IZEST

The International Center Zetta-Exawatt Science and Technology

ICAN and 100GeV's Ascent

"Bringing ICUIL and ICFA Together"

EuroNNAc, May 2012 Meeting

CERN

Gérard Mourou and Toshiki Tajima

IZEST, Ecole Polytechnique, Palaiseau

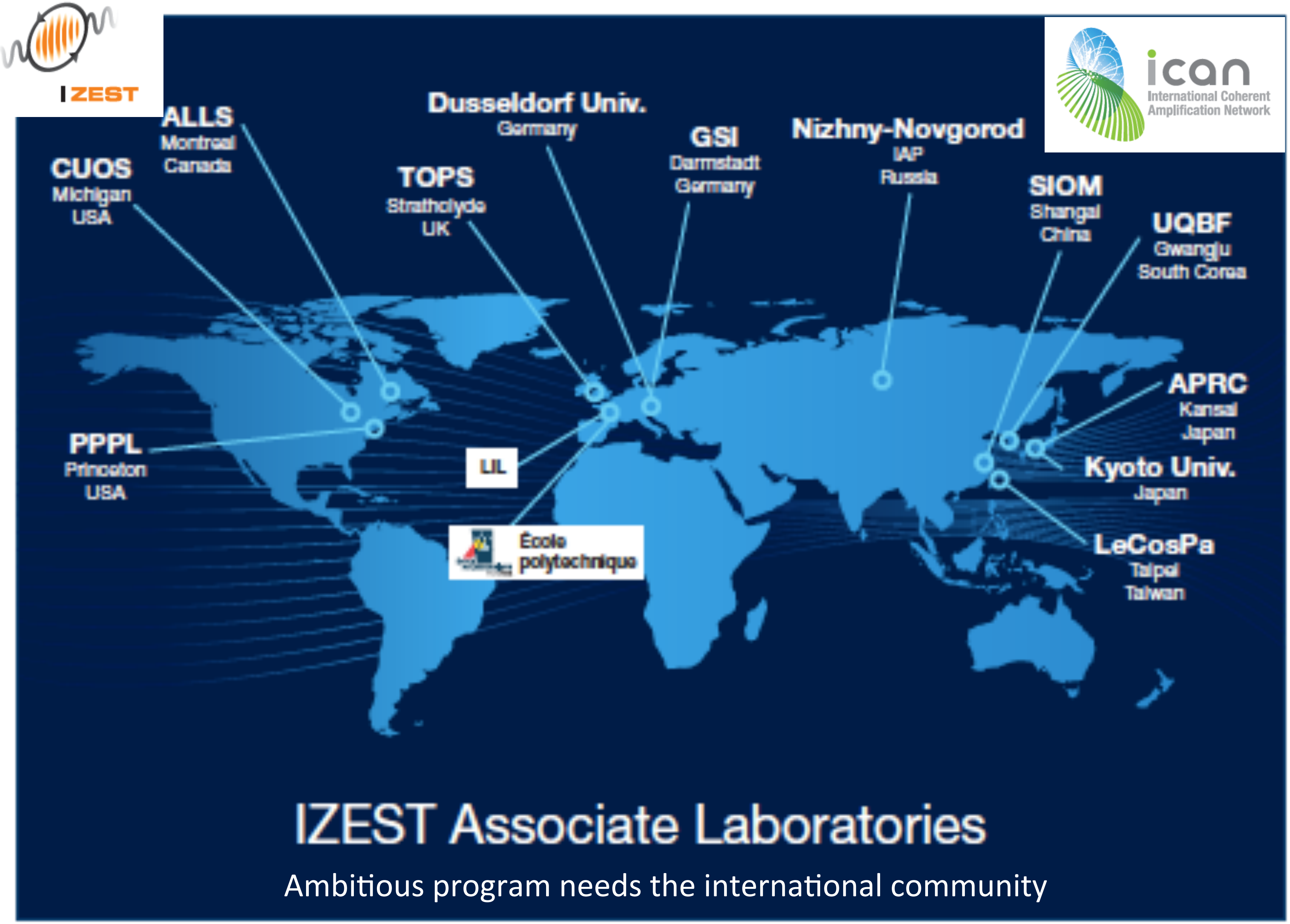
IZEST

Launched by EP, CEA in November 2011

IZEST aspires to be the first international Laser Center designed:

1. ***To explore Fundamental Physics at the highest intensity frontier by showing Exawatt and zettawatt laser peak power, Single shot TeV-PeV, …***

2. ***To solve the High Average Power Quandary plaguing the laser wake field. ICAN (International Coherent Amplification Network), producing MWs average power.***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ican
International Coherent Amplification Network
CUOS
Michigan
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TOPS
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UK
Dusseldorf Univ.
Germany
GSI
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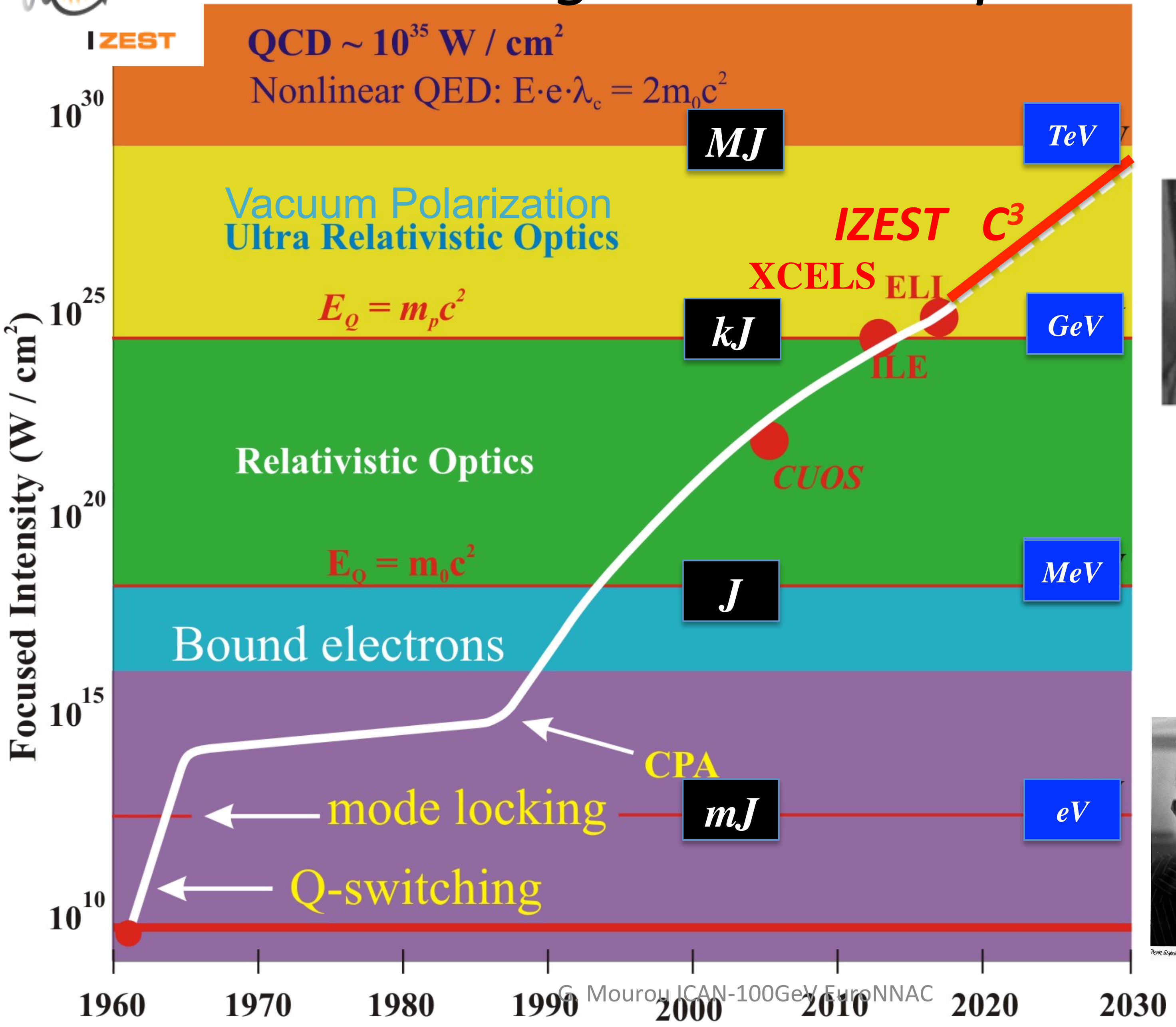
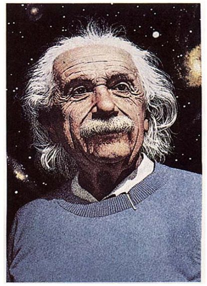
Nizhny-Novgorod
IAP
Russia
SIOM
Shangai
China
UQBF
Gwangju
South Corea
APRC
Kansai
Japan
Kyoto Univ.
Japan
LeCosPa
Taipei
Taiwan
PPPL
Princeton
USA
LIL
École polytechnique
IZEST Associate Laboratories
Ambitious program needs the international community

Extreme Light Road Map





Why this Ultimate Intensity Pursuit?

This Intensity can produce the:

- *shortest pulse: yocto sec 10^{-24}s,*
- *Highest field (near the critical Field: 10^{16}V/cm),*
- *highest radiation energy: TeV.*

- *highest energy particle: TeV, …..PeV*
- *applications that could impact society, humanity …*

ICAN

International Coherent Amplifcation Network
Collider High Luminosity Paradigm

A EU funded project sudying the posssibility to produce efficiently Petawatt Peak Power at Megawatt Average Power (10kHZ, Rep. Rate).

Beneficiaries: ***Ecole Polytechnique, The Optoelectronic Research Centre (ORC), The Fraunhofer Institute for Applied Optics and Precision Engineering, CERN (Organisation européenne pour la recherche nucléaire)***

European Commission

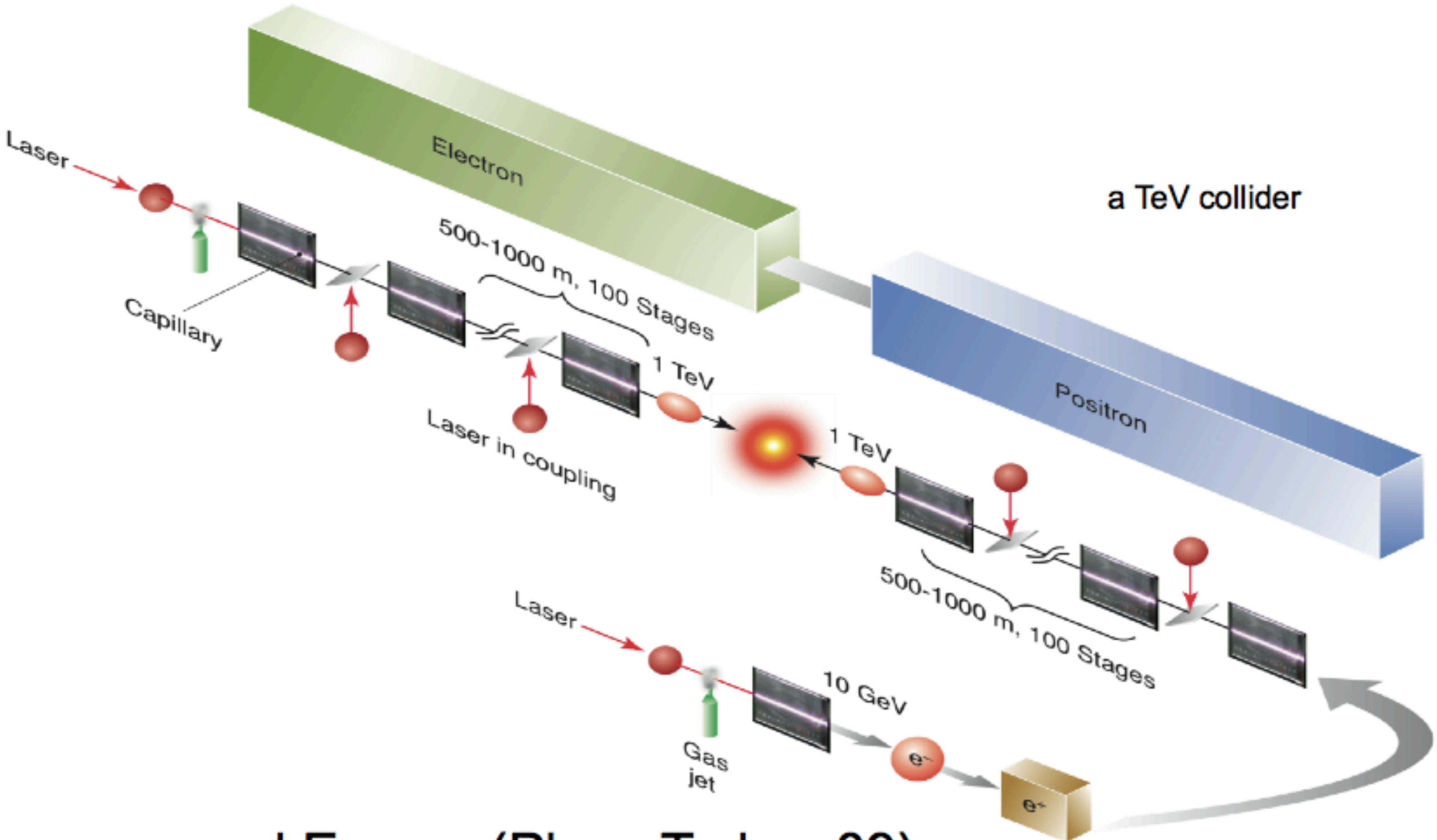
ICAN and FP7

The cold "facts and figures"

- ICAN — International Coherent Amplification Network
- In "FP7 language", ICAN is a support action responding to a year 2011 call for proposals to *support policy development, including international cooperation, in its field of S & T*
- It was assigned the project number 284437
- It will last 18 months as from 16 January 2012
- The maximum EU contribution is EUR 500,000.00
- 4 beneficiaries form the Consortium (EP, ORC, FhG and CERN)
- The EC signed the Grant Agreement on 7 February 2012

Research & Innovation

Laser driven collider concept



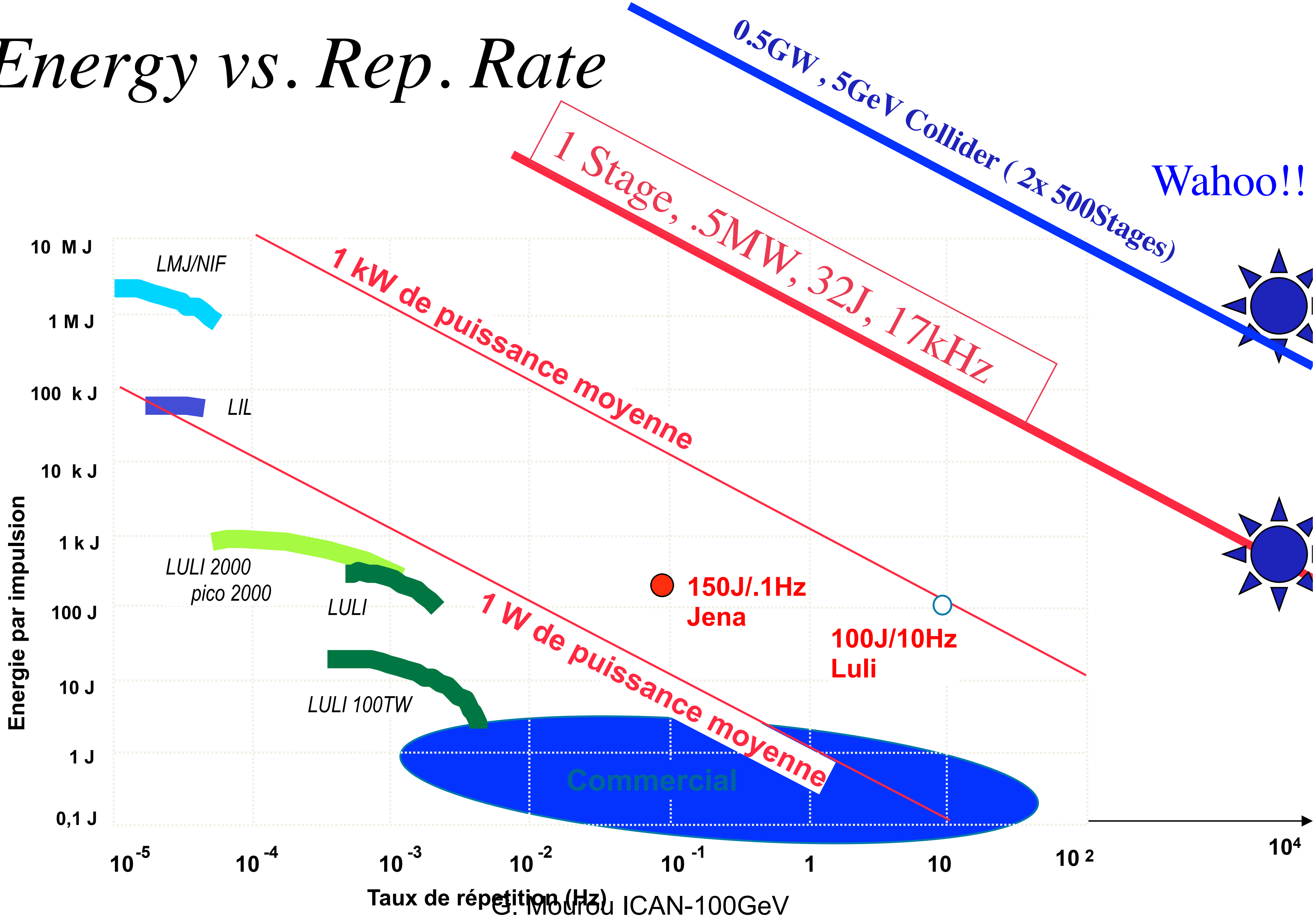
Leemans and Esarey (Phys. Today, 09)

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

Laser requirements for such colliders

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

Energy vs. Rep. Rate



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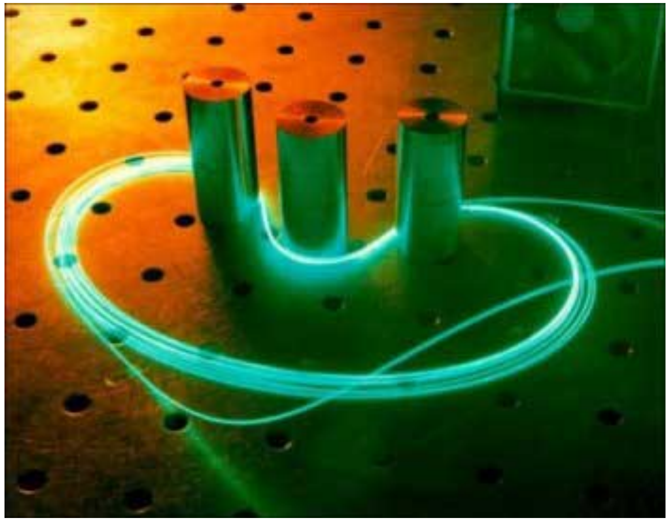
Fiber laser Driver

Fiber vs. Bulk laser

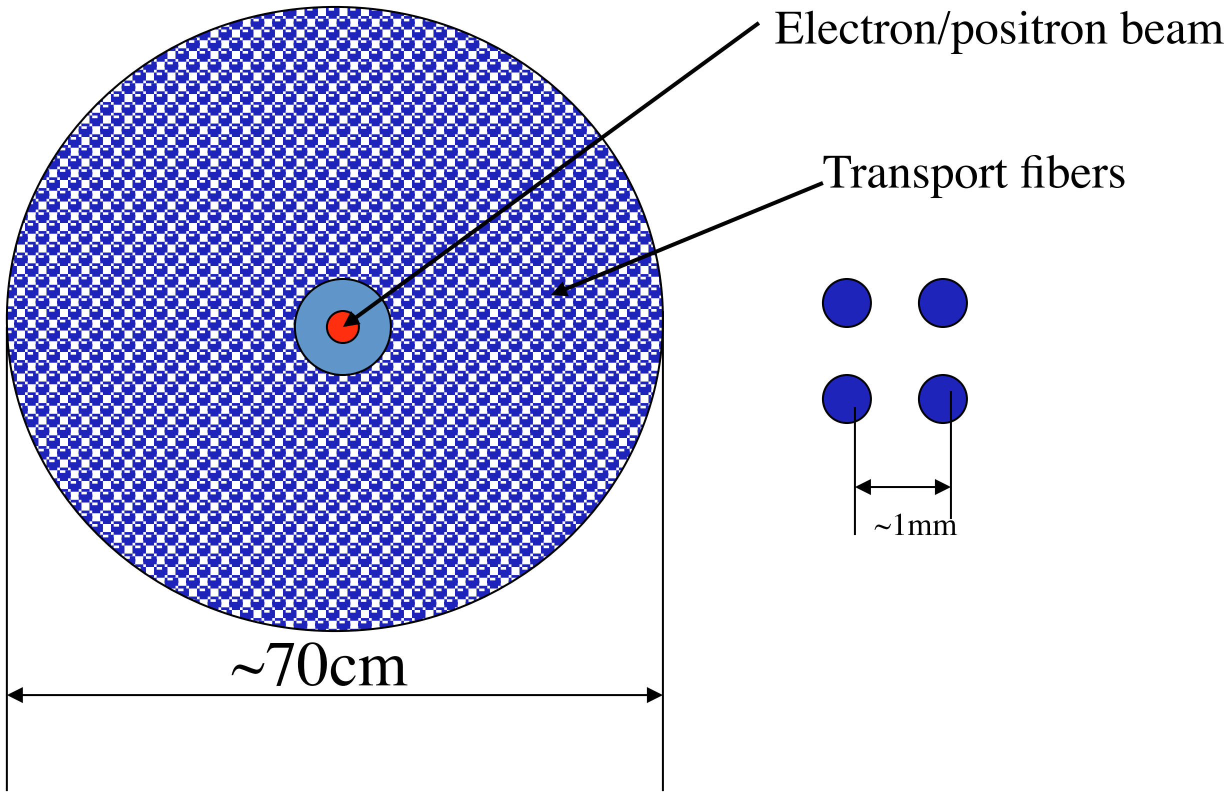
- *High Gain fiber amplifiers allow ~ 50% total plug-to-optical output efficiency reachable*

- *Single mode fiber amplifier have reached 10kW optical power because the large surface area volume ratio.*
- *large bandwidth (100fs)*
- *High rep. rate 10kHz>1/τf, highly desirable for diode stability, lifetime and system noise*
- *Excellent beam quality*
- *Efficient, diode-pumped operation*

  Pigtail pumping vs stacks
- *They can be mass-produced at low cost.*

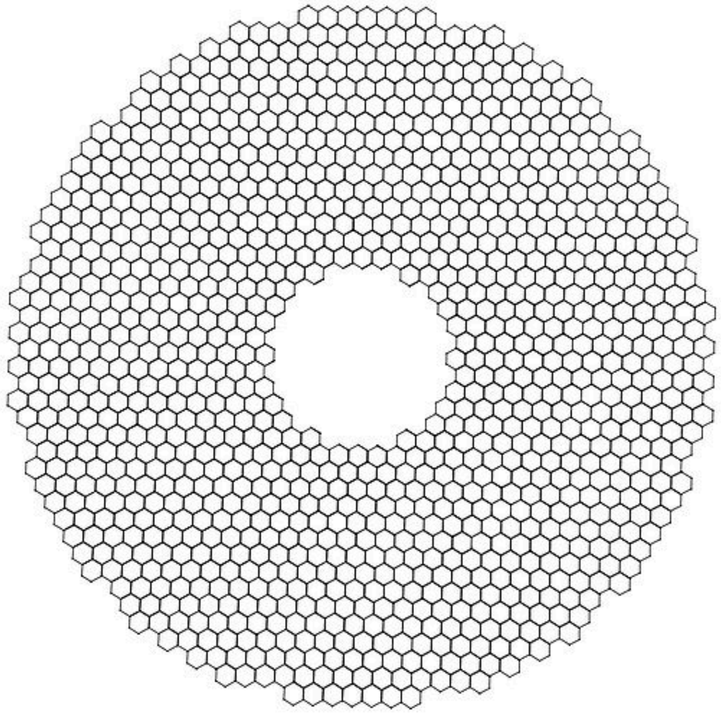


However Needs to Phase 32 J/1mJ/fiber~ 30 10^3 Phased Fibers!!



Length of a fiber ~2m Total fiber length~ 5 10^4km

Close Similarity to 42m ELT(Extreme Large Telescope, ESO)

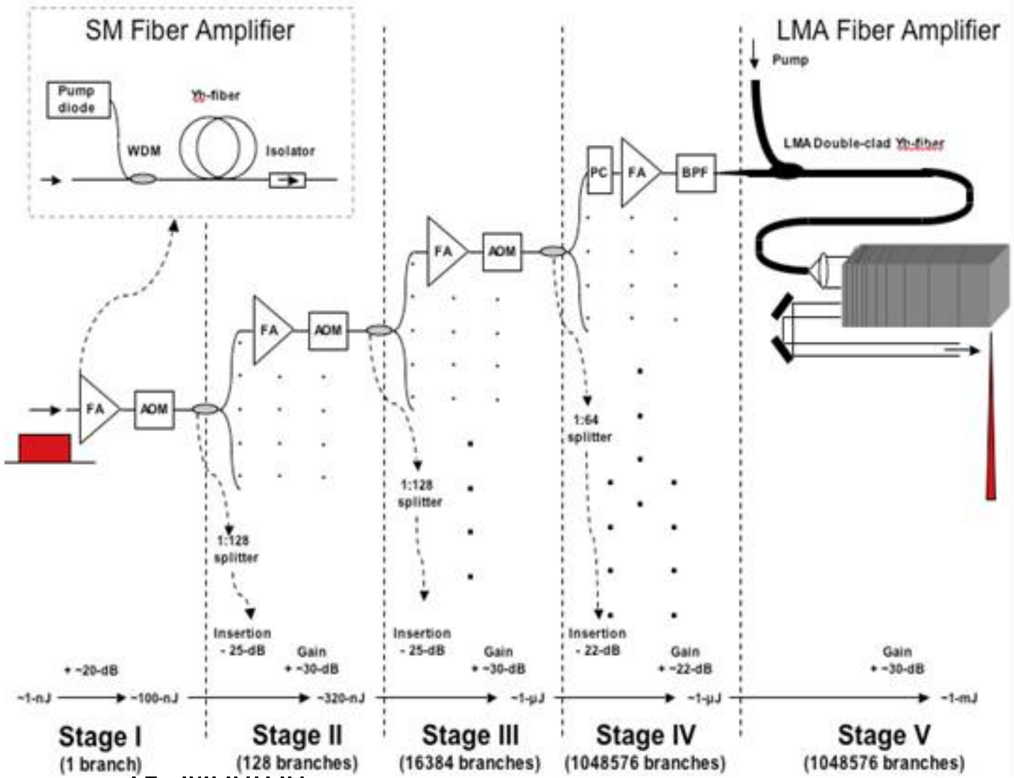


50 000 actuators, ~1000 mirrors, 1.5m @ 2kHz sampling, λ/50

The CAN concept, opening to the scalability

→ Laser concept based on a diode-pumped fiber network of femtosecond pulses

→ Device possibly based on standard, cheap and reliable telecom components



- Laser architecture allowing high peak / high average powers are desired for future societal application

- Coherent combining demonstrated for CW regime, few experiments in ns regime, no results yet in fs regime

- Coherent combining required for some application not for all of them

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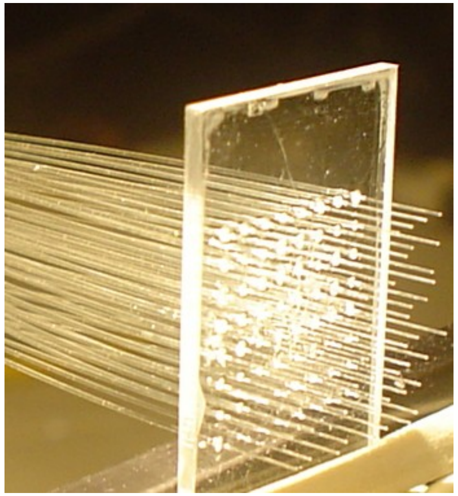
The CAN Project:

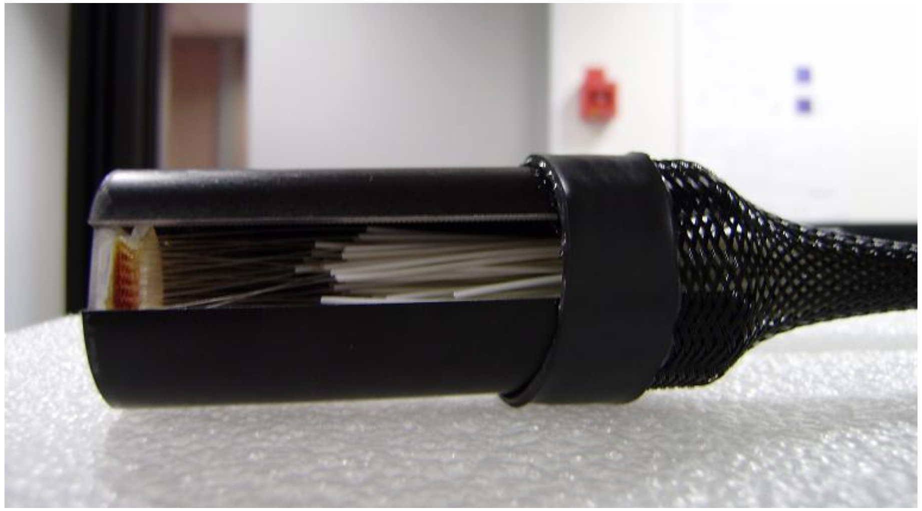
(a ANR-National Project)

- **Equipe CAN**
  - Gérard Mourou, Matthieu Somekh
  - Patrick Georges, Marc Hanna, Raymond Mercier, Mathieu Paurisse
  - Jérôme Primot, Bruno Toulon, Laurent Lombard
  - Arnaud Brignon, Jean-Pierre Huignard
- **Unité mixte CNRS/Thales LIGA**
  - Fayçal Bouamrane, Thomas Bouvet, Stéphane Megter
- **IDIL Fibres Optiques**
  - Lionel Quétel, Tristan Allain
- **Phasics SA**
  - Sabrina Velghe, William Boucher
- **TRT**
  - Sébastien, Arnaud, Bastien, Sylvain, JPH, JP², Daniel, Joseph, Pascale, Eric, Jérôme, Gilles, Patrick, Christian, Guillaume, Rémi, François, Perrine, Ghaya, Loïc, Stéphanie, Grégoire, Arnaud, Christine, Hamza, Muriel, Dominique, Yves, Arnaud, Frédéric, Romain, Brigitte, Anne, Laure, Landry, Jean Luc,Thierry, Sylvain, Alfredo, Barbara, ….

64-Fiber Mock-up

- Insertion des fibres
  - Insertion des 64 fibres, alignement PM (° près), collage
  - Polissage collectif de la surface de sortie des fibres





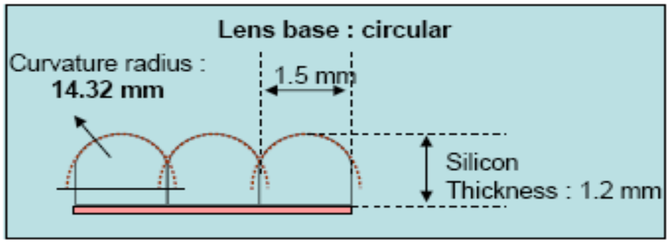
- Composant intégré pour le maintien des fibres

IDIL FIBRES OPTIQUES

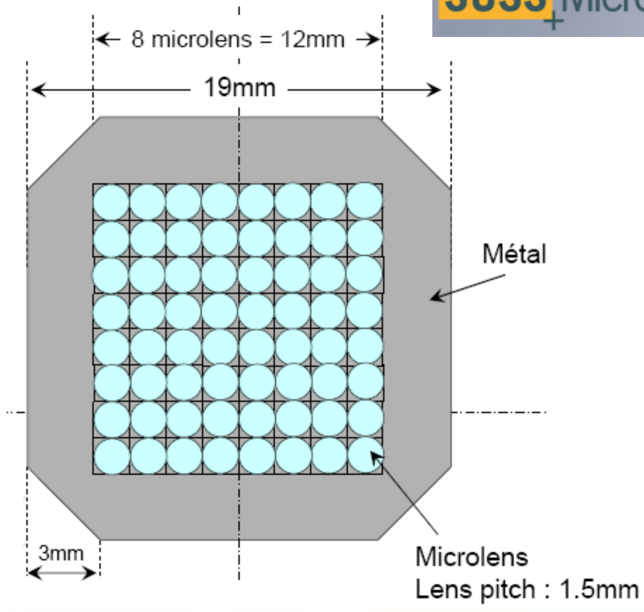
Matrice de microlentilles

- Caractéristiques

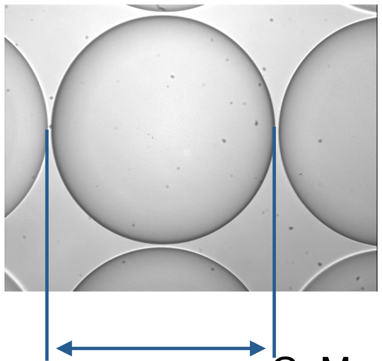
F = 5,7mm

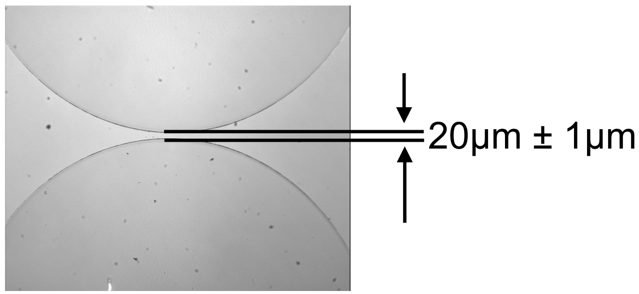


Réalisation par lithographie



- Mesure du pas





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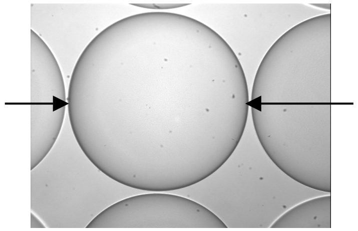
Matrice de microlentilles

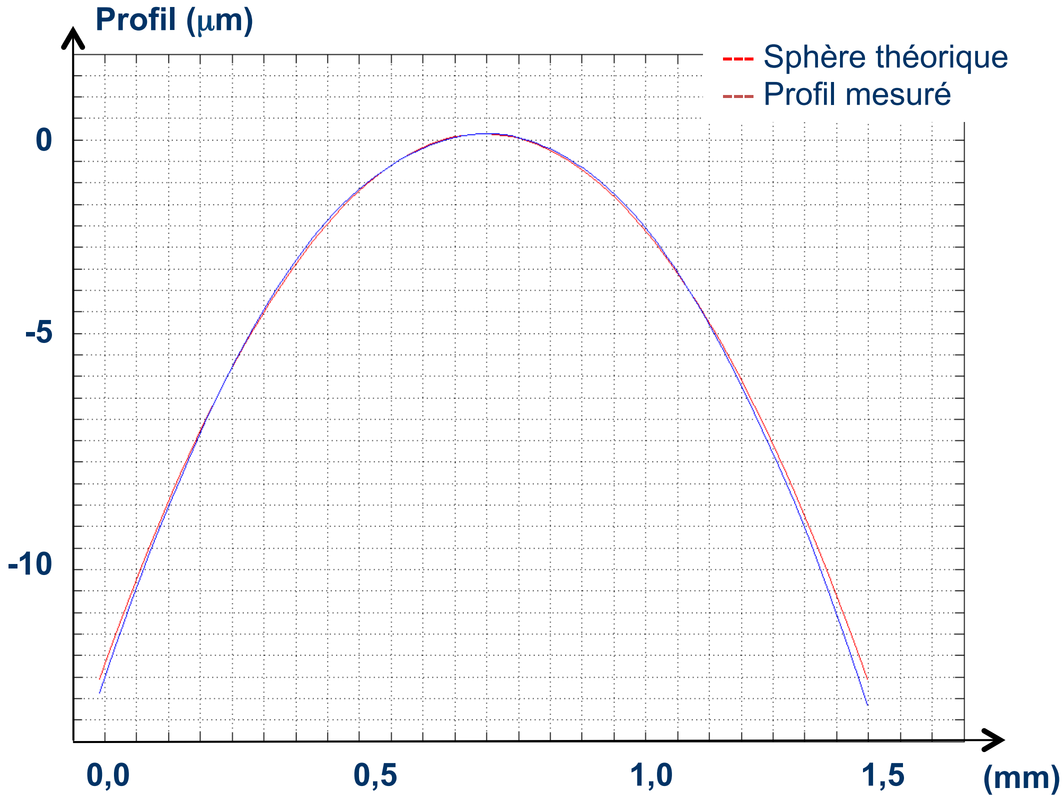
- Mesure du profil



Comparaison avec la sphère théorique

λ / 10 sur 80% de l' ouverture

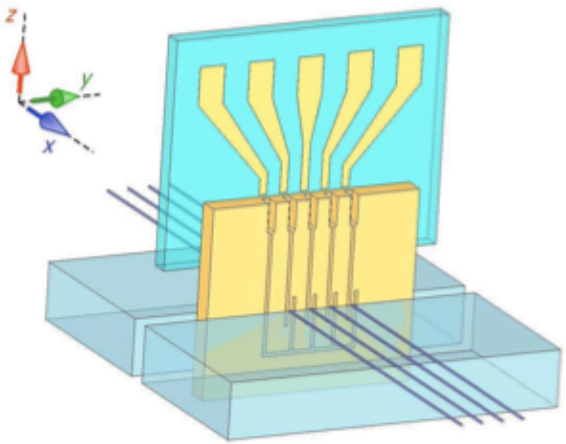
λ / 3 sur la totalité

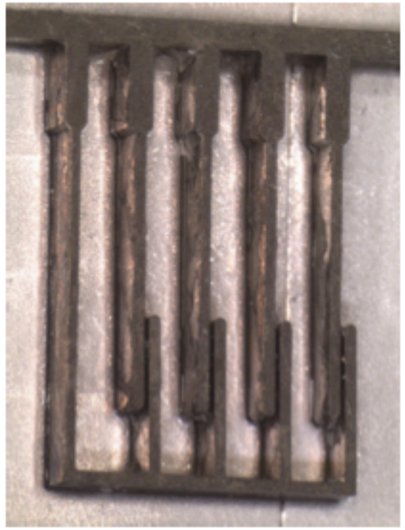


Phase control

Réalisation des composants

- Modulateurs matriciels céramiques





Outil de perçage réalisé par l'équipe LIGA

- Fabrication du masque (07/08)
- Réalisation outils de perçage (10/08)
- Commande des plaques 2'' de PMN-PT , PLZT (10/08)
- Usinage première matrice (prév. 11/08)
- Fibrage du premier composant (prév. 12/08)

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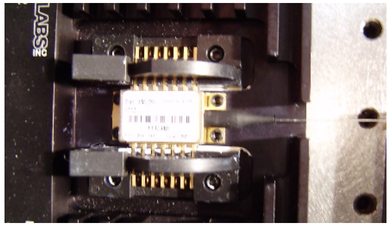
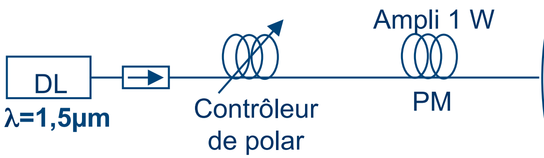
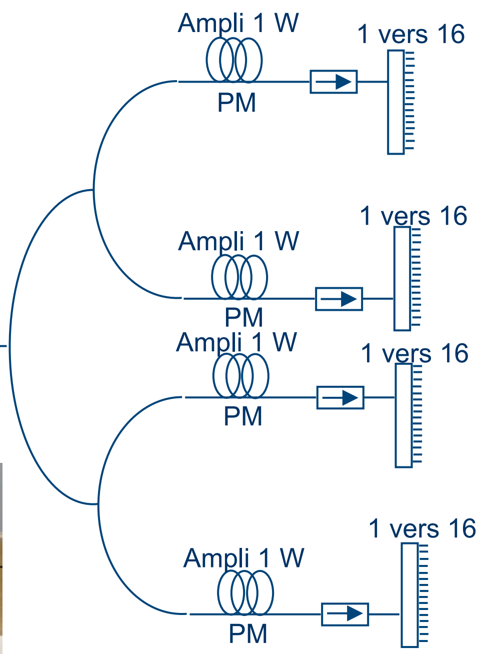
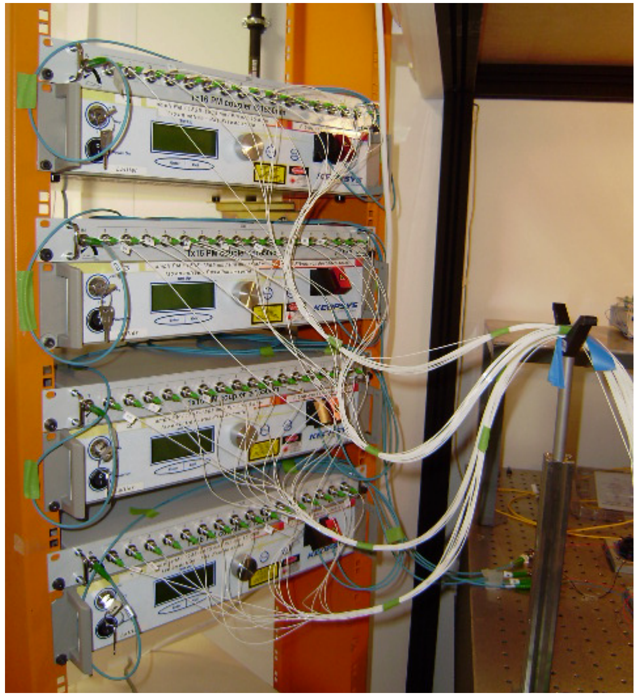
Génération des 64 faisceaux

- Génération de 64 faisceaux fibrés









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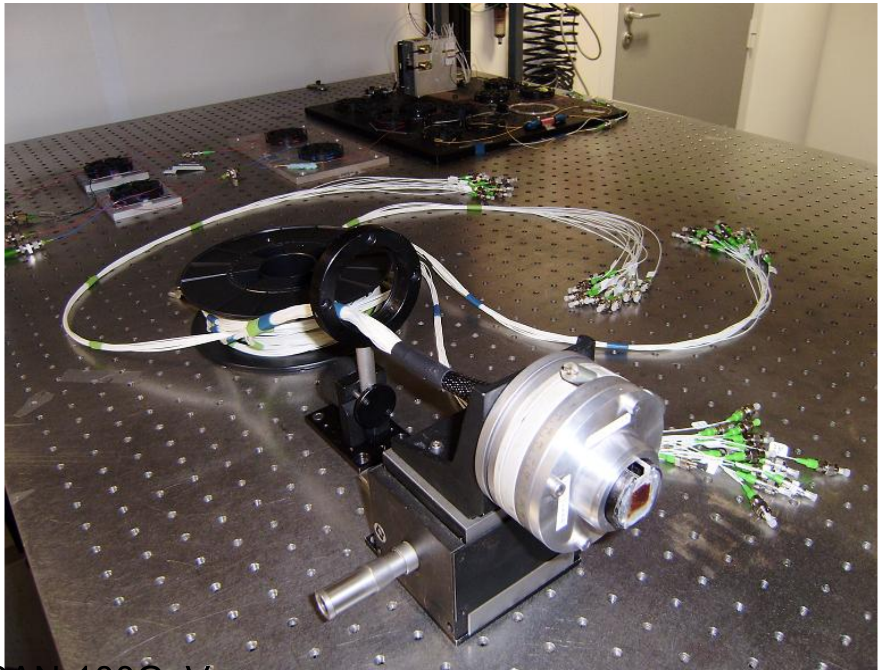
Insertion des fibres

- Toron de 64 fibres réalisé

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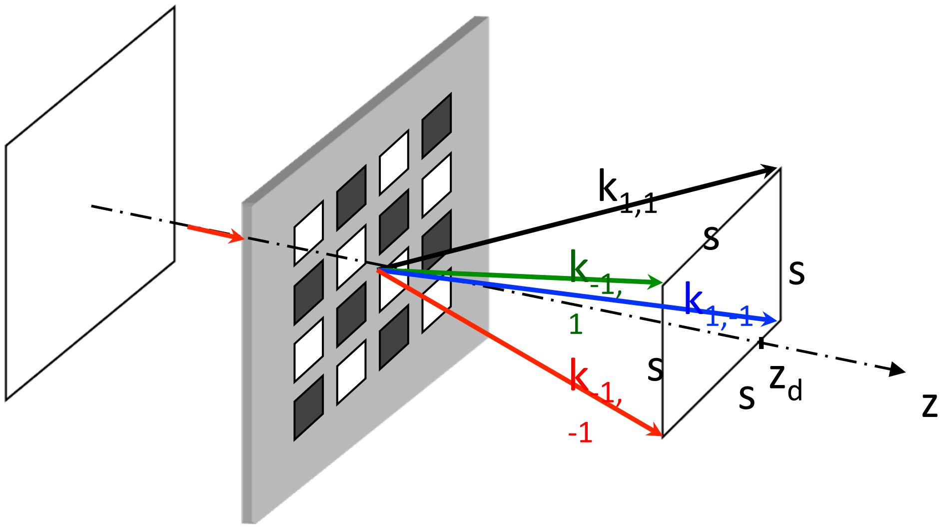
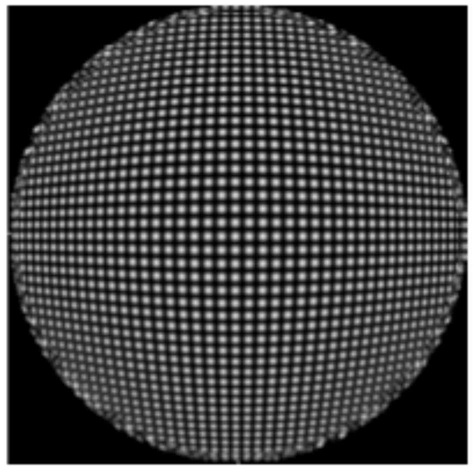
Wave-front Measurement

Généralités sur l’ IDQL

- IDQL: Interféromètre à Décalage Quadri-Latéral
  - Technique d’analyse de front d’onde auto-référencée
  - Principe: analyse de l’interférence du front d’onde avec lui même après duplication et décalage latéral



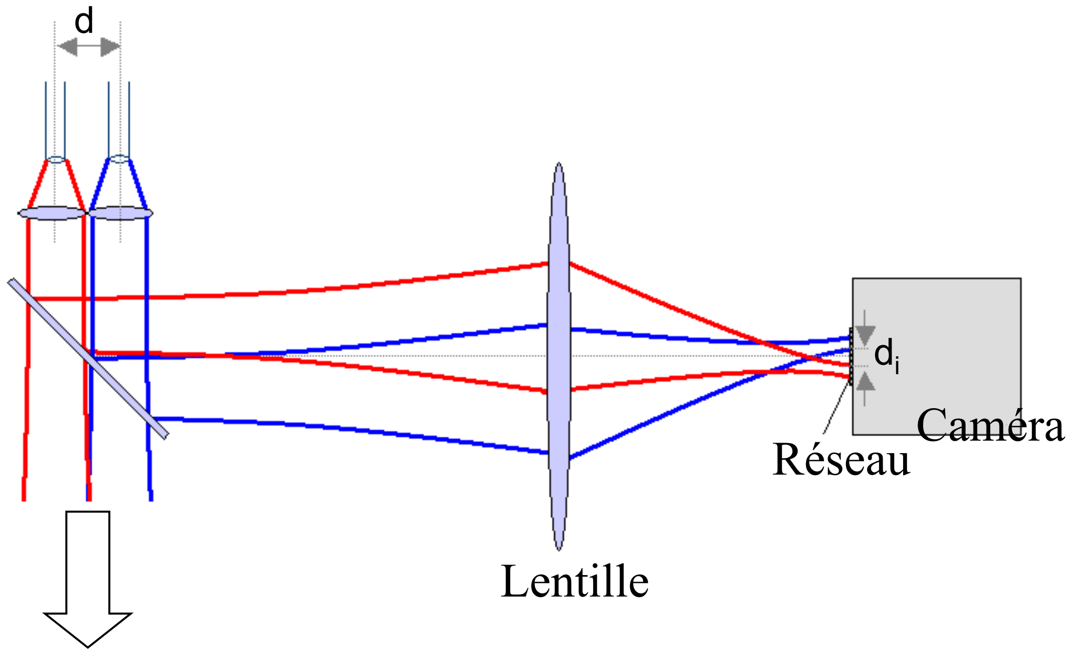


Aberration sphérique

- Utilisations usuelles: Métrologie optique, caractérisation laser, optique adaptative sur des surfaces continues
- Fonctionne également sur des surfaces segmentées (marches de phase)

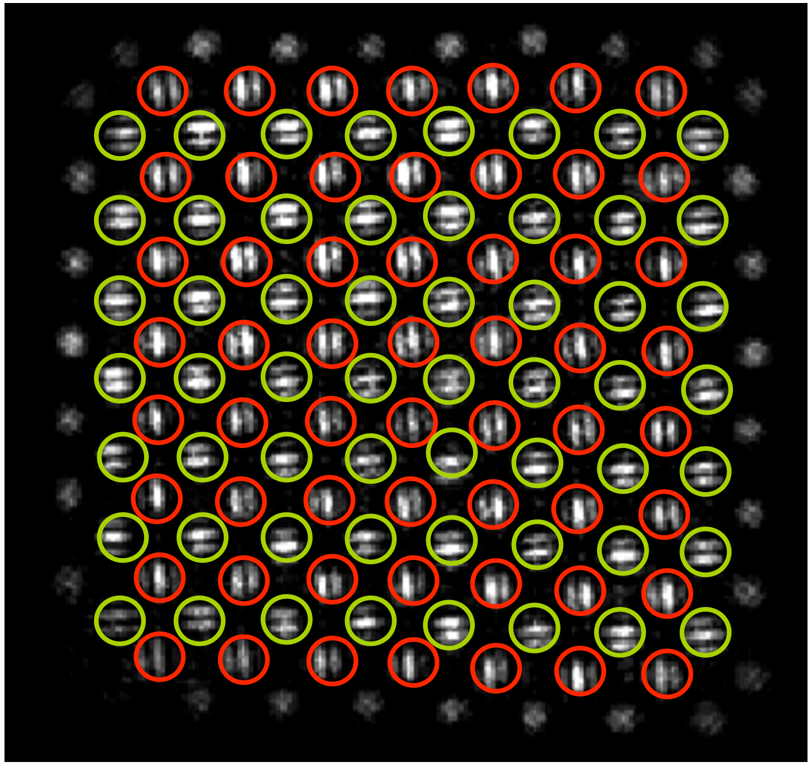
Expérimentalement

- Avec notre analyseur expérimental: ajout d'une lentille d'imagerie
  - Nécessité d'adapter la taille de la matrice de faisceaux (grandissement g)
  - Nécessité d'éliminer l'effet de la divergence des faisceaux gaussiens au niveau du détecteur (conservation de la lacunarité)



Condition: $s = gd\frac{\sqrt{2}}{2}$

Analyse de l' interférogramme



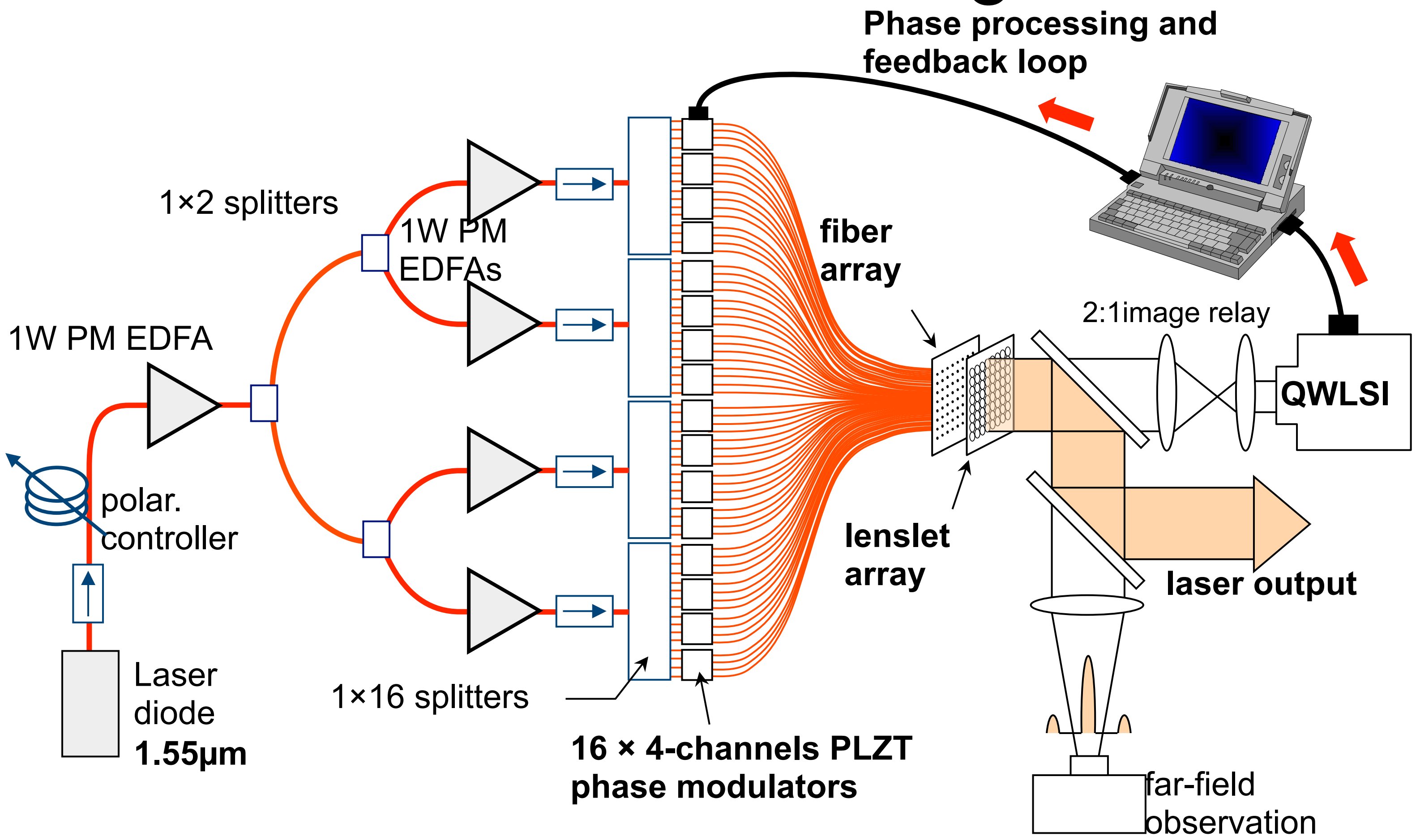
Interférogramme expérimental

Gradient X   Gradient Y

- Jeux de franges de même pas dans les deux sens
  - Déphasage entre deux fibres adjacentes codé dans le déplacement des franges
- Analyse du déplacement relatif des franges
  - Sinusoïdes → Démodulation synchrone spatiale sur toute la figure
  - Récupération des 7x8 8x7 valeurs de différences
  - Reconstruction de la cartographie de phase matriciellement

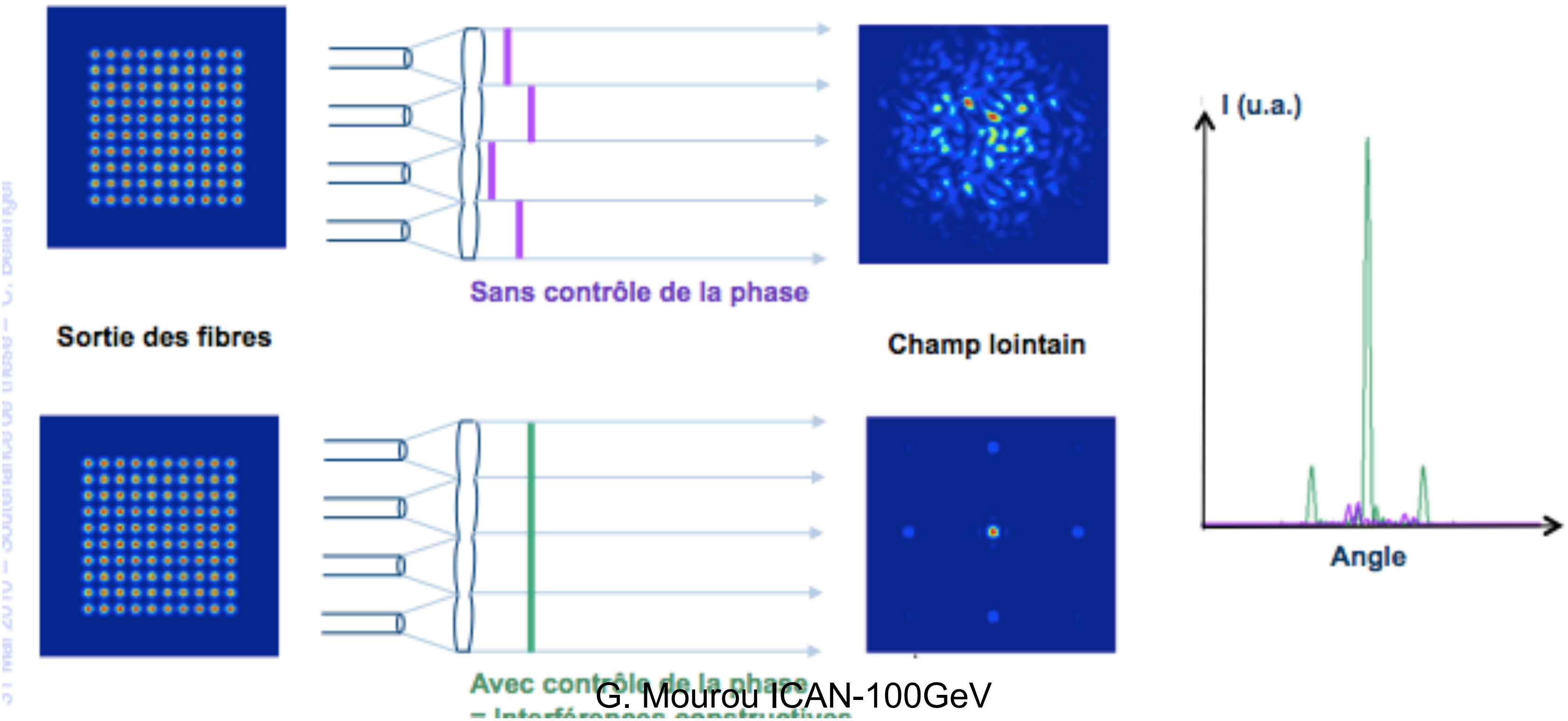
J. Bourderionnet, A. Brignon (Thales), C. Bellanger, J. Primot (ONERA)

Coherent Fiber Combining



Achievement 2011
→ 64 phase-locked fibers

64 CW fibers have been phased (Thales)



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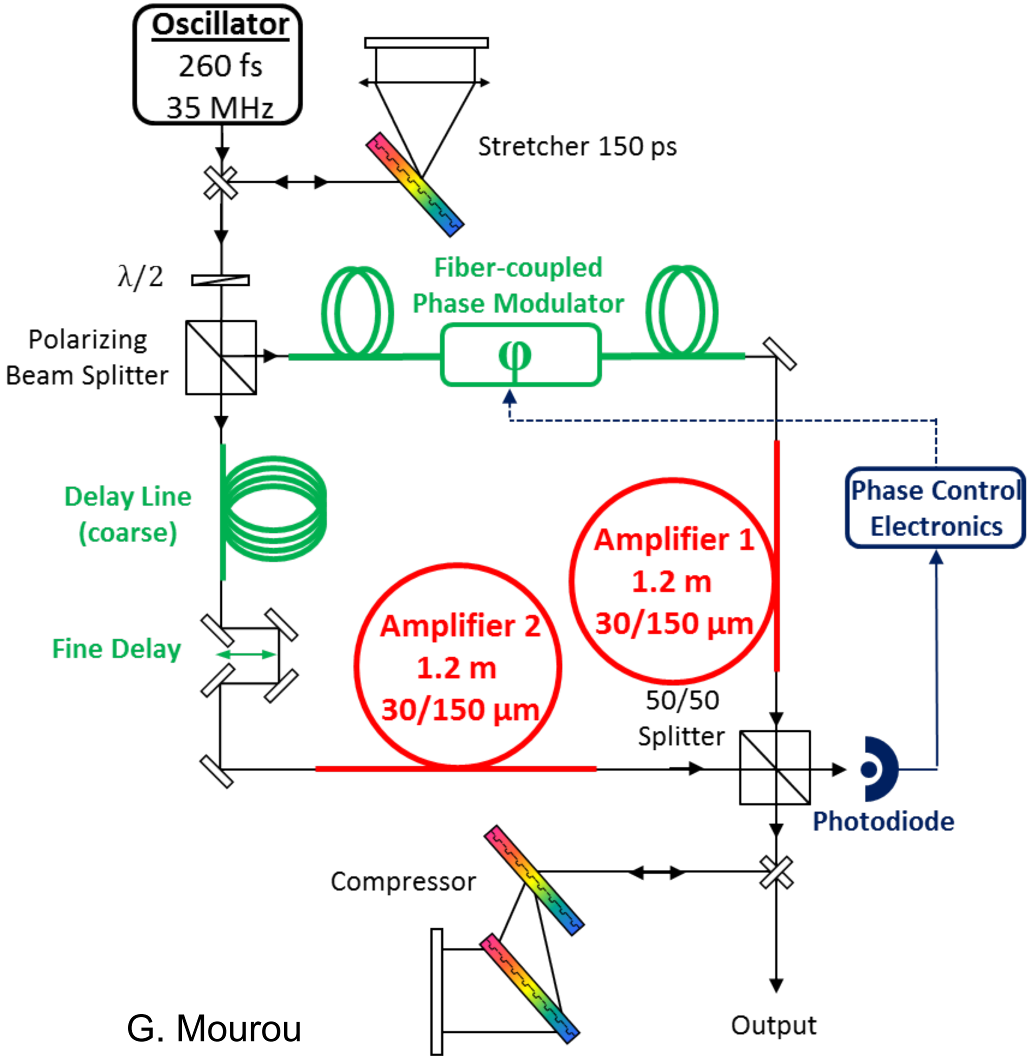
Phase Locking in the Femtosecond Regime

CAN results / phase locking technique
In the femtosecond



Combining efficiency > 90%

L. Daniault, M. Hanna, L. Lombard, D. Goular, P. Bourdon, F. Druon, P. Georges
“Coherent combining of two femtosecond fiber chirped pulse amplifiers“
Oral : Advanced Solid State Photonics, ASSP 2011, Istanbul, Turkey (February 13-16 2011)

Accepted: Optics Letters, L. Daniault et al,
« Coherent beam combining of two femtosecond fiber chirped pulse amplifiers »

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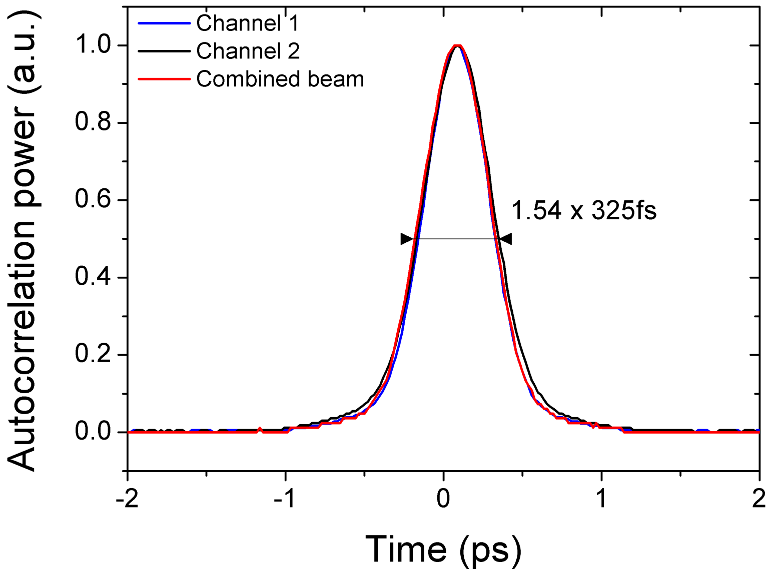
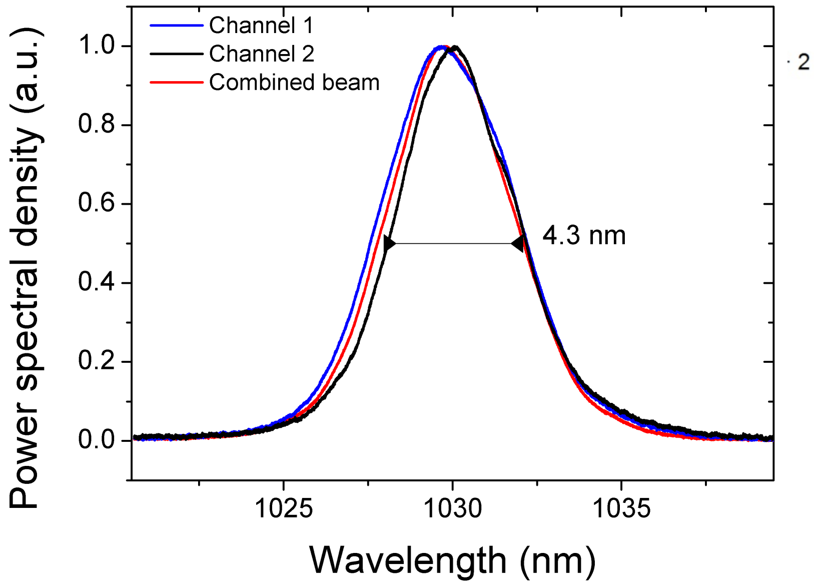
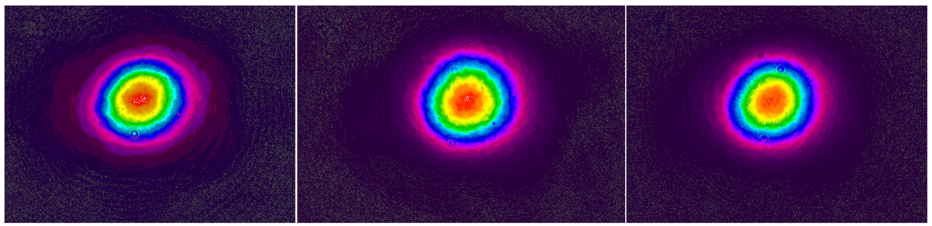
CAN recent results / phase locking technique *(2)*



Autocorrelations
325 fs pulsewidth



Spectra
4.3 nm FWHM



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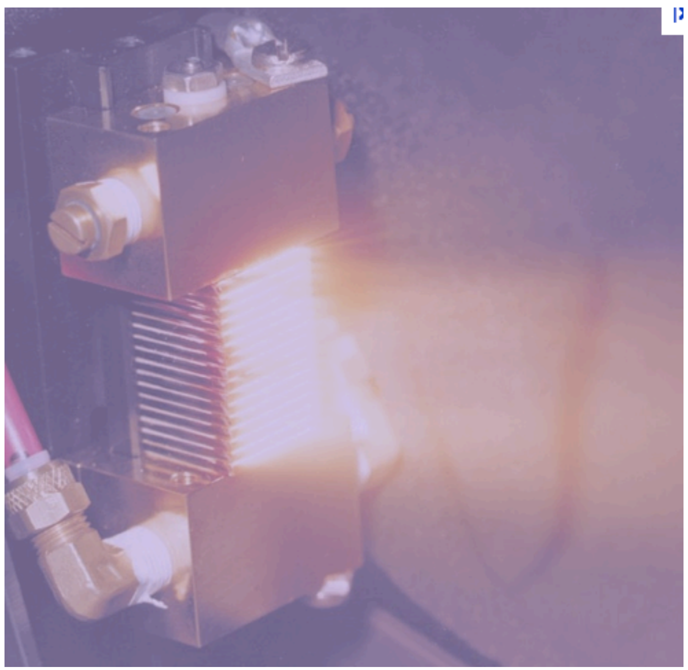
INSTITUT d'OPTIQUE GRADUATE SCHOOL

Diode Cost

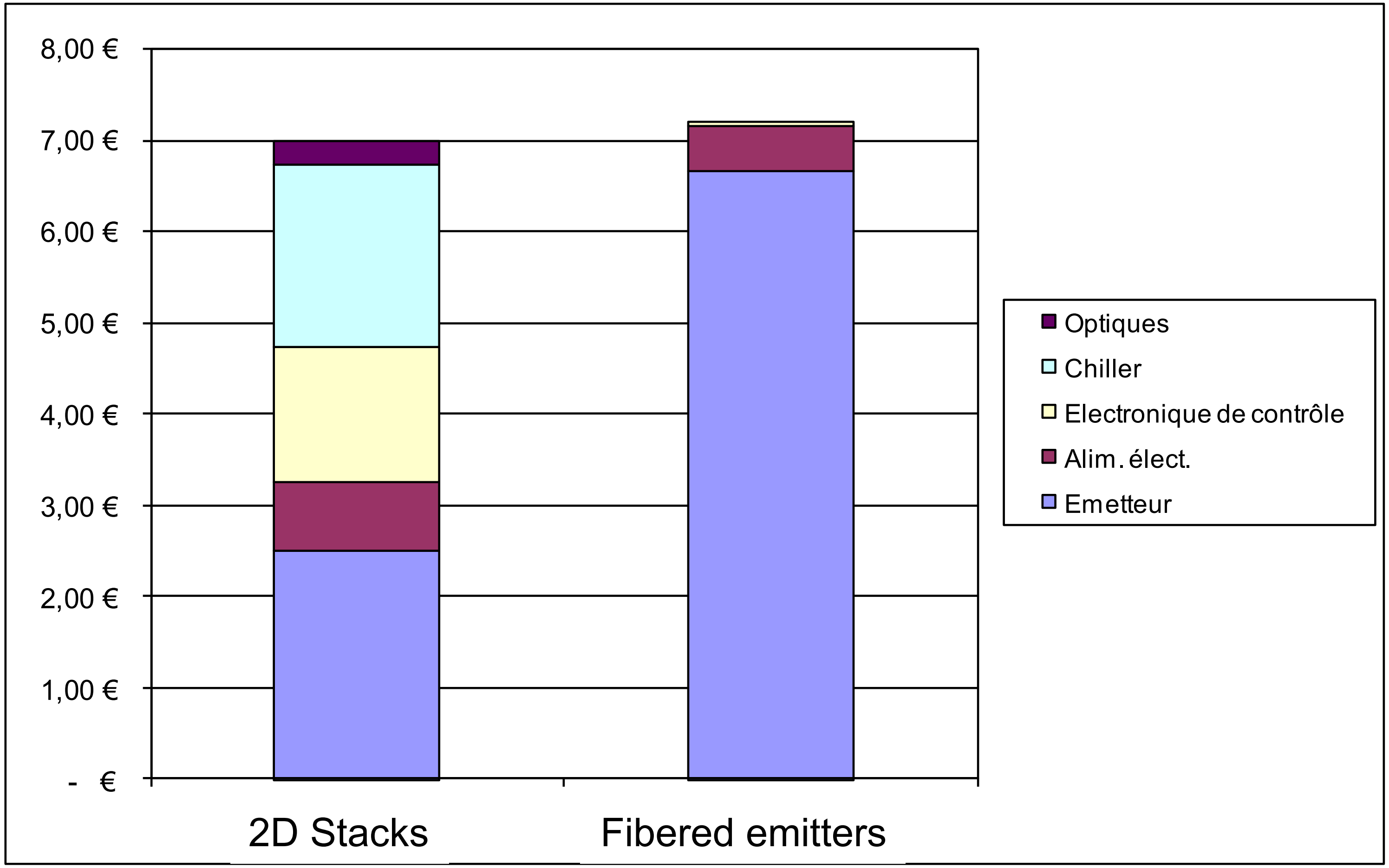


Stacks Laser Diode
20000 hours

Pigtailed Diode
>50000 hours

Fiber pigtailed single emitters VS stacks

Cost in € / Watt



3.5 B€ in laser diodes

The International Coherent Amplification Initiative

CERN

Different communities joining their efforts towards the collaborative evaluation of the fiber CAN concept as one of the possible solutions for the next laser-based driver generation:

- Laser & fibre communities
- High energy physics community

→ Final goal : definition, conception, design and realisation of such a laser

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ICAN Beneficiaries and Experts

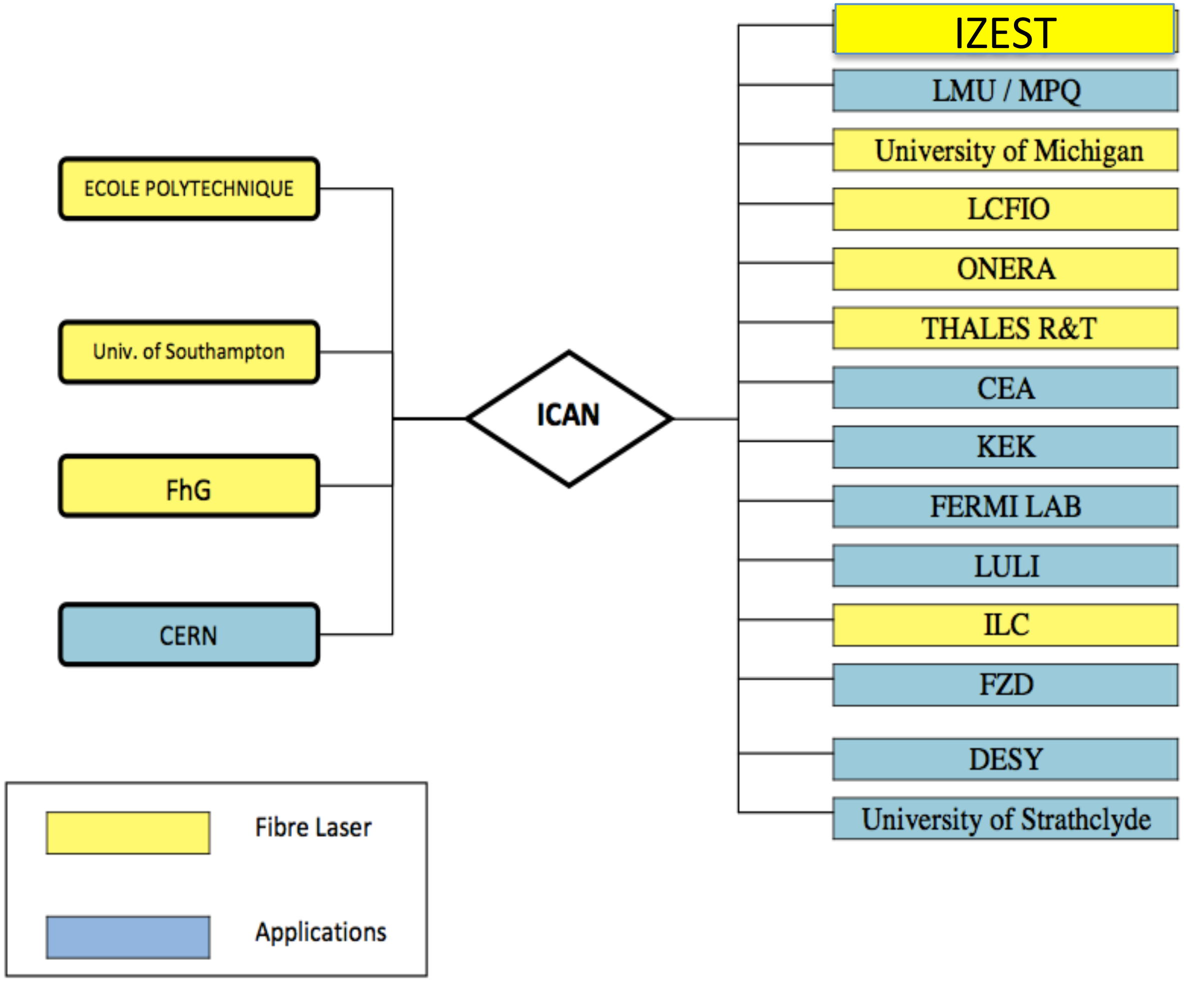
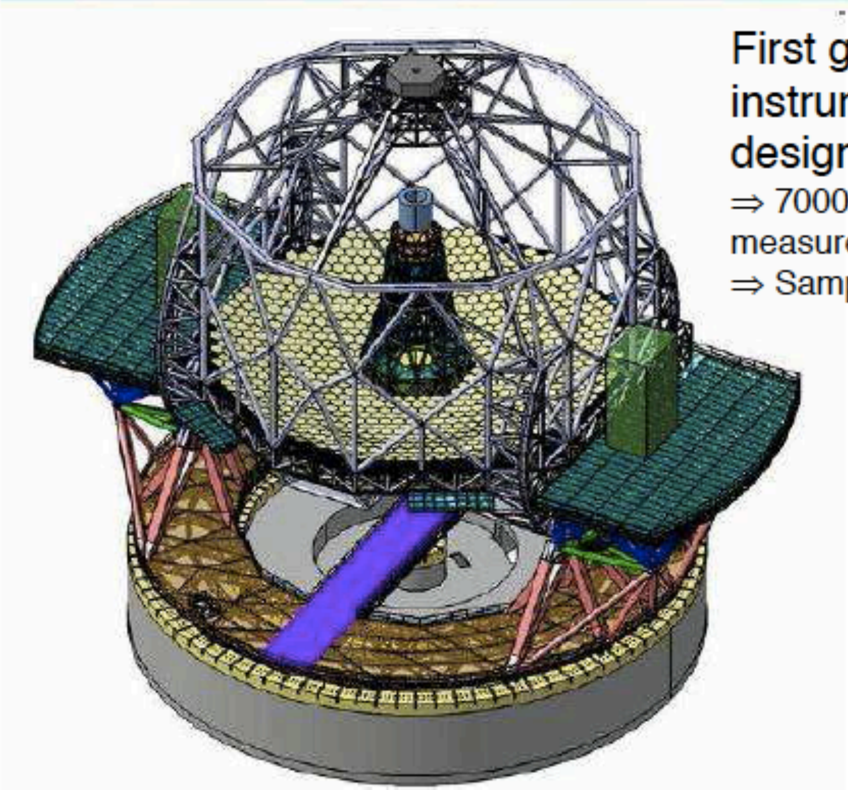


Figure 3 – Schematic description of the experts to the ICAN Project. The beneficiaries are presented on the left and the other experts on the right. The layout is given at the left bottom.

Overall strategy and general description

Workshops	Related WP	Topics	Date of event
WS1	WP21	Components	Q1
WS2	WP21 / WP22	Phasing & Wavefront measurement	Q1
WS3	WP30	Driver	Q2
WS8	WP22	System for peak power scaling	Q2
WS4	WP21	Optical Fibre	Q3
WS5	WP21	Pump	Q3
WS6	WP30	Fusion / Nuclear transmutation	Q4
WS7	WP22	System for energy scaling	Q4
WS9	WP21	Components	Q5
WS10	WP21 / WP22	Phasing & Wavefront measurement	Q5

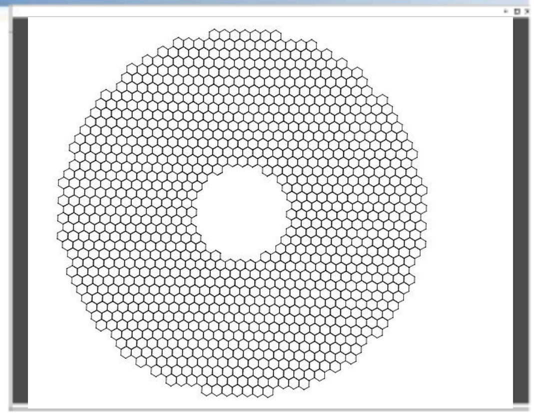
Preliminary design of AO systems for E-ELT (42m)

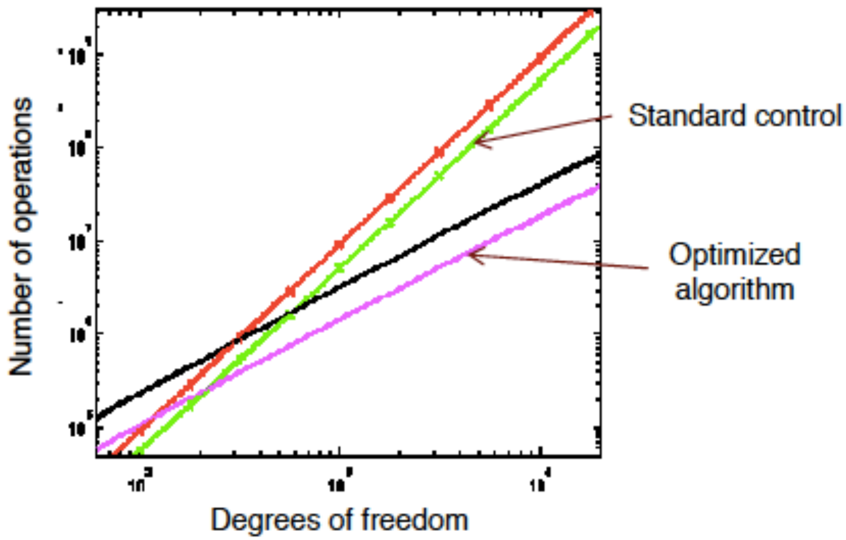


First generation instruments: AO system design led by Onera

⇒ 7000 actuators / WFS measurements

⇒ Sampling frequency = 500 Hz





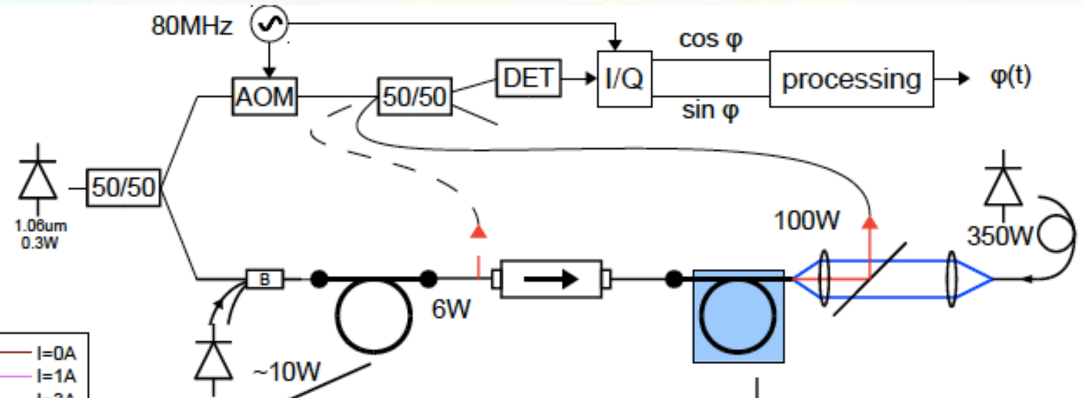
Next generation: XAO system

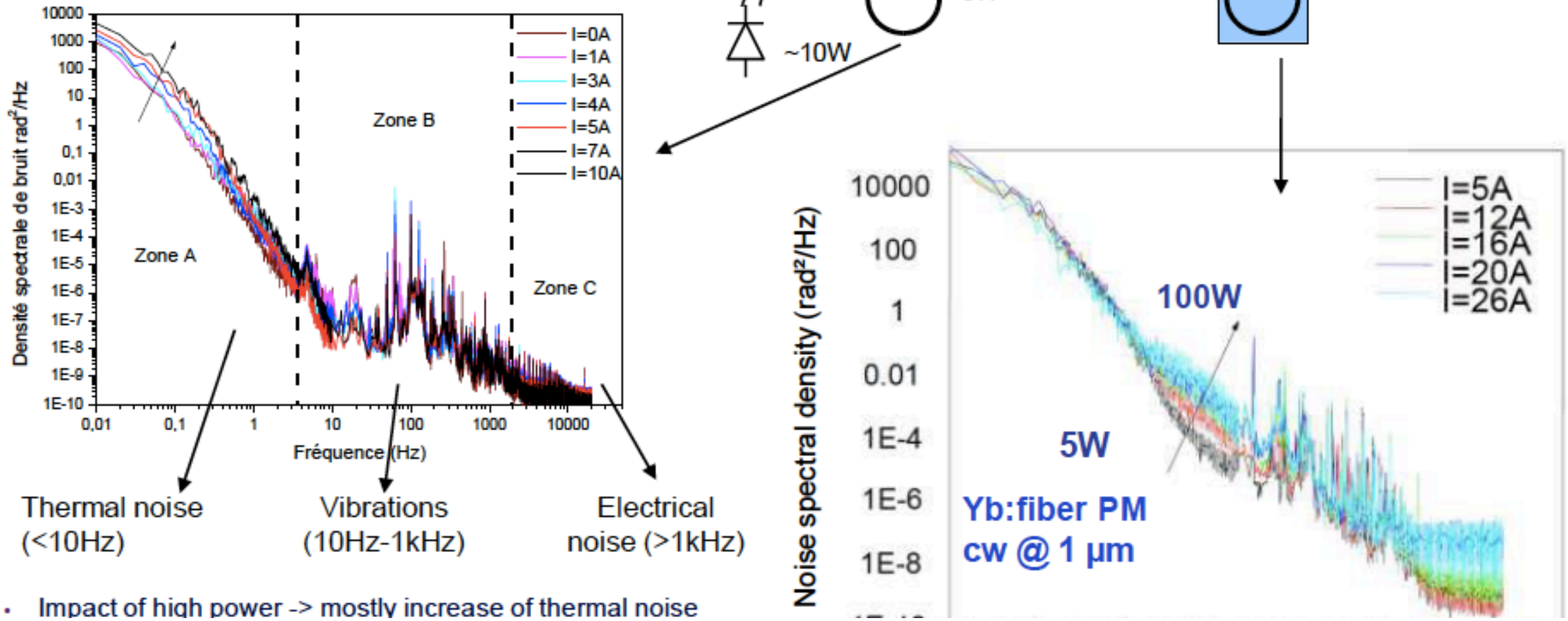
⇒ 7000 + 40000 actuators / WFS measurements

⇒ sampling frequency > 2000 Hz

ELT-ICAN

What are the main sources of phase noise?





- Impact of high power -> mostly increase of thermal noise

ICAN KOM

ELT-ICAN

- ICAN wavefront sensing issues have to be addressed
  - Test Quadri-Wave Lateral Shearing Interferometer with large number of fibers (accuracy …),
  - Test Phase Diversity with large number of fibers and spectral bandwidth representative of femto (accuracy …),
  - Estimate the computational burden related to both wavefront sensors (propose improvement if necessary),
  - Study and compare possible implementations (preliminary system study).

  - ***Required inputs***
    - ***Wavefront sensing accuracy : λ/50 rms ?***
    - ***Cophasing and beam combiner possible geometries (strawman architecture ☺) ?***

- ICAN control issues are very similar to E-ELTs.
  - Follow development of real time computing solutions,
  - Follow calibration issues.

  - ***Required input***
    - ***Correction frame rate or temporal spectrum of phase perturbations ?***
    - ***Spatial correlations between fiber perturbations?***

ection - Conference

Demonstration of a
PW/>10kW/ 10J/kHz/20% efficient

- ***Preliminary conclusion. Design a demonstrator highly relevant to science, engineering that will put europe in leadership position, benefit the industry. It will include 10^4 fibers:***

  >10J, >1kHz, >20% efficient(>10kW capable to produce 10GeV electrons, GeV protons).

- ***Such an infrastructure could validate:***

  1. TeV laser collider concept

  2. Free Electron Laser in the High X-ray regime comparable to LCLS-SLAC but at >1kHz and much more compact.

  3. X-ray, Gamma ray

  4. Proton therapy

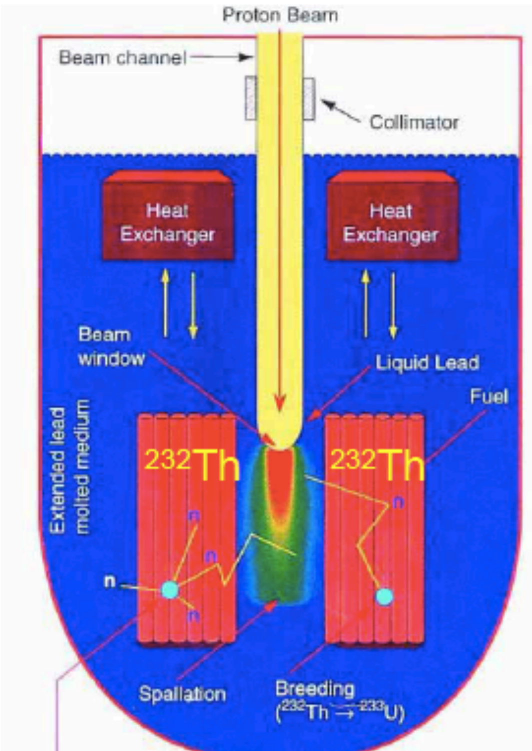
  5. Laser Fusion (No need for cophasing)

  6. B-Factory and such.

  6. And the « Summum Bonum »; Accelerator Driven Reactor(ADR)

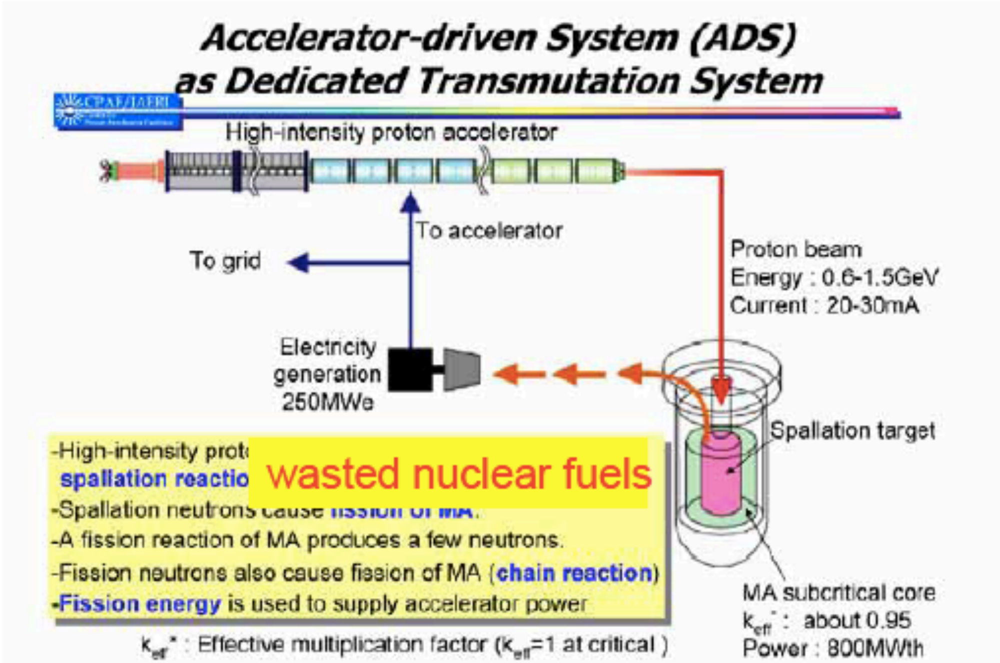
Accelerator Driven (Subcritical) Reactor and Nuclear Waste Transmutation

Subcritical reactor alone



Fuel: Thorium

Electric power generation & nuclear transmutation

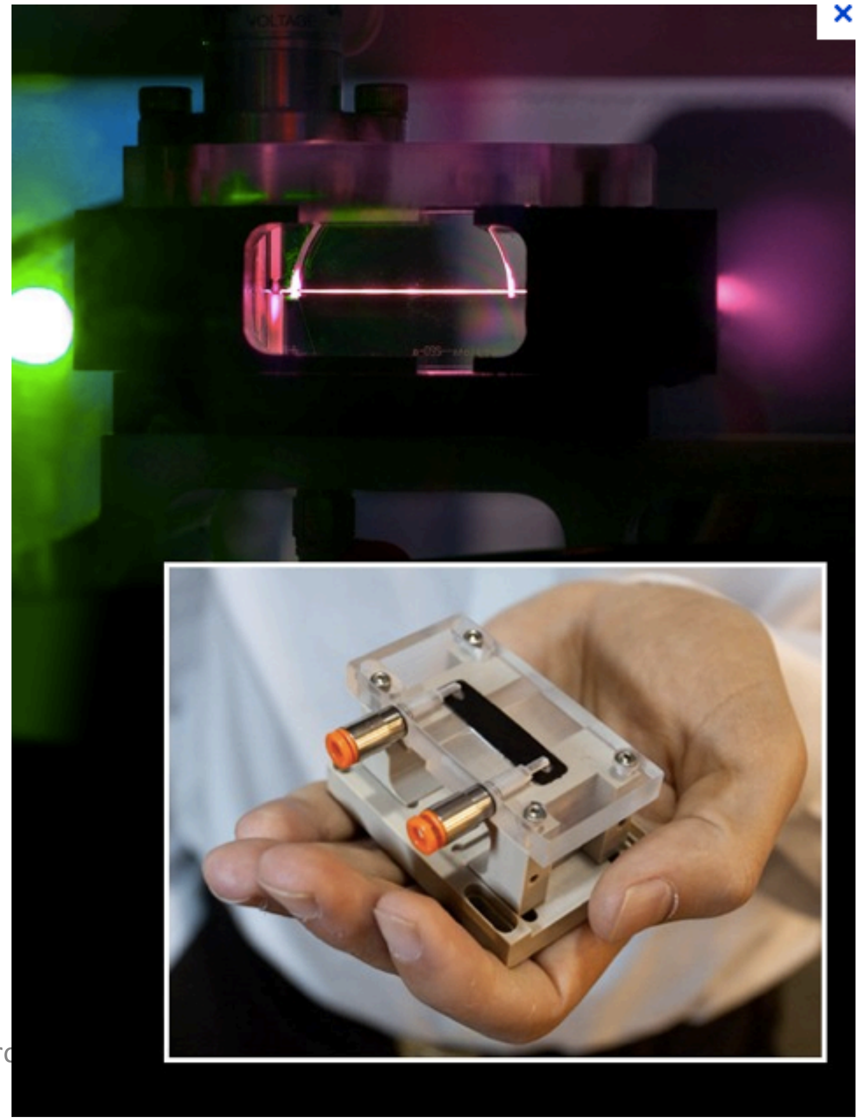


MA: minor actinide


I ZEST
ican
International Coherent
Amplification Network
Acceleration to the TeV and Beyond
Low Luminosity Non-collider Paradigm

GeV in the Palm

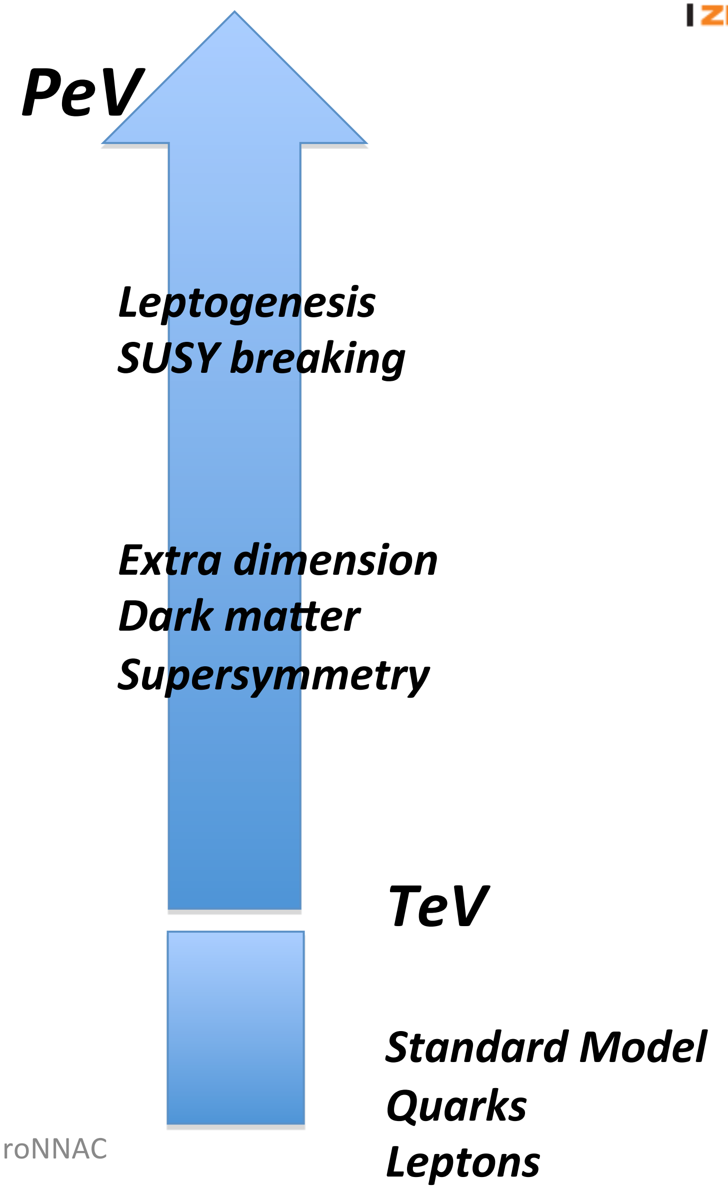
First GeV on few cm
(W. Leemans et al)



IZEST's Mission: Responding to <u>Suzuki's</u> <u>Challenge</u>

Atsuto Suzuki:
KEK Director General,
ICFA Chair

New Paradigm

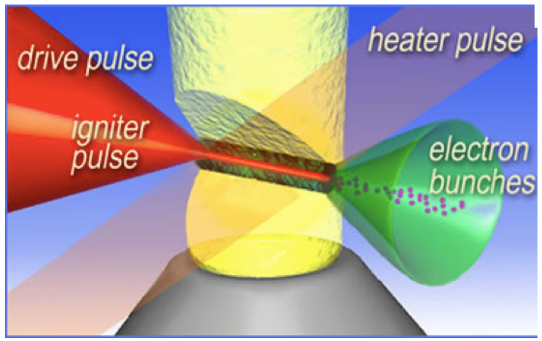


PeV Accelerator

With conventional Technology
The accelerator would Girdle the Earth:
Fermi's vision (1954)

Toshiki Tajima,Masaki Kando and Masahiro Teshima
Progress of Theoretical Physics, Vol. 125, No. 3, March 2011

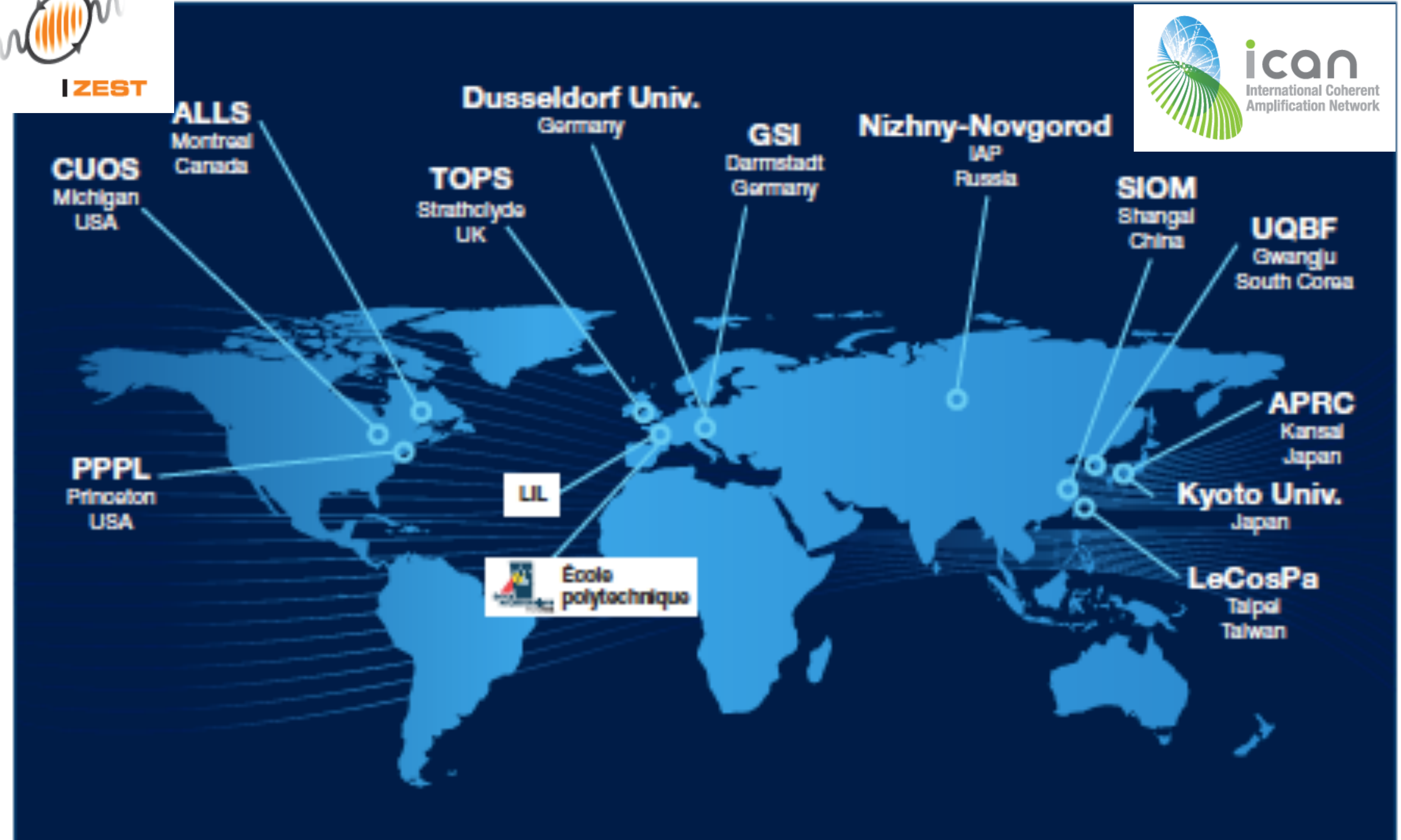
1km laser Plasma accelerator
with LIL or LMJ
(Vision 2011)



Laser-Based High Energy Physics Non-collider Paradigm

- *Physics beyond TeV with the Non-Collider Paradigm*
- *TeV Astrophysics, cosmic ray Knee energy mass scale, Dark matter particle Family(8TeV-3PeV)*
- *Nonlinear Effects in Vacuum*
- *Dark matter, low energy*
- *Lorentz Invariance (gamma rays, neutrino, ...)*
- *as /zs Ultrafast Science*
- *Radiation near the Schwinger field*
- *Precision particle/Radiation Metrology*
- ***Exawatt and Zettawatt Laser Technology***

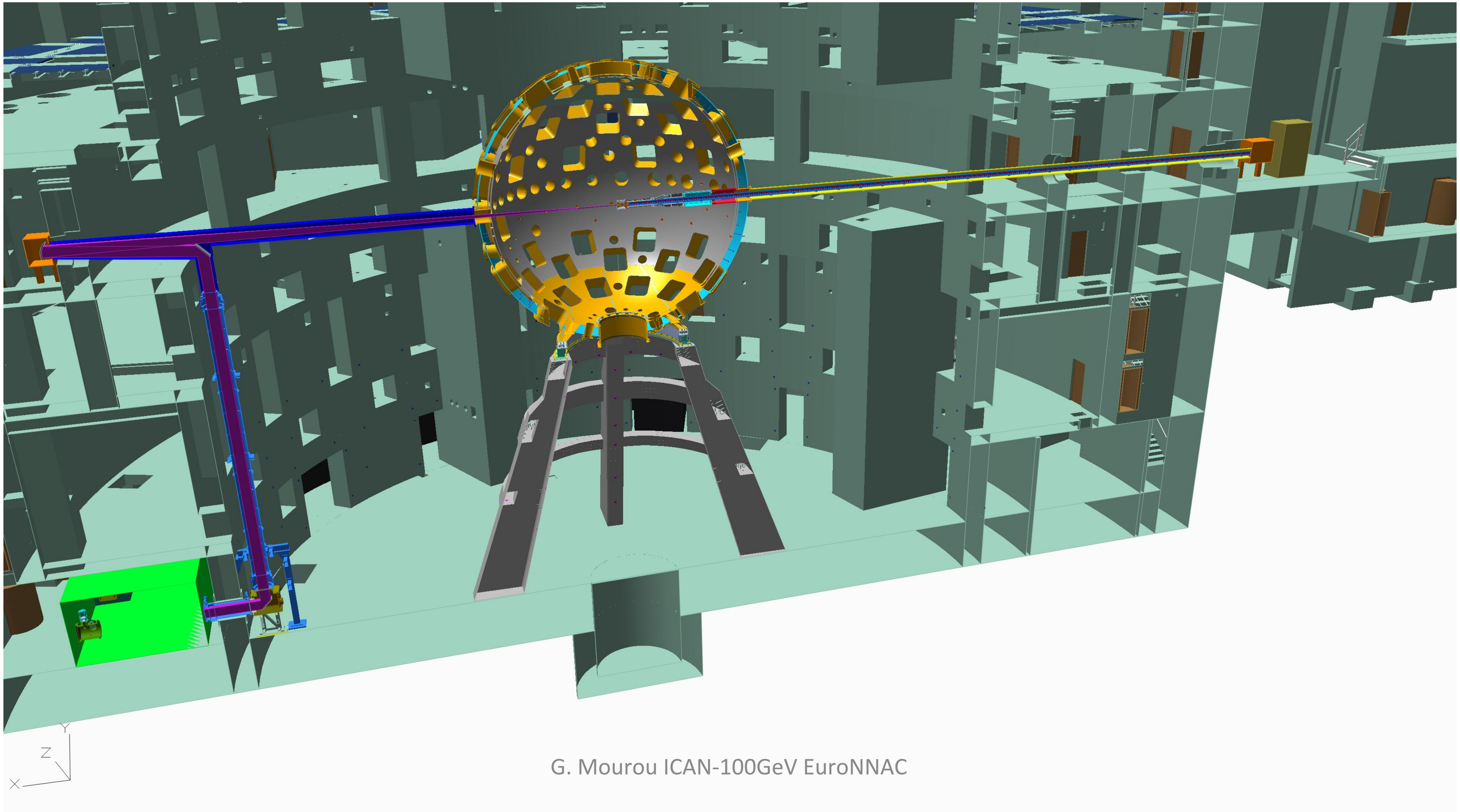
IZEST' 100GeV Ascent



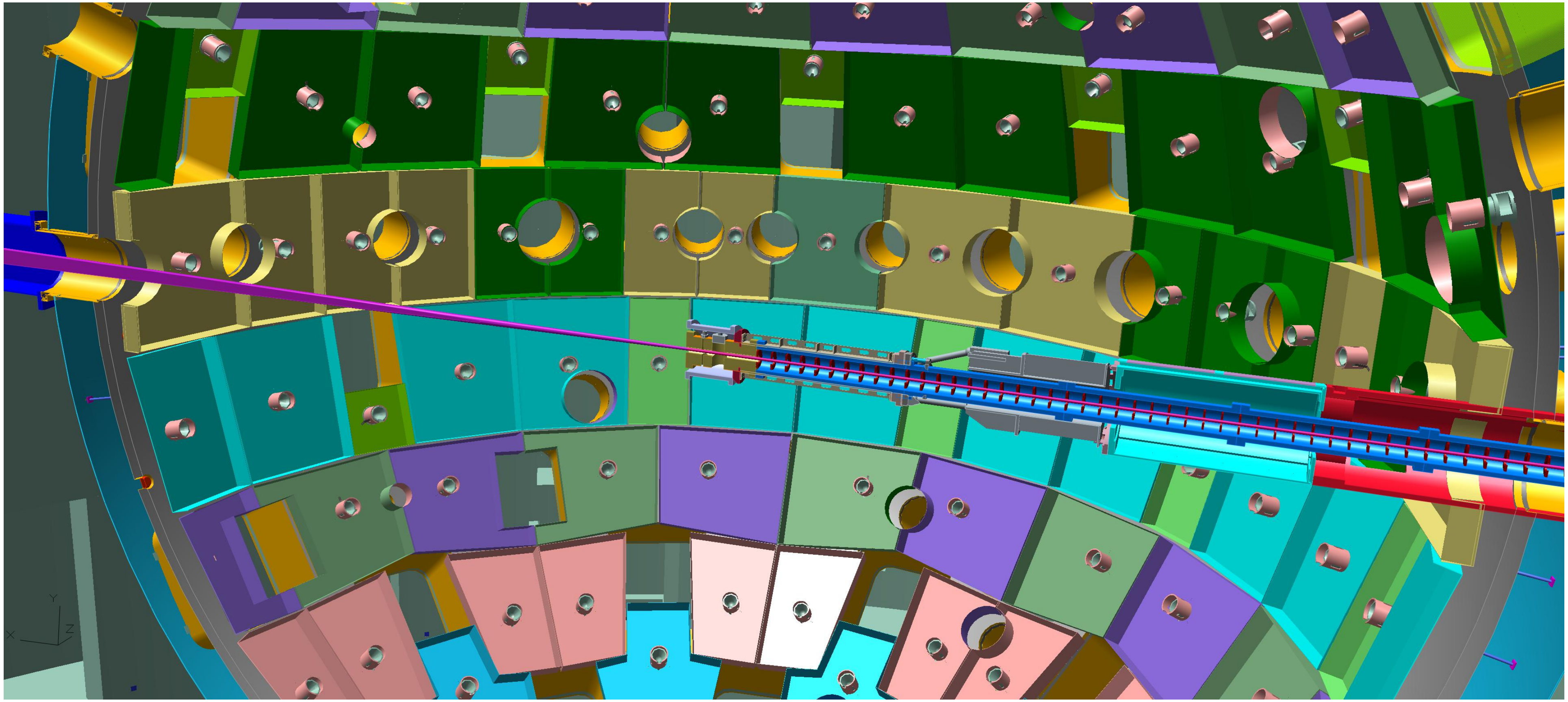
IZEST Associate Laboratories

Ambitious program needs the international community

100GeV Electron Generation
Laser-Plasma Wakefield on PETAL



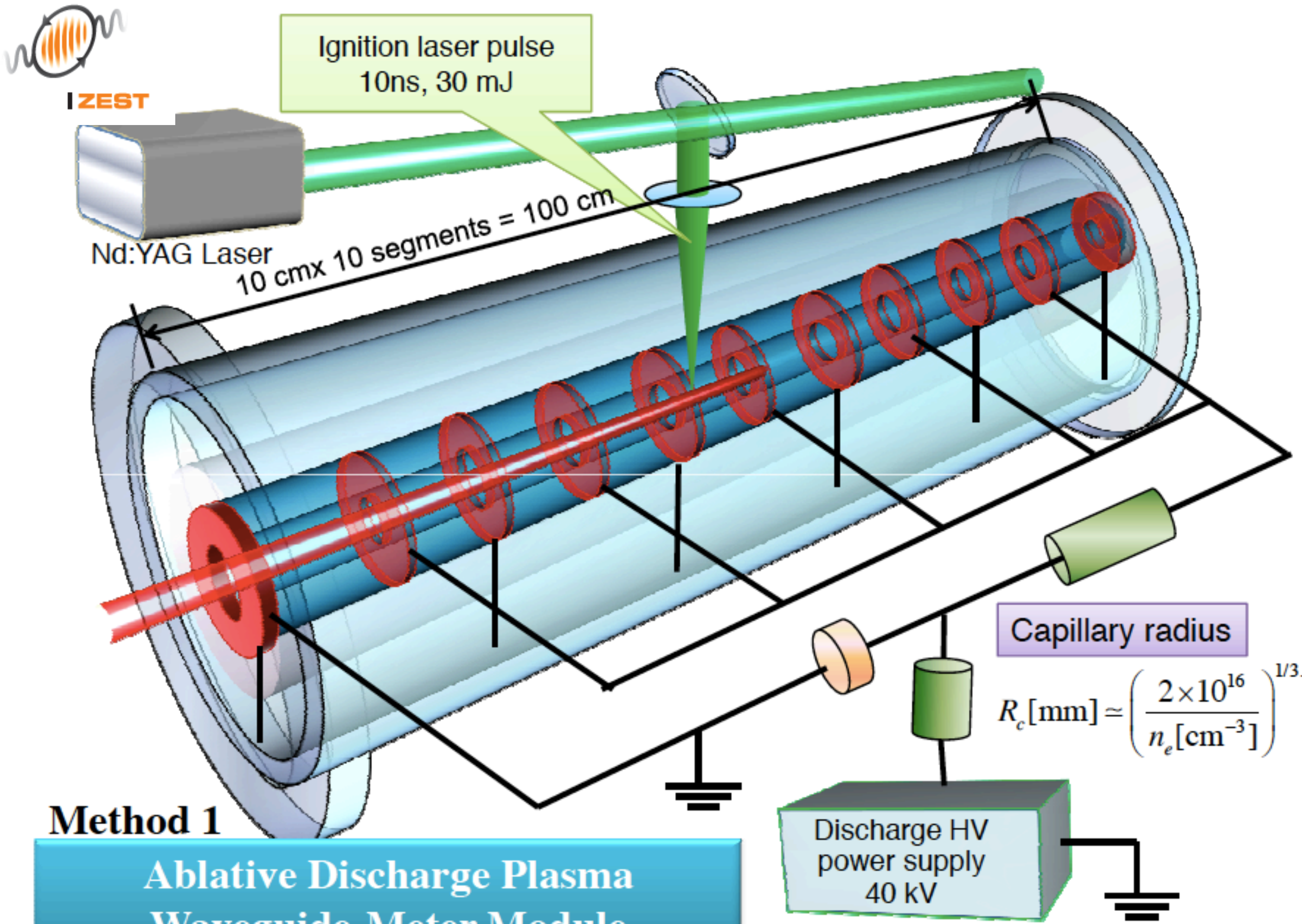
100GeV Electron Generation
Laser-Plasma Wakefield on PETAL



IZEST

n parameters of 100 GeV laser-plasma accelerator experiment at IZEST

		INJECTOR	PHASE I	PHASE II
Energy gain per stage [GeV]	W_{stage}	~1	~5	~ 100
Injection beam energy [GeV]	E_i	Ionization-injection	~ 1	~1
Plasma density [cm-3]	n_p	2×10^{18}	3.5×10^{15}	3.5×10^{15}
Plasma wavelength [µm]	λ_p	23.6	564	564
Accelerating field [GV/m]	E_z	192	3.3	3.3
Focusing constant	K/k_p	0.71	0.35	0.35
Stage length [m]	L_{stage}	0.006	1	30
Number of electrons	N_b	1×10^9	1×10^9	1×10^9
Charge per bunch [pC]	Q_b	160	160	160
Matched beam radius [µm]	σ_{r0}		90	90
Laser wavelength [µm]	λ_L	1.053	1.053	1.053
Normalized vector potential	a_L	3.2	1.5	1.5
Laser pulse duration [fs]	τ_L	500	500	500
Laser spot radius [µm]	r_L	126	273	273
Laser peak power [PW]	P_L	3.1	3.1	3.1
Laser energy per stage [kJ]	U_L	1.5	1.5	1.5
Plasma channel depth	$\Delta n_c/n_p$	0	0.44	0.44

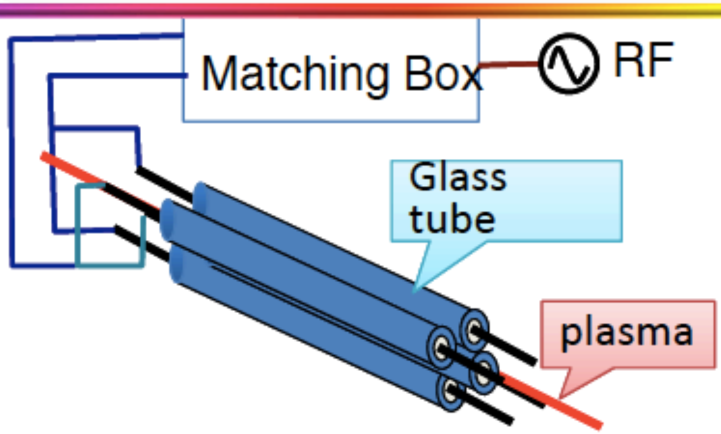


$$R_c[\text{mm}] \simeq \left(\frac{2\times10^{16}}{n_e[\text{cm}^{-3}]} \right)^{1/3.2}$$

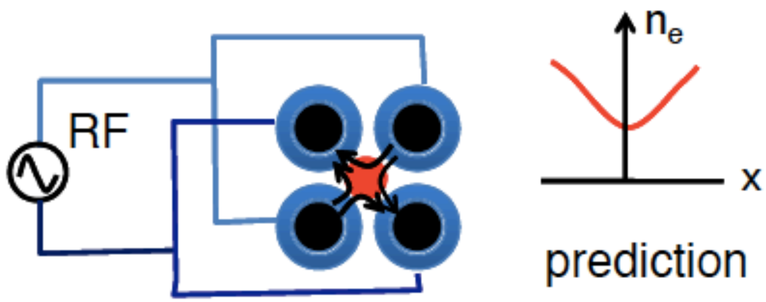
Method 1

Ablative Discharge Plasma Waveguide-Meter Module

New method for a long-range plasma channel generated by RF discharge at Nagoya University

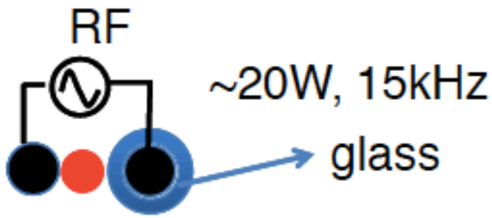


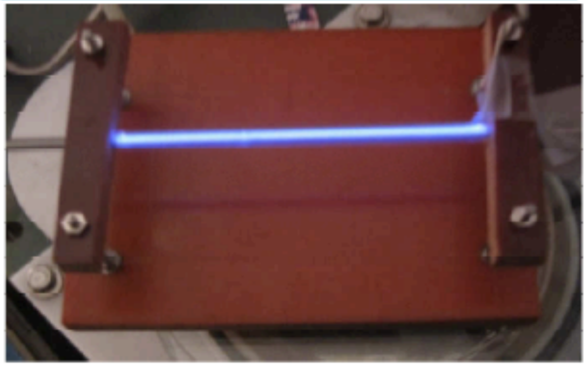
Capacitive (quadrupole field) discharge

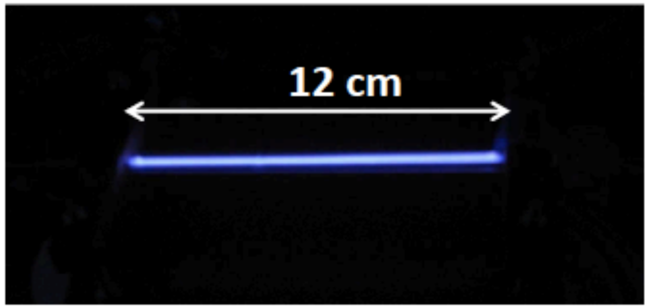


Test line plasma
Diameter: ~0.5mmϕ,
Length: 120 mm long
Gas: N_2 discharge at 1 atm

SIOM laser-machined hollow waveguide is tested in Nagoya Univ.



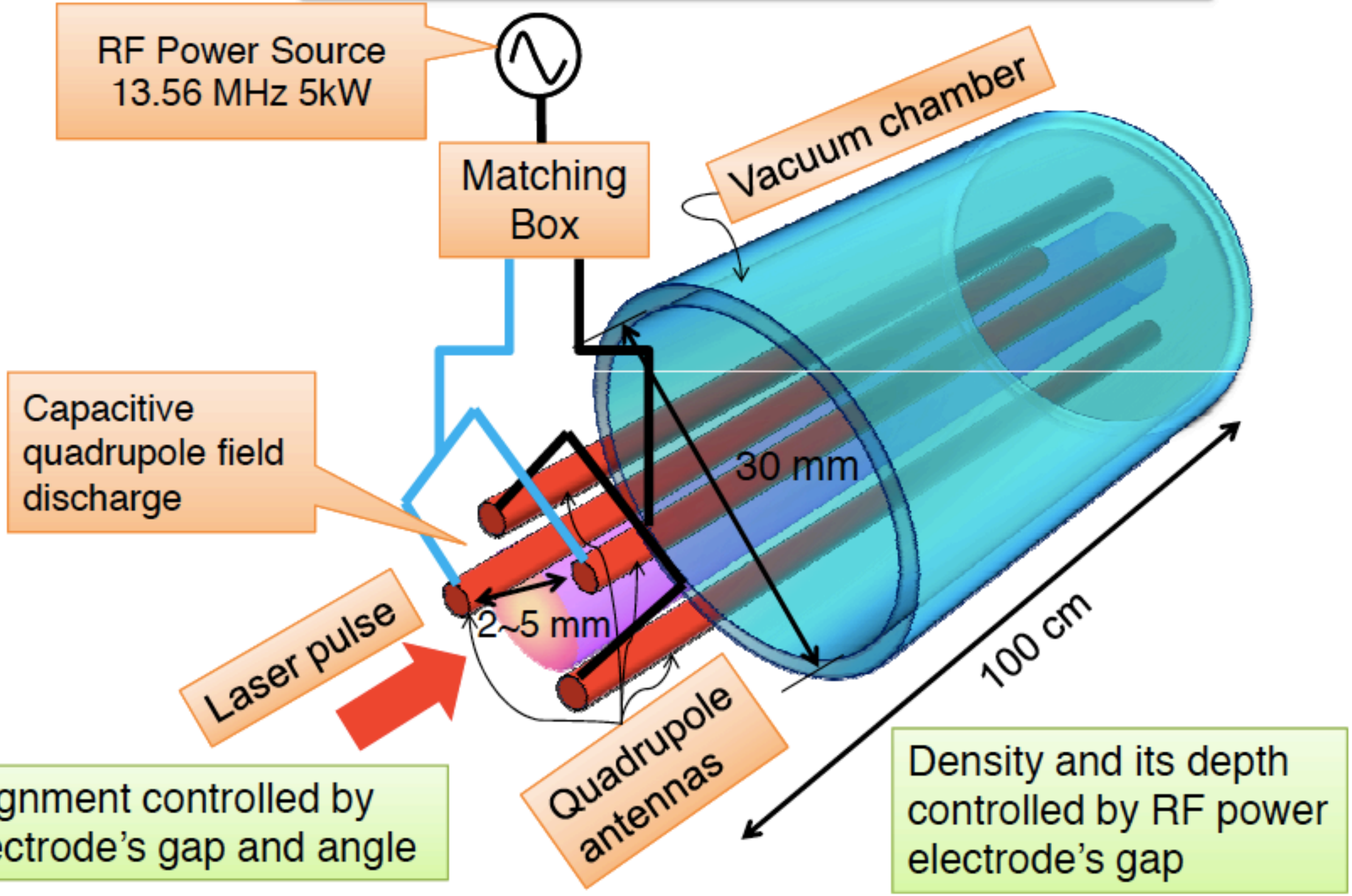




(by courtesy of T. Shoji, Nagoya U.)

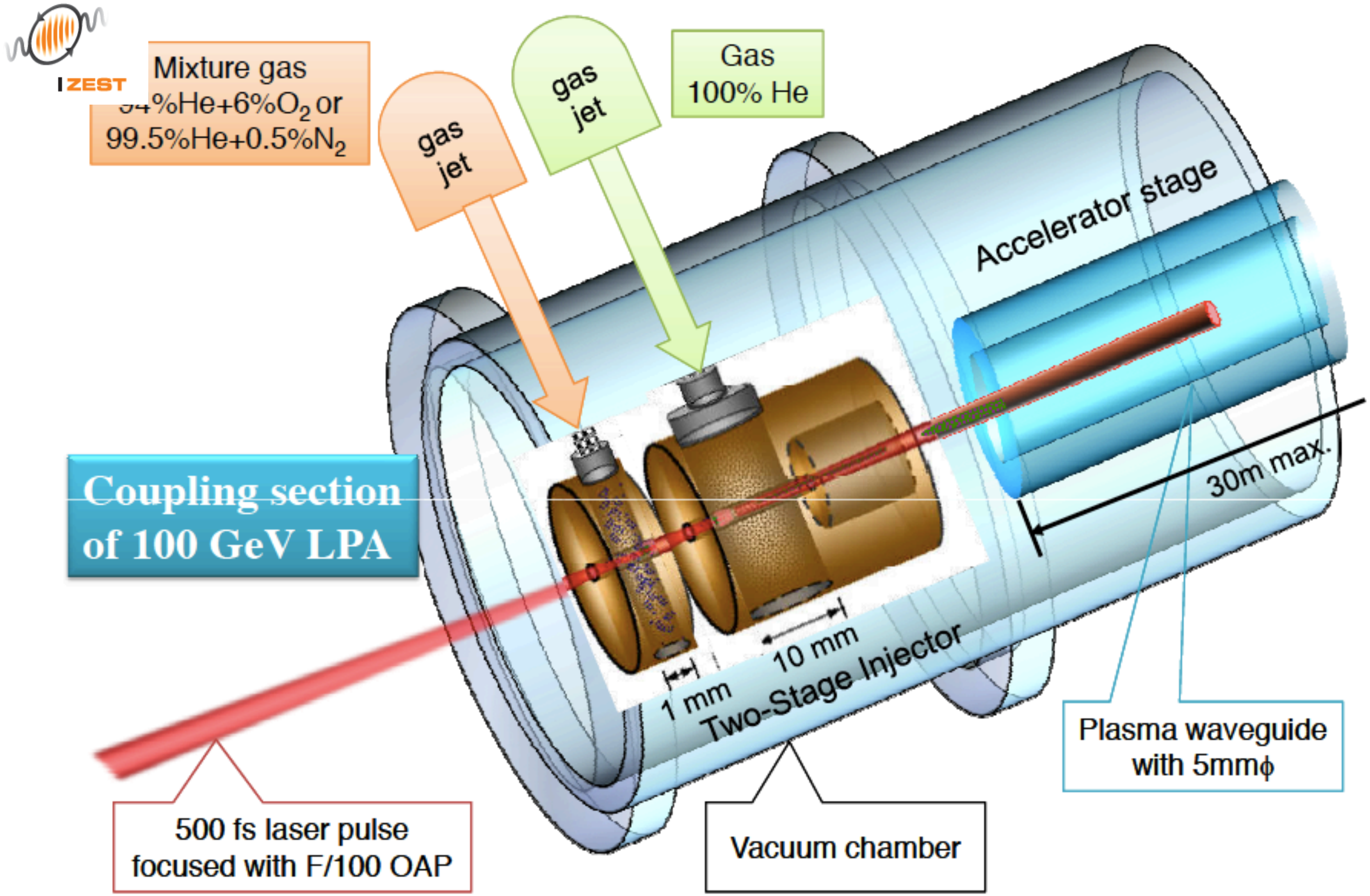
ethod 2

RF Discharge Plasma Waveguide Meter Module

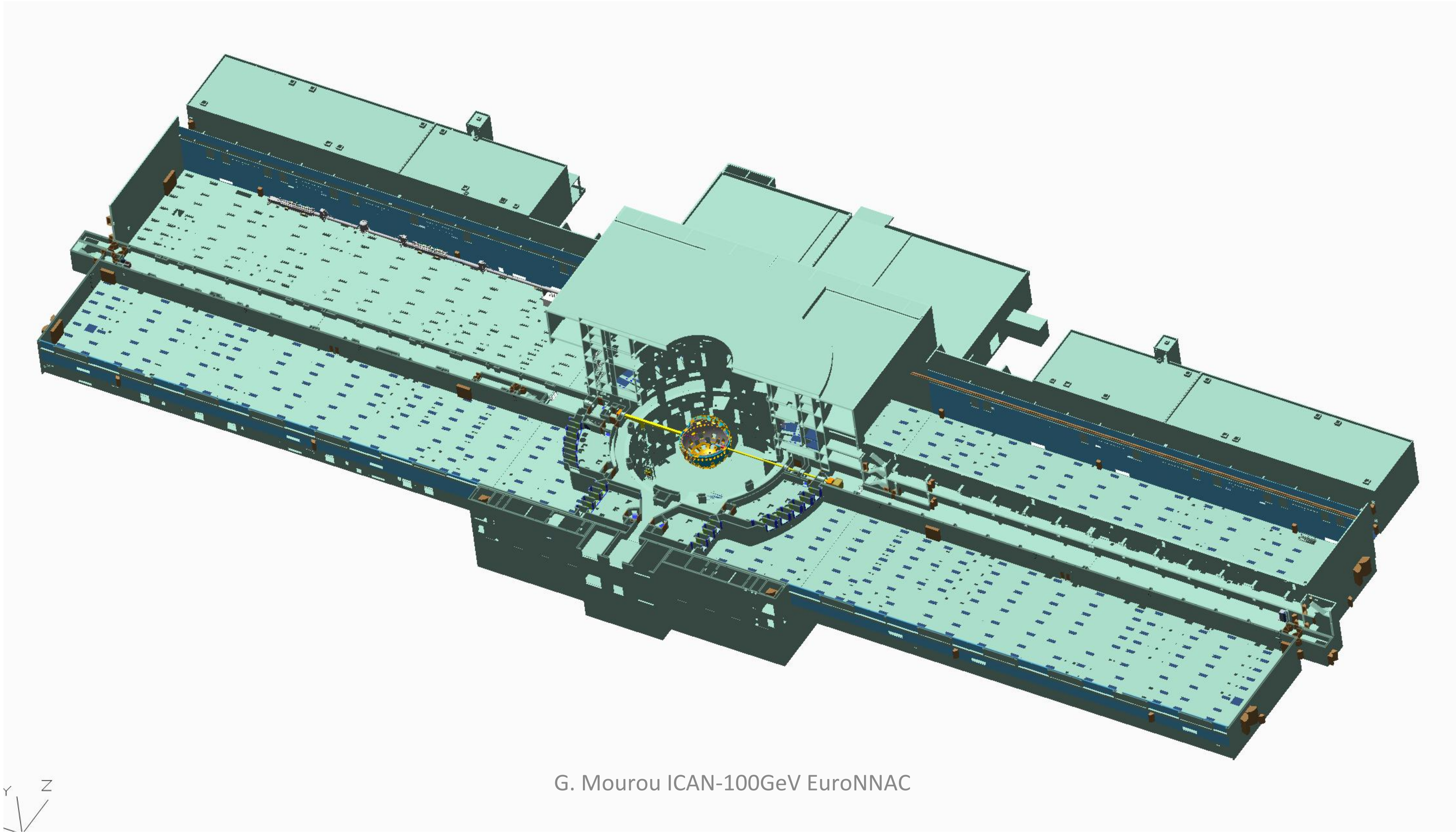


Alignment controlled by electrode's gap and angle

Density and its depth controlled by RF power electrode's gap


Mixture gas
%He+6%O2 or
99.5%He+0.5%N2
gas jet
gas jet
Gas
100% He
Accelerator stage
Coupling section
of 100 GeV LPA
30m max.
10 mm
1 mm
Two-Stage Injector
Plasma waveguide
with 5mmϕ
500 fs laser pulse
focused with F/100 OAP
Vacuum chamber

Towards the TeV Electrons



IZEST Step wise Approach

- *IZEST goals are extremely challenging and need the effort of the whole International community.*
- *Experiments will be tested at different levels in steps*
  - *100TW, Strathclyde, Dusseldorf, ALLS, Saclay*
  - *1PW, GSI*
  - *7PW, PETAL*

To tackle the challenge

Workshop
IZEST' 100GeV Ascent

Bordeaux,
May 31-June 1, 2012

Conclusions

Low luminosity Paradigm: TeV-PeV particles, single shot could be produced by laser acceleration using C^3-compressed laser fusion. Experiments on Petal are planned. New paradigm in particle physics/

High Luminosity Paradigme: Preliminary studies with CAN and ICAN hint to the possibility to build an efficient laser driven TeV collider. High average and High Peak Power, gateway to impressive applications, including, B-factory, laser fusion and ADR(Accelerator-Driven Reactor). .

A ICAN program within 18 months followed by a demonstrator >10kWmodule, will help us to confirm these predictions