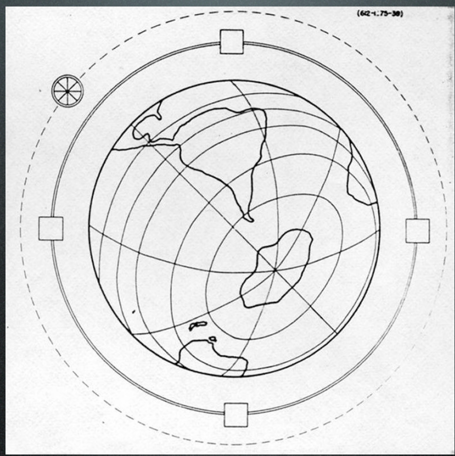
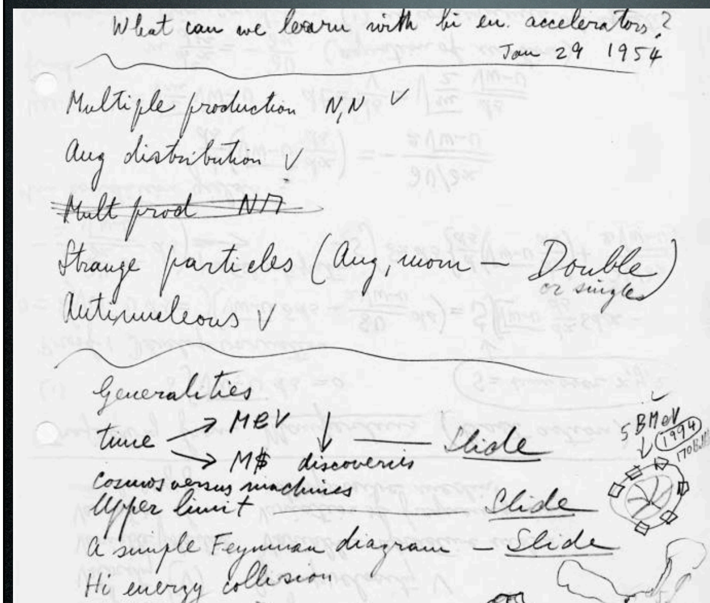
Novel acceleration techniques

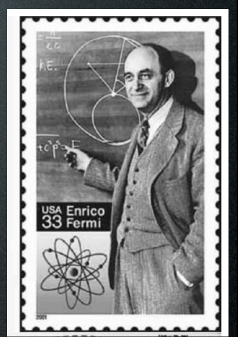
Massimo Ferrario
INFN-LNF

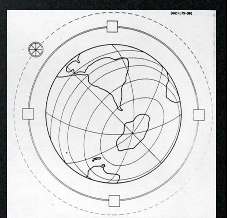


LNF Test Lab – Frascati, June 18, 2014

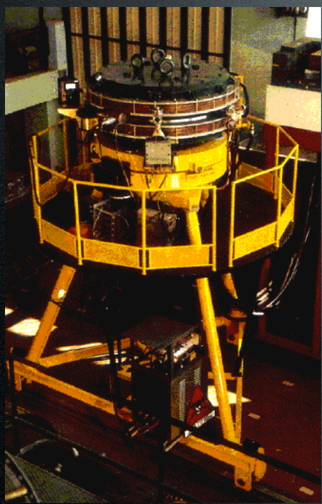
1954 Fermi Globatron: 5000 TeV, 170 B$, fixed target 3 TeV cm

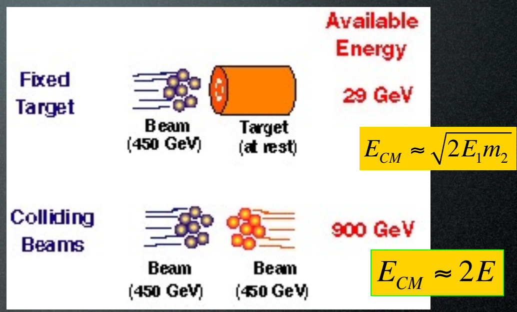


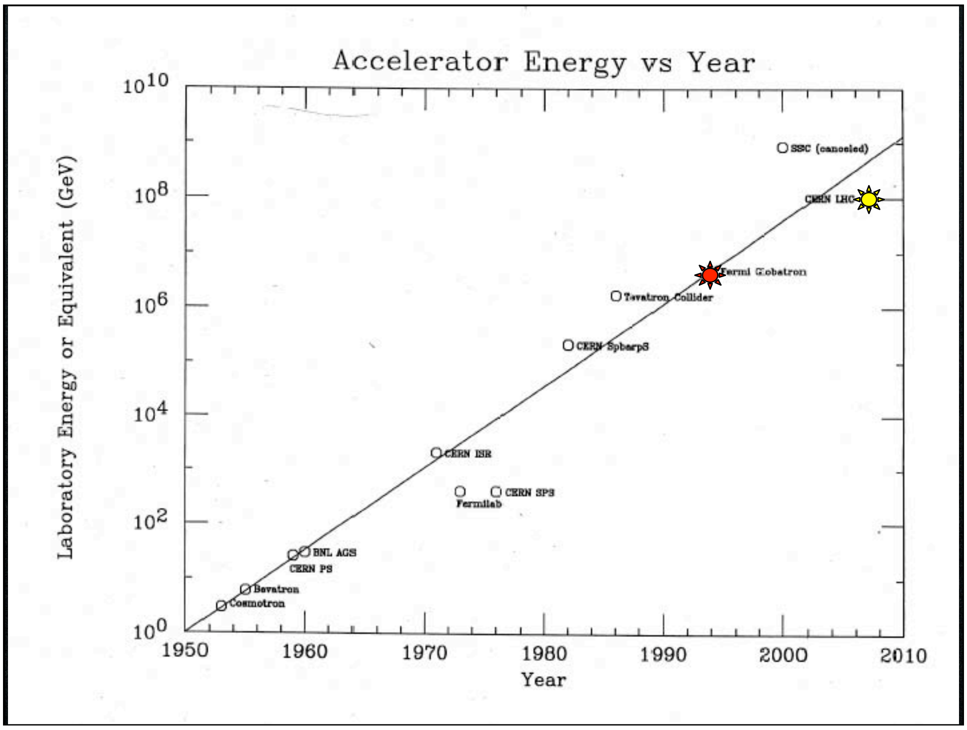




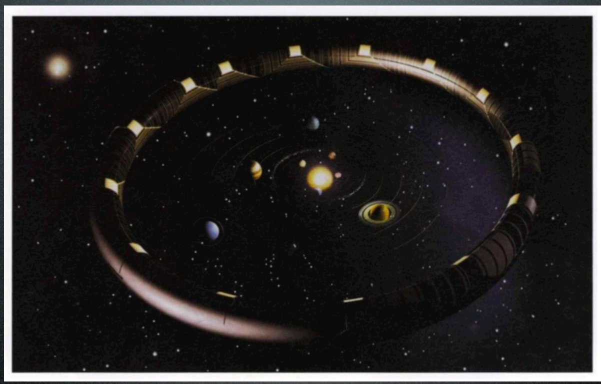
6 years later Touschek revolutionary idea:
ADA (Anello Di Accumulazione), 1961-1964
the first e+e- Collider







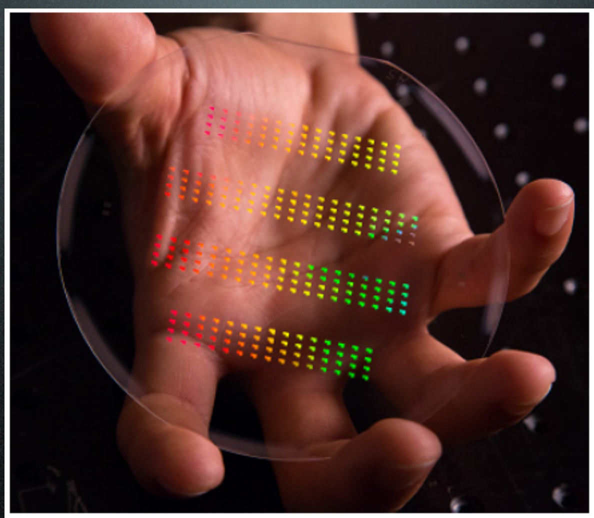
2001 Hawking: the Heliotron



Without further novel technology, we will eventually need an accelerator as large as Hawking expected.

The Universe in a Nutshell, by Stephen William Hawking, Bantam, 2001

2020? Accelerator on a Chip



2 WAYS NTA ROAD MAP

① Miniaturization of the accelerating structures (resonant)

② Wake Field Acceleration (transient) (LWFA,PWFA,DWFA)

- Power sources
- Accelerating structures
- High quality beams

Modern accelerators require high quality beams:

==> High Luminosity & High Brightness

==> High Energy & Low Energy Spread

$$\uparrow \quad L = \frac{N_{e+} N_{e-} f_r}{4\pi \sigma_x \sigma_y}$$

- –N of particles per pulse => 10^9
- –High rep. rate f_r=> bunch trains
- –Small spot size => low emittance

$$\uparrow \quad B_n \approx \frac{2I}{\varepsilon_n^2}$$

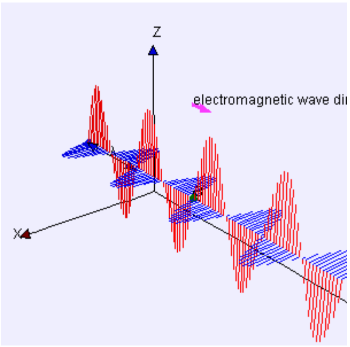
- –Short pulse (ps to fs)
- –Little spread in transverse momentum and angle => low emittance

Lawson-Woodward Theorem

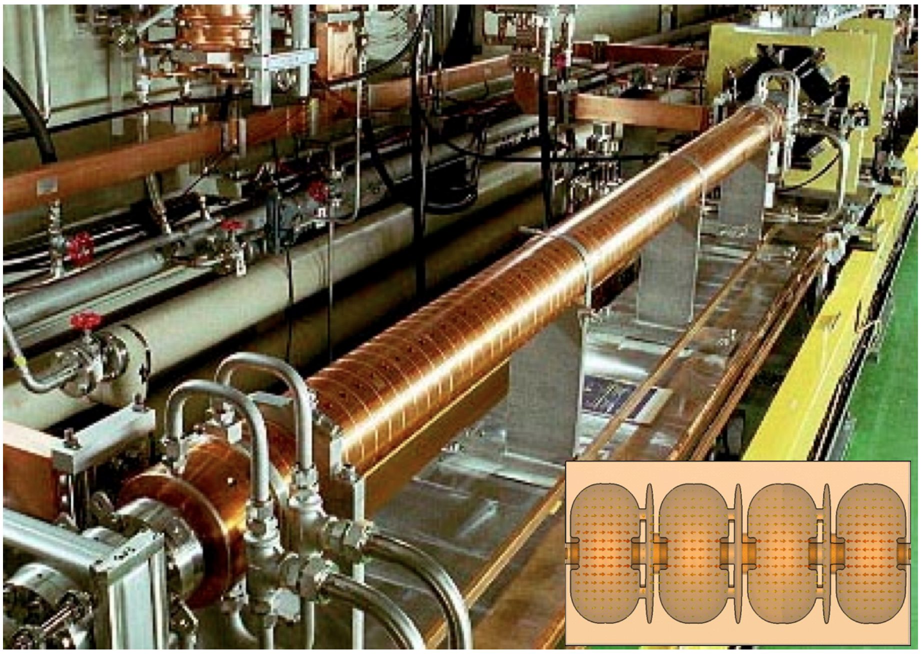
(J.D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217, 1979)

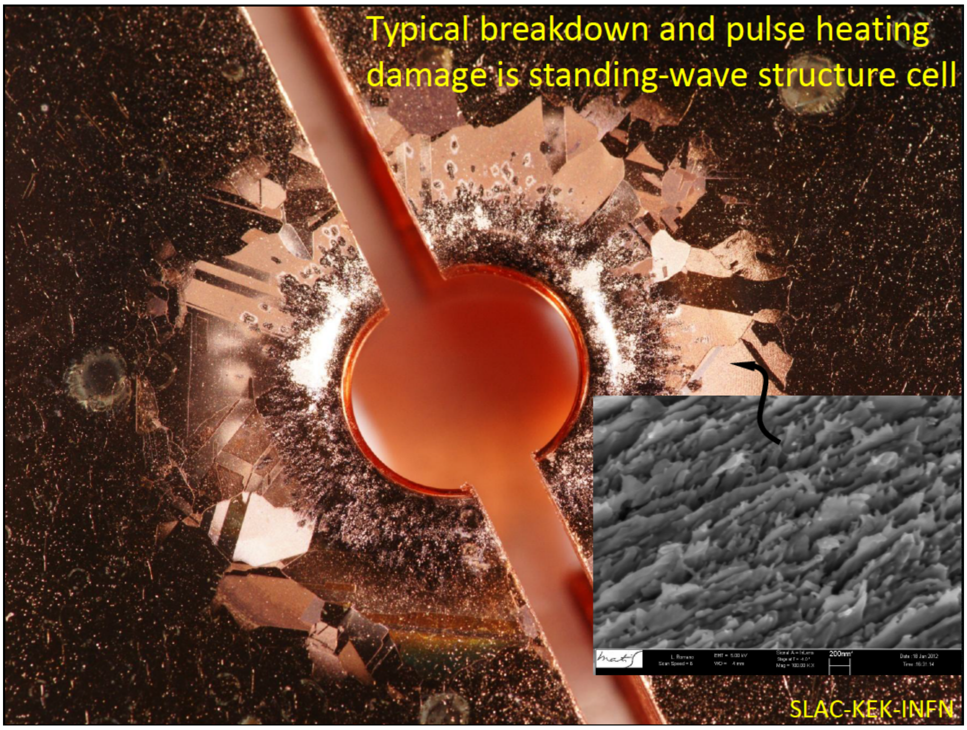
The net energy gain of a relativistic electron interacting with an electromagnetic field **in vacuum** is zero.

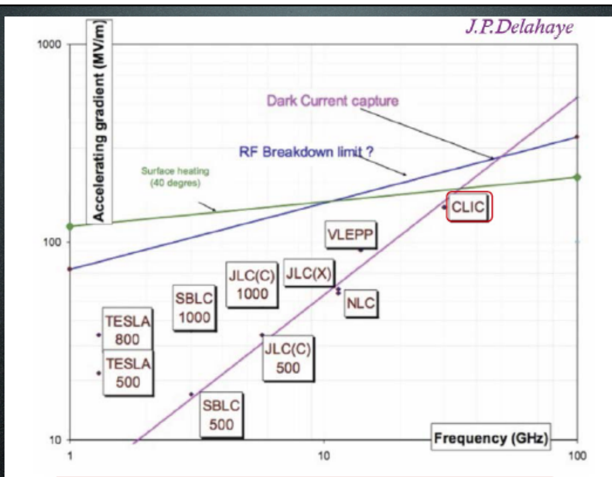
The theorem assumes that
(i) the laser field is in vacuum with no walls or boundaries present,
(ii) the electron is highly relativistic ($v \approx c$) along the acceleration path,
(iii) no static electric or magnetic fields are present,
(iv) the region of interaction is infinite,



$$F_\perp \cong \frac{eE_x}{2\gamma^2}\cos\left(\frac{\omega t}{2\gamma^2}\right)$$







Breakdown limits metal:

$$E_s = 220(f\,[\mathrm{GHz}])^{1/3}\ \mathrm{MV/m}$$

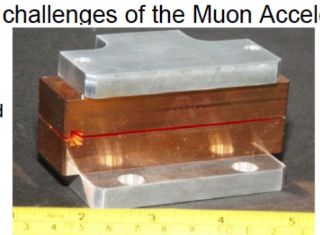
high field ->short wavelength->ultra-short bunches-> low charge

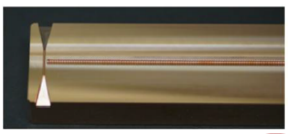
Miniaturization of the accelerating structures

Future plans for the high gradient collaboration

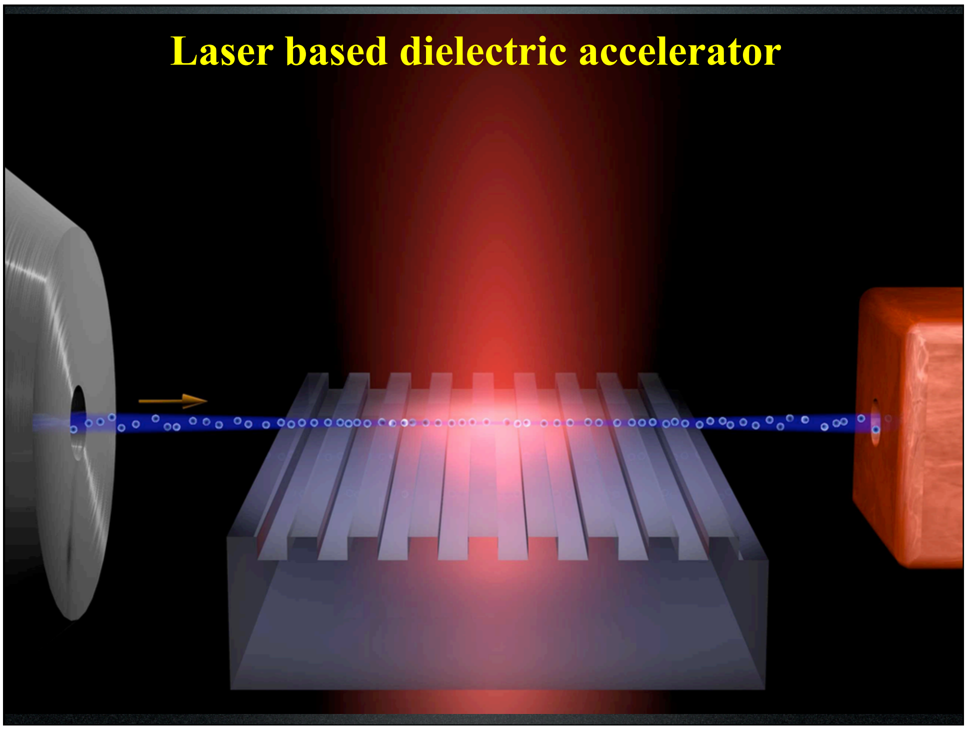
- The collaboration during the next 5 will address 4 fundamental research efforts:
  - Continue basic physics research, materials research frequency scaling and theory efforts.
  - Put the foundations for advanced research on efficient RF sources.
  - Explore the spectrum from 90 GHz to THz
    - Sources at MIT
    - Developments of suitable sources at 90 GHz
    - Developments of THz stand alone sources
    - Utilize the FACET at SLAC and AWA at ANL
    - Address the challenges of the Muon Accelerator Project (MAP)

mm-Wave structure to be tested at FACET

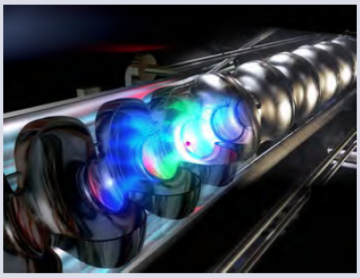




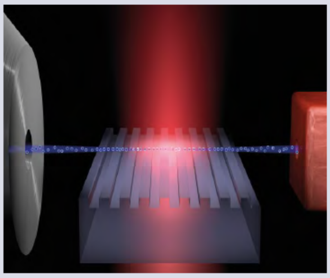
SLAC NATIONAL ACCELERATOR LABORATORY



Particle accelerators: from RF to optical/photonic drive?



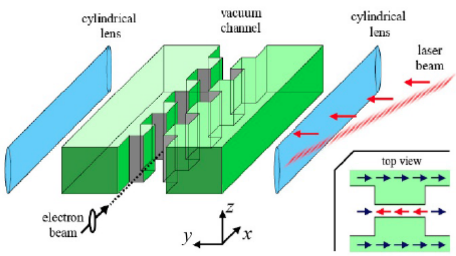
RF cavity (TESLA, DESY)



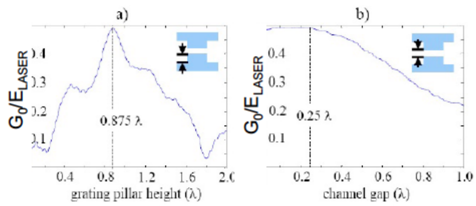
	Conventional linear accelerator (RF)	Laser-based dielectric accelerator (optical)
Based on	(Supercond.) RF cavities	Quartz grating structures
Peak field limited by	**Surface breakdown: 200 MV/m**	**Damage threshold: 30 GV/m**
Max. achievable gradients	**50 MeV/m**	**10 GeV/m**

P. Hommelhoff, ARD lunch sem., DESY, Jan. 2014

Grating-Based Planar Structure

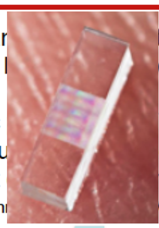


T. Plettner, et al. PRST-AB **9**, 111301 (2006).

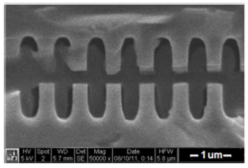


SiO_2 plar th side-
coupled l eam.

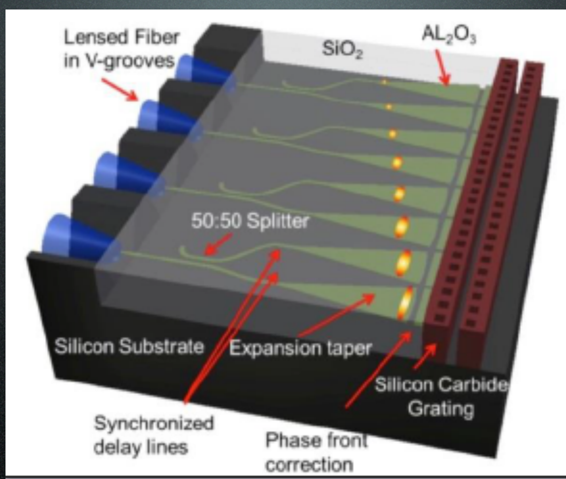
Periodic the EM
field resu ccelerating
gradient iods.
damage thr V/m @ 1ps



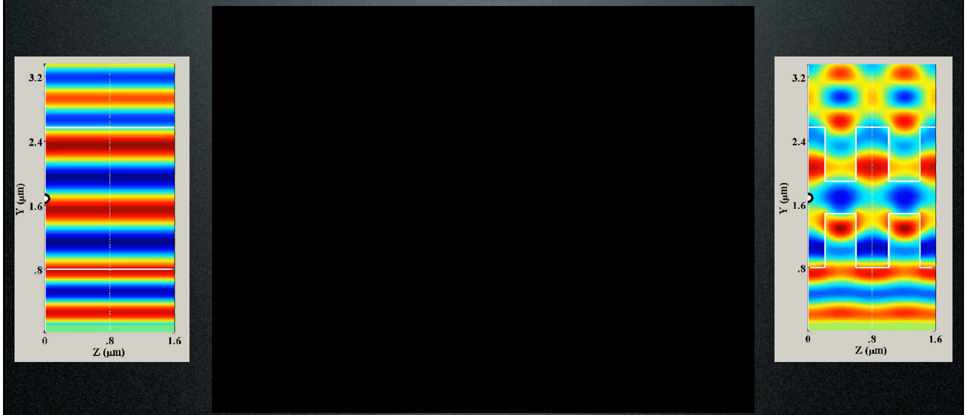
$G_{0,max}$ ~ 1GV/m



E. Peralta, recently fabricated prototype structure



Accelerator on a Chip: how it works



Light Source on a Chip

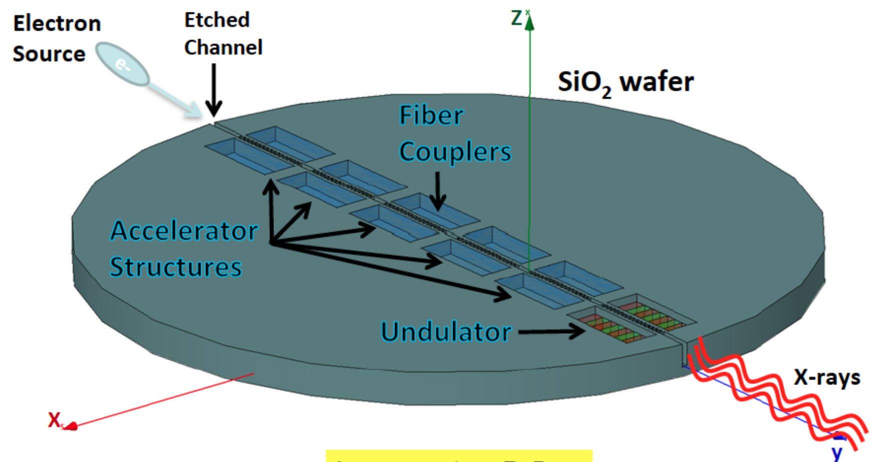
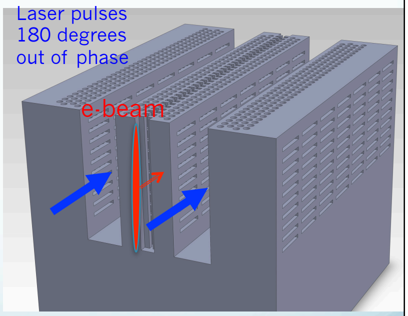


Image courtesy R. Byer

Dielectric Structure Design Philosophies

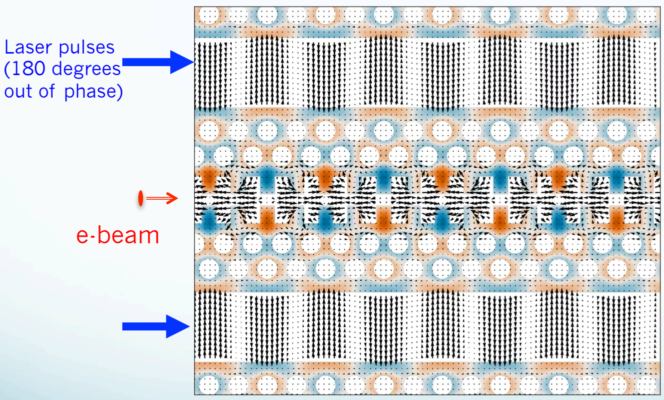
- Why dielectric?
  - *Dissipation and breakdown* in metals
- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication
- Dynamics concerns
- External coupling schemes



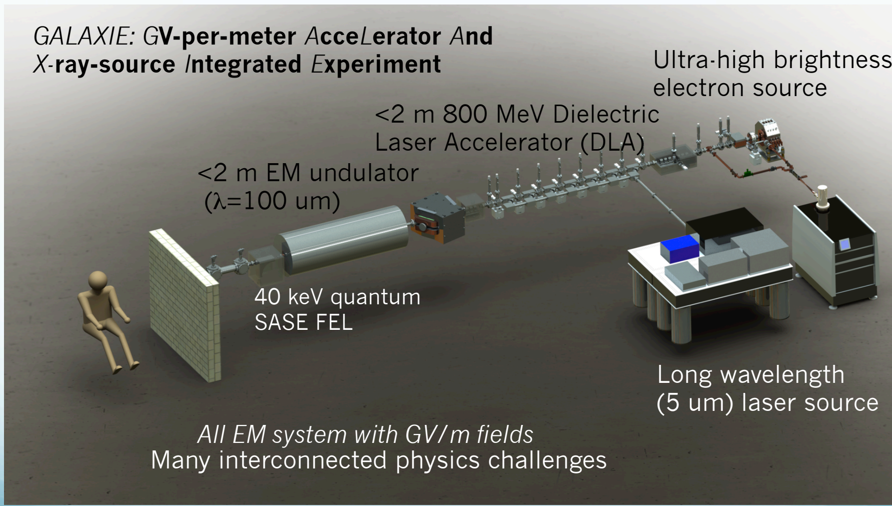
Schematic of GALAXIE monolithic photonic DLA

Laser-Structure Coupling: TW

GALAXIE Dual laser drive structure, large reservoir of power recycles



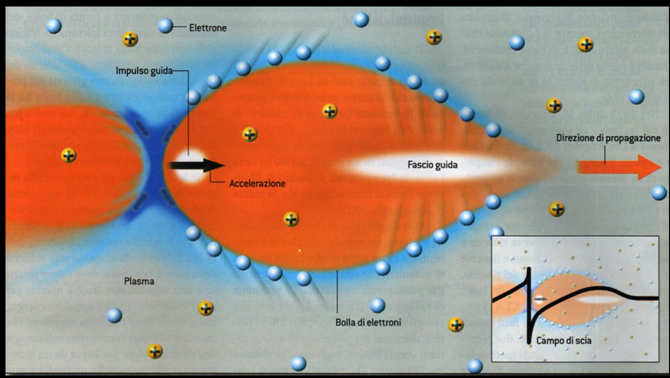
5^{th} Gen Light Source: A Table-top X-ray FEL



Ambitious program supported by DARPA AXiS initiative

Wake Field Acceleration
LWFA

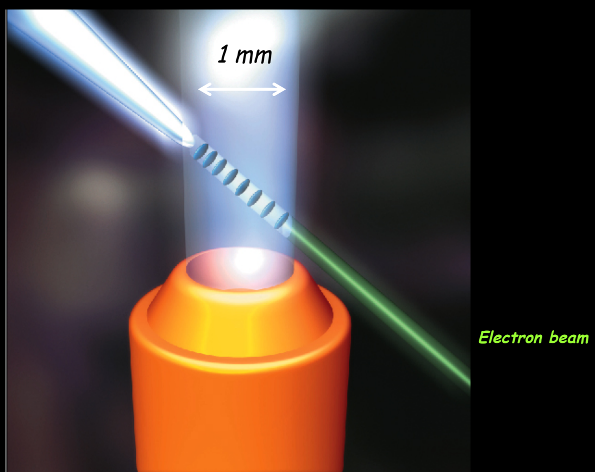
High quality beam Plasma Acceleration

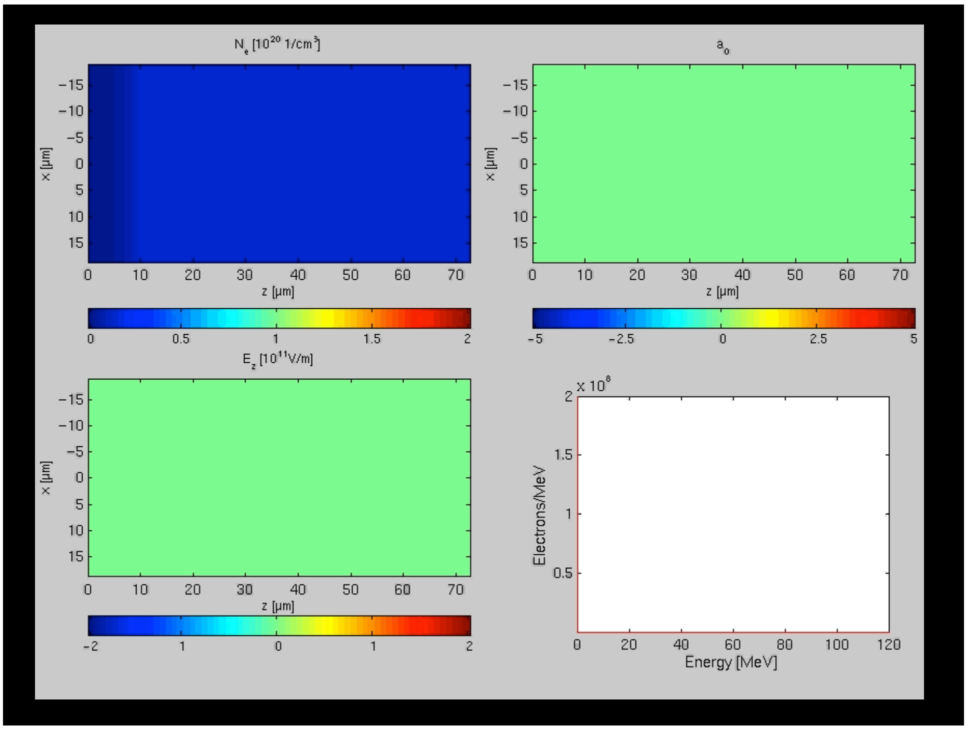


Breakdown limit?

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Direct production of e-beam





2005 The Dream Beam

Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

S. P. D. Mangles[1], C. D. Murphy[1,2], Z. Najmudin[1], A. G. R. Thomas[1], J. L. Collier[2], A. E. Dangor[1], E. J. Divall[2], P. S. Foster[2], J. G. Gallacher[3], C. J. Hooker[2], D. A. Jaroszynski[3], A. J. Langley[2], W. B. Mori[4], P. A. Norreys[2], F. S. Tsung[4], R. Viskup[3], B. R. Walton[1] & K. Krushelnick[1]

[1]The Blackett Laboratory, Imperial College London, London SW7 2AZ, UK
[2]Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK
[3]Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK
[4]Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. G. R. Geddes[1,2], Cs. Toth[1], J. van Tilborg[1,3], E. Esarey[1], C. B. Schroeder[1], D. Bruhwiler[4], C. Nieter[4], J. Cary[4,5] & W. P. Leemans[1]

[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2]University of California, Berkeley, California 94720, USA
[3]Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, the Netherlands
[4]Tech-X Corporation, 5621 Arapahoe Ave. Suite A, Boulder, Colorado 80303, USA
[5]University of Colorado, Boulder, Colorado 80309, USA

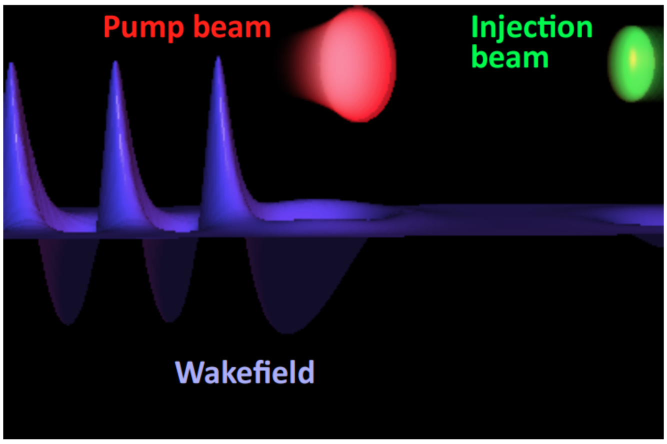
A laser–plasma accelerator producing monoenergetic electron beams

J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]

[1]Laboratoire d'Optique Appliquée, Ecole Polytechnique, ENSTA, CNRS, UMR 7639, 91761 Palaiseau, France
[2]Institut fur Theoretische Physik, 1, Heinrich-Heine-Universitat Duesseldorf, 40225 Duesseldorf, Germany
[3]Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, 91680 Bruyères-le-Châtel, France

Colliding Laser Pulses Scheme

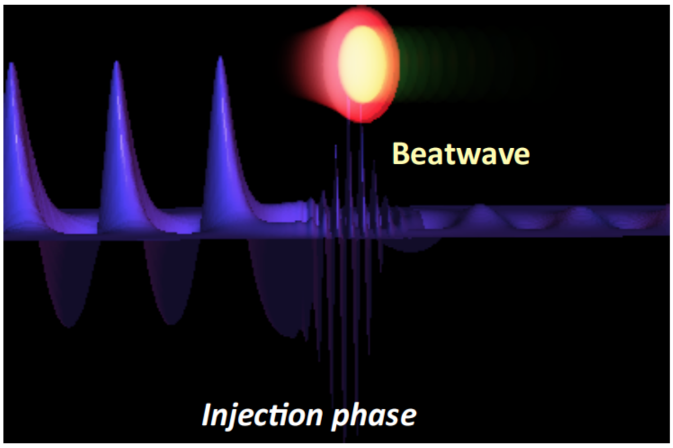
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

Colliding Laser Pulses Scheme

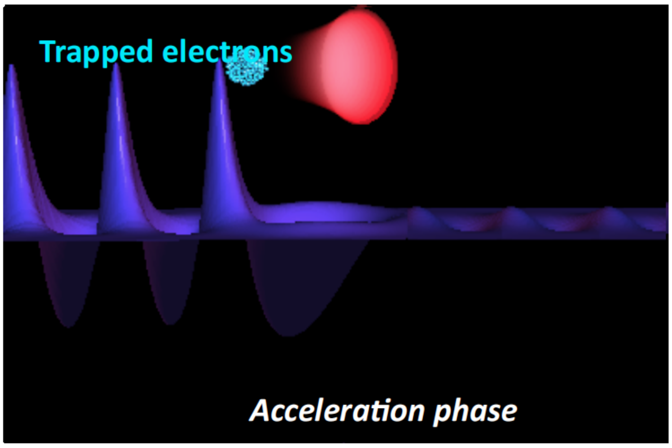
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

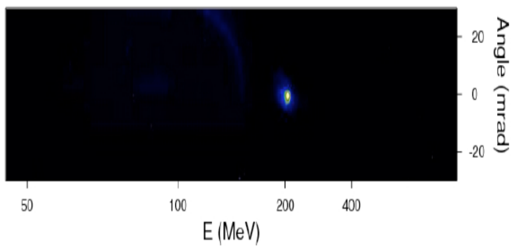
Colliding Laser Pulses Scheme

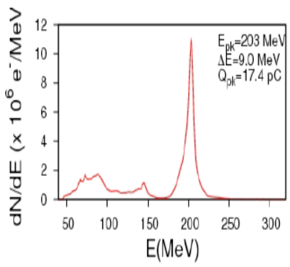
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



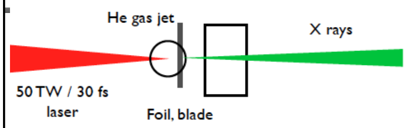
Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

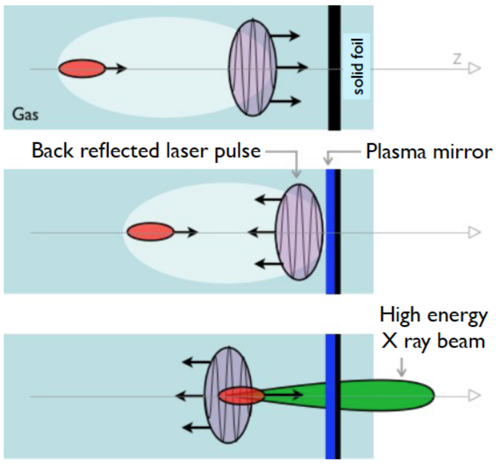
Stable Laser Plasma Accelerators





Inverse Compton Scattering : New scheme





A single laser pulse

A plasma mirror reflects the laser beam

The back reflected laser collides with the accelerated electrons

No alignment : the laser and the electron beams naturally overlap

Save the laser energy !

Conclusions

Accelerators point of view :

- Good beam quality & Monoenergetic dE/E down to 1 % √
- Beam is very stable √
- Energy is tunable: up to 400 MeV √
- Charge is tunable: 1 to tens of pC √
- Energy spread is tunable: 1 to 10 % √
- Ultra short e-bunch : 1,5 fs rms √
- Low divergence : 2 mrad √
- Low emittance[1-3] : < π.mm.mrad √

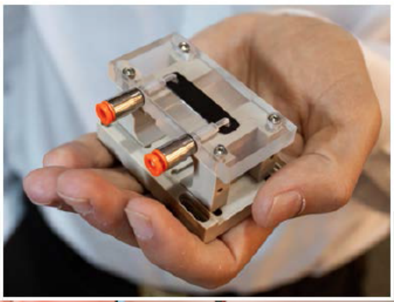
With PW class laser : peak energy at 3 GeV √

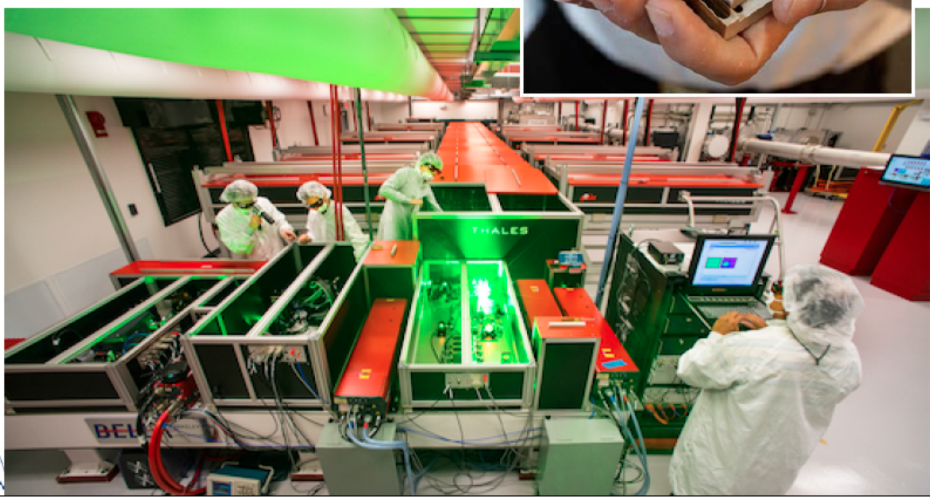
[1]S. Fritzler *et al.*, Phys. Rev. Lett. **92**, 165006 (2004), [2]C. M. S. Sears *et al.*, PRSTAB **13**, 092803 (2010)
[3]E. Brunetti *et al.*, Phys. Rev. Lett. **105**, 215007 (2010)

World Leader

BELLA LPWA facility:

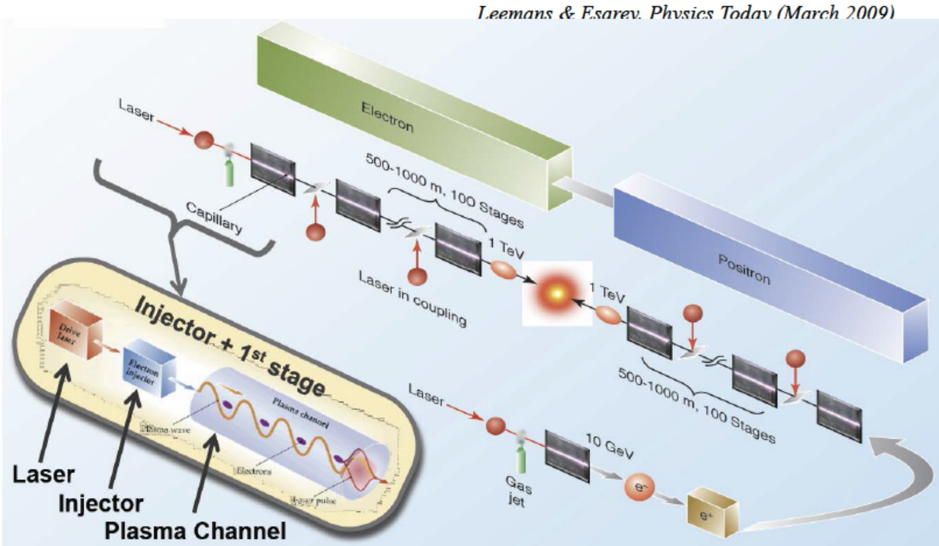
3 cm 1 GeV 40 TW laser ~1Hz
10-30 cm 5-10 GeV PW laser, ~1 Hz





Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)



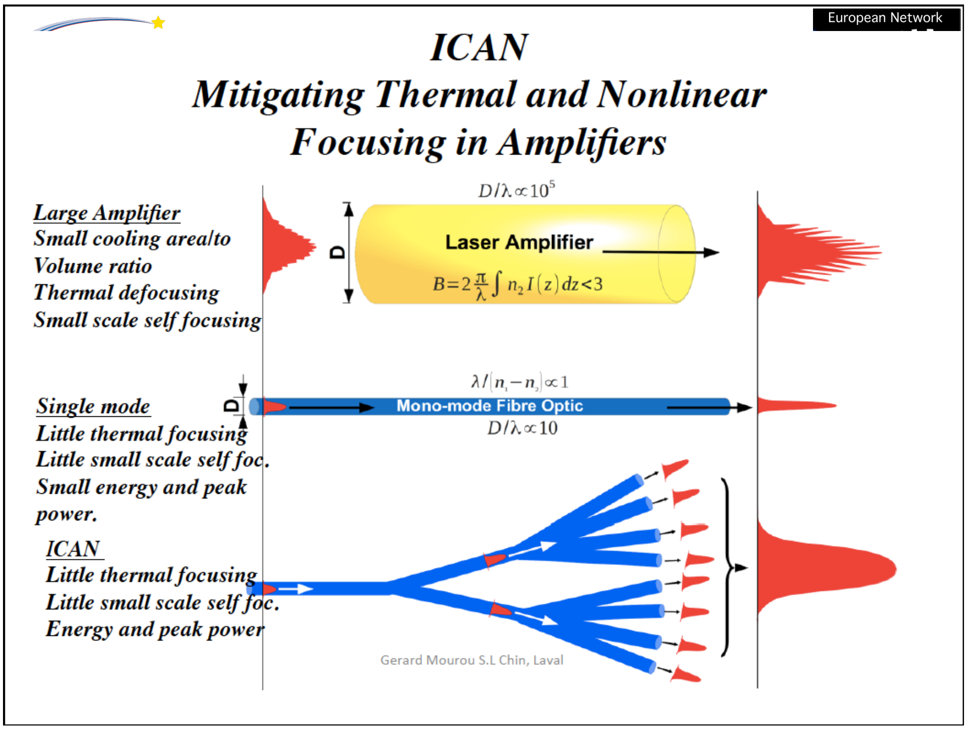
Parameter Set for LPWA LC

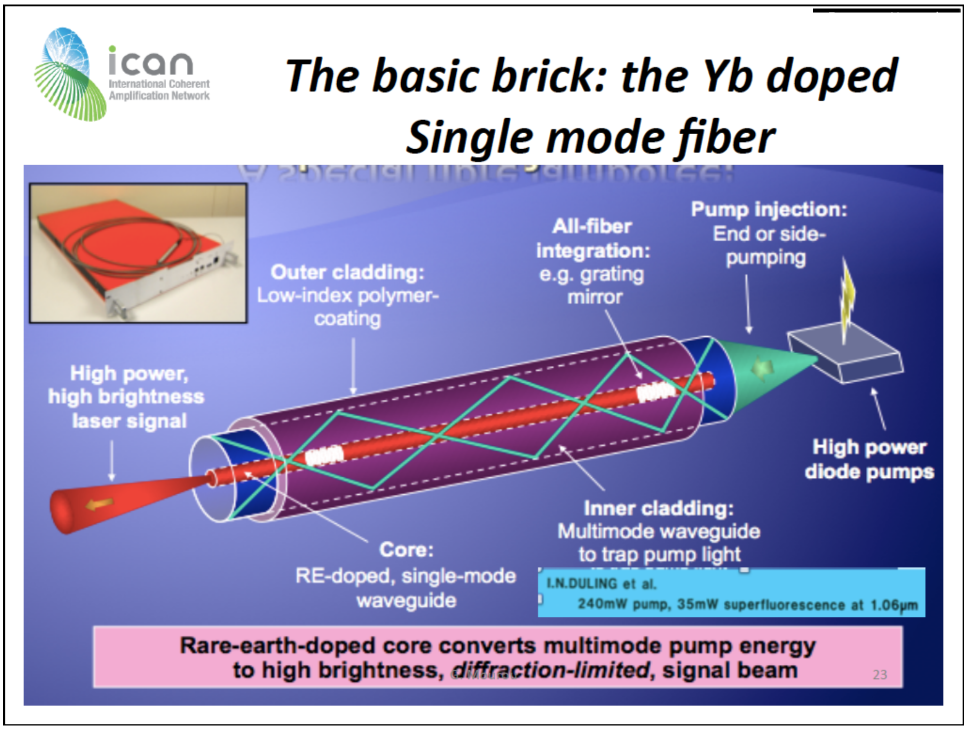
Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV (2×10^{15} cm^{-3})	10 TeV (10^{17} cm^{-3})	10 TeV (2×10^{15} cm^{-3})
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	2	200	200
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8
Bunch repetition rate (kHz)	15	0.3	15	0.3
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	100	100	50	50
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	100	100	50	50
β* (mm)	1	1	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	10	10	1	1
Vertical beam size at IP σ^*_y (nm)	10	10	1	1
Disruption parameter	0.12	5.6	1.2	56
Bunch length σ_z (μm)	1	7	1	7
Beamstrahlung parameter ϒ	180	180	18,000	18,000
Beamstrahlung photons per e, n_γ	1.4	10	3.2	22
Beamstrahlung energy loss δ_E (%)	42	100	95	100
Accelerating gradient (GV/m)	10	1.4	10	1.4
Average beam power (MW)	5	0.7	50	7
Wall plug to beam efficiency (%)	6	6	10	10
One linac length (km)	0.1	0.5	1.0	5

×2+FF

W.Leemans, ICFA BD Newsletter, No.56 (2011)

Vladimir Shiltsev - Colliders - DESY, Jan 15, 2014 46

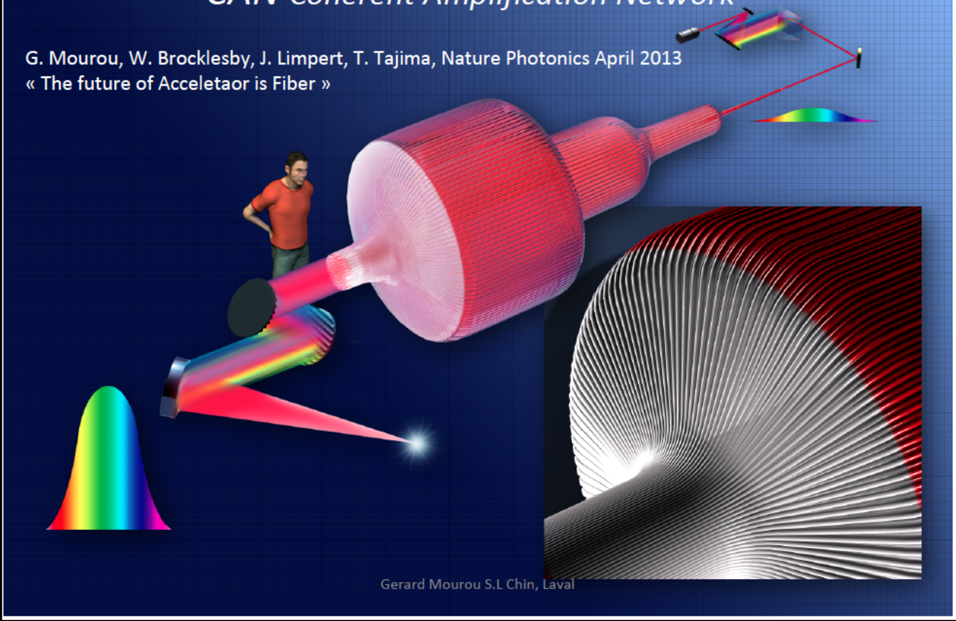

European Network
ICAN
Mitigating Thermal and Nonlinear Focusing in Amplifiers
Large Amplifier
Small cooling area/to Volume ratio
Thermal defocusing
Small scale self focusing
$D/\lambda \propto 10^5$
D
Laser Amplifier
$B=2\frac{\pi}{\lambda}\int n_2 I(z)\,dz<3$
Single mode
Little thermal focusing
Little small scale self foc.
Small energy and peak power.
$\lambda/(n_1-n_2)\propto 1$
Mono-mode Fibre Optic
$D/\lambda \propto 10$
ICAN
Little thermal focusing
Little small scale self foc.
Energy and peak power
Gerard Mourou S.L Chin, Laval


ican
International Coherent Amplification Network
The basic brick: the Yb doped Single mode fiber
Pump injection:
End or side-pumping
All-fiber integration:
e.g. grating mirror
Outer cladding:
Low-index polymer-coating
High power, high brightness laser signal
High power diode pumps
Inner cladding:
Multimode waveguide to trap pump light
Core:
RE-doped, single-mode waveguide
I.N.DULING et al.
240mW pump, 35mW superfluorescence at 1.06μm
Rare-earth-doped core converts multimode pump energy to high brightness, diffraction-limited, signal beam
23

ICAN (European Project)

CAN Coherent Amplification Network

G. Mourou, W. Brocklesby, J. Limpert, T. Tajima, Nature Photonics April 2013
« The future of Acceletaor is Fiber »



Protons and ions are too slow to catch the wave - only indirect acceleration via electrons

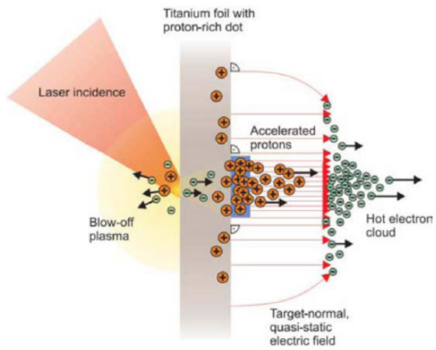
Laser Driven Acceleration of Protons

- Direct acceleration in laser field > 10^{25} W/cm² far beyond current lasers
- Plasma wakefield phase velocity too fast for protons & ions
- → only indirect ways

Need typically:
50 J 500 fs → 100 TW
30 µm radius → 10^{19} W/cm²

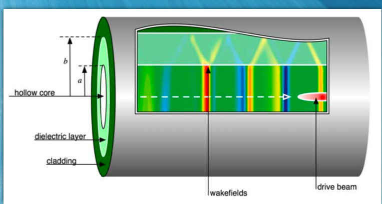
Target Normal Sheath Acceleration
"best understood" candidate:

- laser creates blow-off plasma on front surface
- backside expansion accelerated electrons ionize hydrogen
- hot electrons create electric field (by space charge)
- causes acceleration of protons (electrons slowing down – end of acceleration)
- neutralized bunch of comoving p and e generated

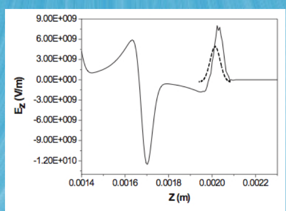


Wake Field Acceleration
PWFA & DWFA

Dielectric Wakefield Accelerator



- Design Parameters a,b σ_z ε



Ez on-axis, OOPIC

- Electron bunch (β ≈ 1) drives wake in cylindrical dielectric structure
  - Dependent on structure properties
  - Generally multi-mode excitation
- Wakefields accelerate trailing bunch
  - Mode wavelengths (quasi-optical

$$\lambda_n \approx \frac{4(b-a)}{n}\sqrt{\varepsilon-1}$$

- Peak decelerating field

$$eE_{z,dec} \approx \frac{-4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}}\,\varepsilon\sigma + a\right]}$$

Extremely good beam needed

- Transformer ratio (unshaped beam)

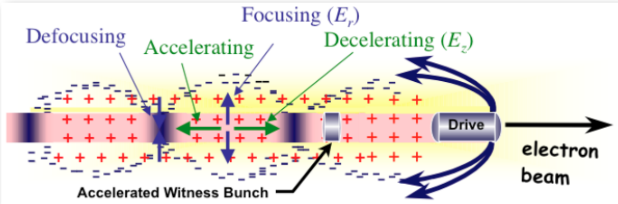
$$R = \frac{E_{z,acc}}{E_{z,dec}} \leq 2$$

A Beam Driven Plasma Wakefield Accelerator

SLAC

A very high frequency structure acting as an energy transformer

- Accelerating structure is created anew every shot
- High gradients need high density plasmas
  - ~10^{17} e^-/cm^3
  - >10GeV/m acceleration
  - >MT/m focusing



For wake excitation need a beam matched to plasma dimensions:

•Individual bunches, or a bunch train, 100's fs apart (or use SMI for long bunches)

•Individual bunches small in all three dimensions

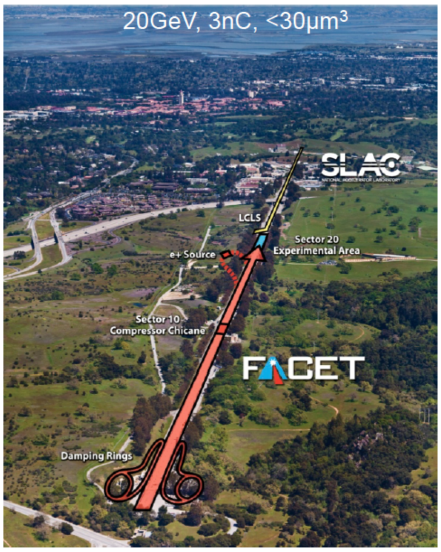
- High bunch charge for blow-out with large wake amplitude & good transport

•Need long, uniform high-density plasmas

2

FACET Has a Multi-year Program to Study PWFA

SLAC



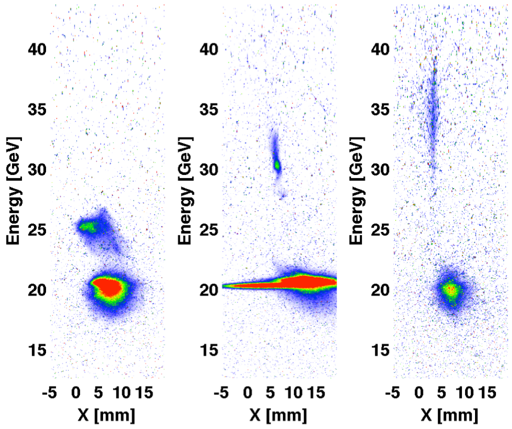
- Demonstrate a single-stage high-energy plasma accelerator for electrons
- Meter scale, high gradient, preserved emittance, low energy spread, and high efficiency
  - Commission beam, diagnostics and plasma source (2012)
  - Produce independent drive & witness bunch (2012-2013)
  - Pre-ionized plasmas and tailored profiles to maximize single stage performance: total energy gain, emittance, efficiency (2013-2015)
- First experiments with compressed positrons
  - Identify optimum technique/regime for positron PWFA (2014-2016)

4

2014 Results: Two-Bunch Acceleration in a 1.5 m Plasma

SLAC

Plasma Density: $3 \times 10^{16}[\mathrm{cm}^{-3}]$ $5 \times 10^{16}[\mathrm{cm}^{-3}]$ $8 \times 10^{16}[\mathrm{cm}^{-3}]$



We are working to improve our spectrometer's ability to precisely quantify energy spread.

Results from last week! Good agreement between observed and expected energy gain in a longer plasma for several plasma densities.

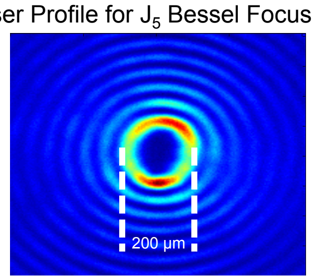
47

Positrons and Hollow Channel Plasma

SLAC

- The physics of accelerating positrons in a plasma is different than that of electrons!
- Hollow channel plasmas might be a viable method for accelerating positrons in a plasma.
- A special optic called a kinoform is used to create a hollow channel plasma.

Laser Profile for J_5 Bessel Focus

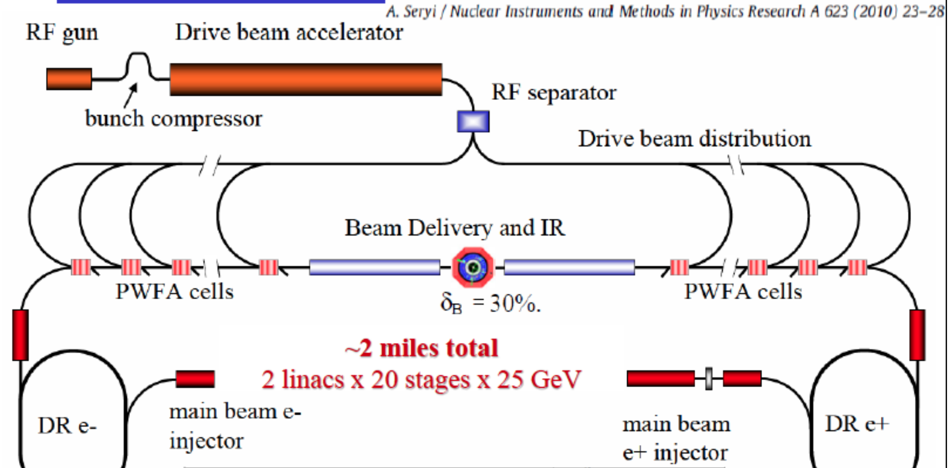


Positrons plasma acceleration is a crucial step towards a plasma based linear collider. FACET hosts the only active research on positron PWFA.

48

Plasma Wake Field $e+e-$ 1 TeV

A. Seryi / Nuclear Instruments and Methods in Physics Research A 623 (2010) 23–28



Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs
Average power of the drive beam	58 MW
Plasma density, accelerating gradient and plasma cell length	1×10^{17}cm^{-3}, 25 GV/m, 1 m
Power transfer efficiency drive beam=>plasma =>main beam	35%
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW
Main beam emittances, x, y	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	0.14, 0.0032, 10 μm
Luminosity	3.5×10^{34} cm^{-2}s^{-1}
Luminosity in 1% of energy	1.3×10^{34} cm^{-2}s^{-1}

SLAC

43

European Network

AWAKE

AWAKE

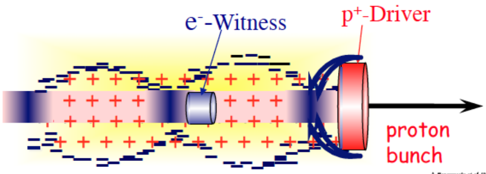
P. Muggli, 06/04/2013, EAAC 2103

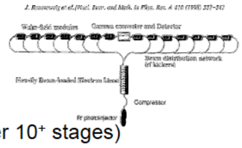
Proton-driven
Plasma Wakefield Acceleration
Collaboration:
Accelerating e^- on the wake of a p^+ bunch

European Network

WHY p+-DRIVEN PWFA?

AWAKE





✧ILC, 0.5TeV bunch with $2x10^{10}e^-$ ~1.6kJ

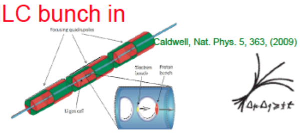
✧SLAC, 20GeV bunch with $2x10^{10}e^-$ ~60J

✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)

✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ

✧A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!

✧Large average gradient! (≥1GeV/m, 100's m)



P. Muggli, 06/04/2013, EAAC 2103

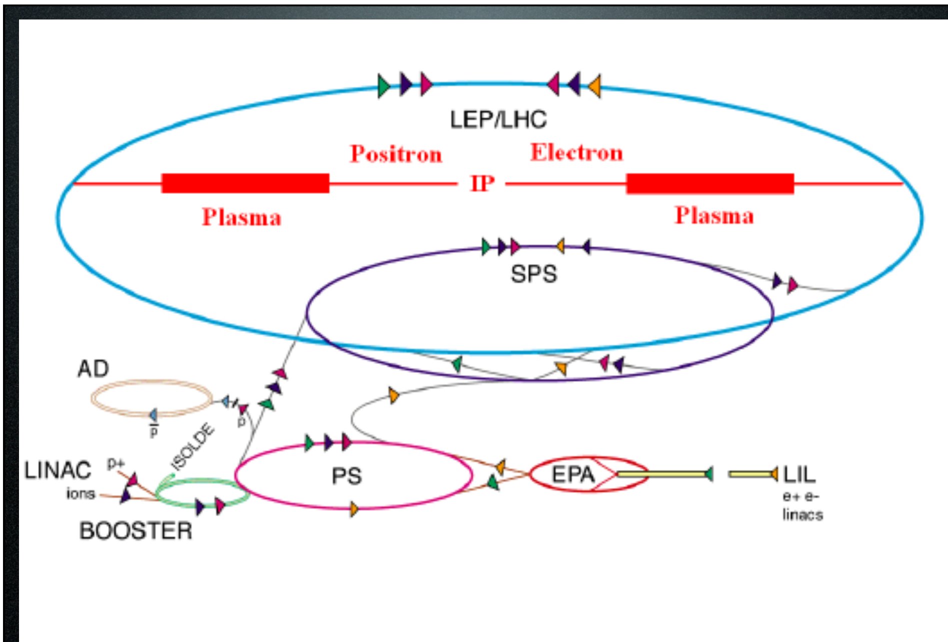


Figure 1: Schematic layout of a 2 TeV CoM electron-positron linear collider based on a modulated proton-driven plasma wakefield acceleration.

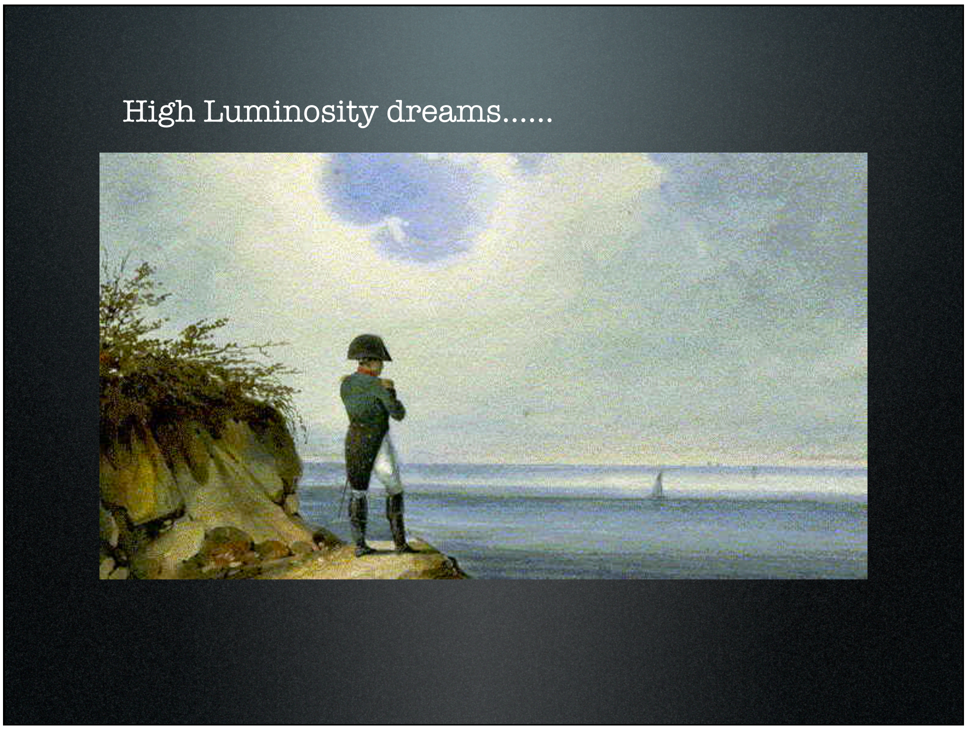

Walt Disney
TOPOLINO
E
L'ACCELERATORE
NUCLEARE
...MA STIAMO PER INAUGURARNE UNO MOLTO PIU' GRANDE! ECCOLO!
OH!
IL NUOVO ACCELERATORE AVRA' UNA CIRCONFERENZA DI BEN TRENTA CHILOMETRI!
QUAL E' LO SCOPO DEI VOSTRI ESPERIMENTI?
LA PACE...
...E IL PROGRESSO DELL'UMANITA', NATURALMENTE! GUAI SE LE SCOPERTE ATOMICHE VENISSERO USATE A FINI MALVAGI E DISTRUTTIVI!
POSSIAMO VEDERE I LAVORI DEL NUOVO IMPIANTO?
CERTAMENTE! VENITE CON ME!
TOPOLINO - 15
ECCO IL TUNNEL DEL NUOVO ACCELERATORE!
QUESTO SEMBRA UN BINARIO!
LO E', INFATTI!
USIAMO DEI CONVOGLI ELETTRICI PER GLI SPOSTAMENTI DEL PERSONALE!
VI MOSTRERO' IL RESTO DELL'IMPIANTO!
YUK! NIENTE MALE QUESTO MODELLINO... INGRANDITO!
BIP BIP! SI PARTE!
FRRR-RR


EAAC2013
1st European Advanced Accelerator Concepts Workshop
2-7 June 2013, La Biodola, Isola d'Elba, Italy
Novel schemes using advanced technologies (table-top FEL, plasma linear collider)
High gradient and multibunch acceleration in metallic structures
(C-X-band and beyond) with innovative power generation schemes
Advanced beam diagnostics for beams and plasma
Dielectric structures and other novel technologies
Plasma accelerators driven by electron beams
Plasma accelerators driven by modern lasers
Plasma accelerators driven by proton beams
Computations for Accelerator Physics
INFN Istituto Nazionale di Fisica Nucleare
The European Advanced Accelerator Concepts workshop has the mission to discuss and foster methods of beam acceleration with gradients beyond state of the art in operational facilities. The most cost effective and compact methods for generating high energy particle beams shall be reviewed and assessed. This includes diagnostics methods, timing technology, special need for injectors, beam matching, beam dynamics with advanced accelerators and development of adequate simulations. This workshop is organized within the 7th European Programme by the European Network for Novel Accelerators (EuroNNAc), representing 52 European Research Institutes. The EAAC will be followed by a 1-day network meeting by invitation only.
CERN
DESY
On Friday 7th: EuroNNAc 2013 yearly meeting
Workshop Organizing Committee
Massimo Ferrario (INFN - LNF), chair
Ralph Assmann (DESY)
Jens Osterhoff (DESY)
Arnd Specka (Ecole Polytechnique)
ÉCOLE POLYTECHNIQUE ParisTech
www.lnf.infn.it/conference/EAAC2013/
International Advisory Committee
Programme Committee
to be announced
Local Organizing Committee
Massimo Ferrario, chair
Maria Pia Anania, Enrica Chiadroni,
Roberto Cimino, Francesca Casarin
Maria Rita Ferrazza, Lucia Lilli
Giancarlo Gatti, Fabio Villa
EuroNNAc
European Network for Novel Accelerators
supported by EU via EuCARD


NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

NIM-A, Vol 740


2nd EAAC 2015
September 13-20, 2015
Isola d'Elba
TALKS
DINNER
BREAKFAST
COFFEE
LUNCH
DISCUSSIONS


High Luminosity dreams......