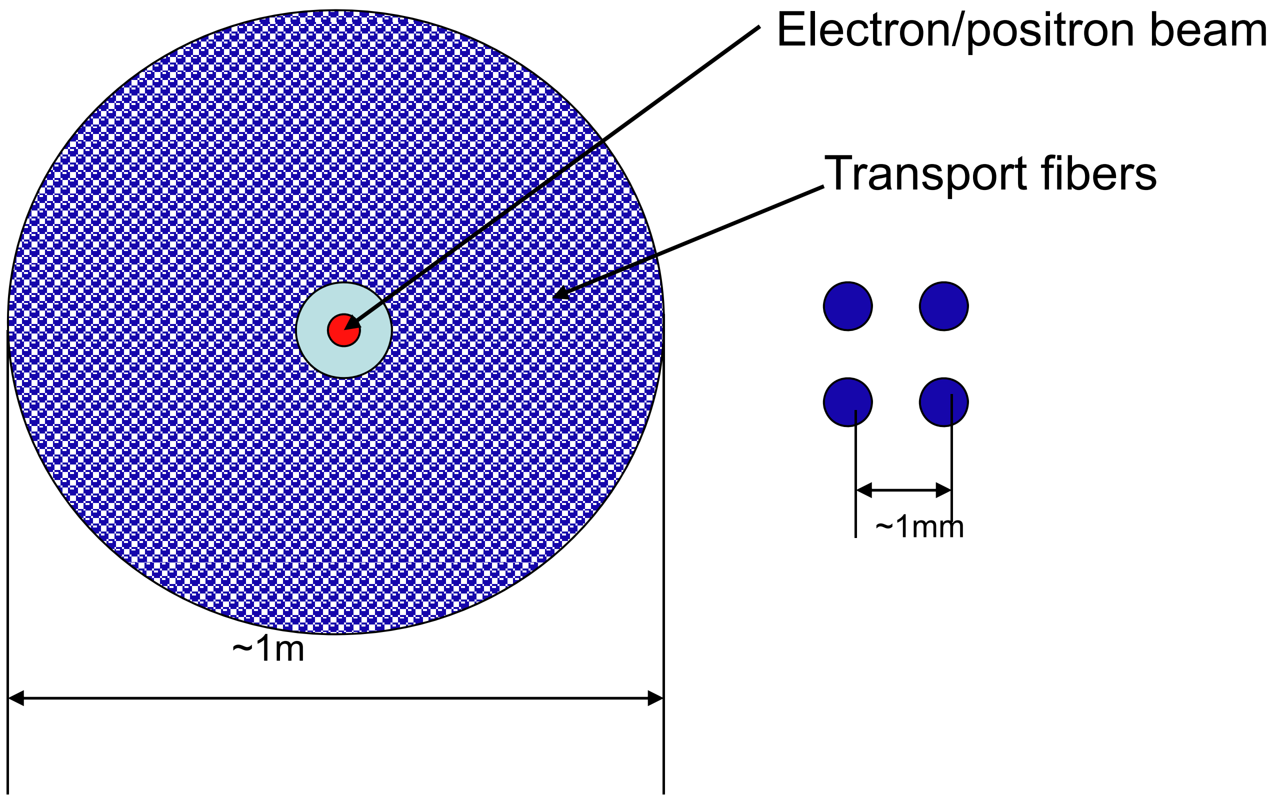


CAN (Coherent Amplifying Network) Group



150 MW Fiber bundle

Because the transport fibers are lossless they will be assembled in a bundle just before the focusing optics. They will be all coherently phased.



Length of a fiber ~5m   Total fiber length~ 5 10^4km

(Mourou et al)

Coherent-Network CPA

Pros

- Extremely high average power(unlimited)(10kW/fiber)
- Very high efficient (70%)
- Perfect beam quality (single mode
- Alignment free (connecting telecom parts)
- Reconfigurable
- Ultrashort pulse possible to 6fs
- Transportable pulses
- Made of cheap robust telecom parts(fiber, isolator, AOM).

. Highly manufacturable

. Small fraction of the world telecom part production

Cons

- Phasing of fibers

(Mourou)

Can technology obey Moore's Law?

Yes for Patterned Structures.

Bob Beyer's dictum

(Mourou)

From Very High to High Average Power: A 10kW Design

A 10 kW will be comprised of 10^3 fibers @ 10W per fiber.

It could produce 1J/100fs at 10kHz.

Further shortening could be done via nonlinear fiber compression to ~10fs.

It will have only two stages of amplification.

At 100$/W its cost could be 1M$

(Mourou)

Conclusions

- Need proof-of-principle experiments at energies serious to HEP (s.a 100GeV)
- Not just laser community project; accelerator community also needs it
- Toward 100GeV: challenges we face
- Need to foster laser technologies that drive 1TeV collider
- These technologies : long-ranged , needs guidance from beneficiary
- Need a connector between vision and real technology
- Not just laser community, but a larger community participates
- Getting within a reach

Centaurus A:

cosmic wakefield linac?

Merci Beaucoup!