The future colliders

Alessandro Variola
LAL Orsay – in2p3

Outlook

1) ENERGY. The technology challenge – linear colliders
LHC - ILC&CLIC
2) LUMINOSITY. The design challenge – high luminosity circular colliders
SuperB
3) FUTURE TECHNOLOGY. The far future. Table top accelerators, plasma acceleration

To address it : Technology and ideas

- ENERGY and LUMINOSITY:
- HADRON colliders : We are already in the future
- LHC

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- Power radiated by an accelerating particle (in our case on a curved trajectory)

$$P_{\perp} = \frac{q^2 c \beta^4 E^4}{6 \pi \varepsilon_0 \rho^2 E_0^4}$$

- Energy radiated in one turn

$$U_0 = \frac{q^2 \beta^3 E^4}{3 \varepsilon_0 E_0^4 \rho}$$

- Average power radiated over one turn

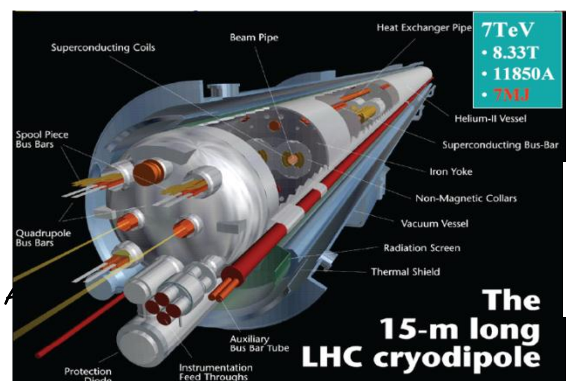
$$P_{av} = \frac{U_0}{T_0}$$

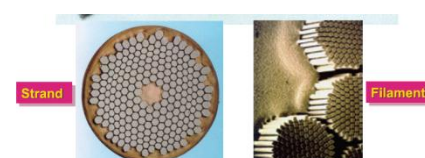
	LEP	LHC
[illegible] [m]	3096.175	2803.95
p_0 [GeV/c]	104	7000
U_0 [GeV]	3.3	$6.7\ 10^{-6}$
p_0 [GeV/c]	104	7000
B [T]	0.11	8.33

!!!!!!!!!!!!!!!!!!!

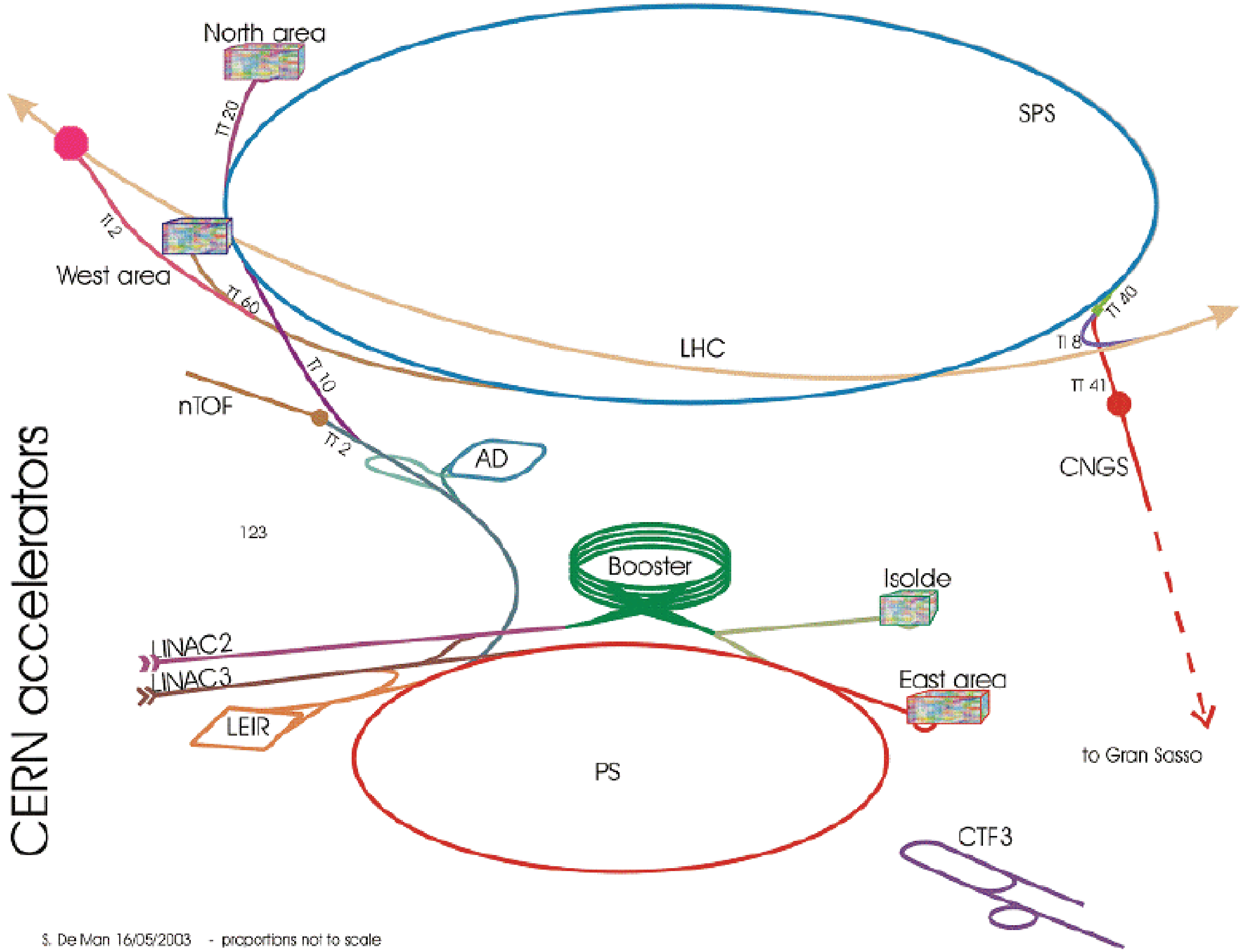
- The difficulty consists in bending TeV range beams …they have the kinetic energy of

TECHNOLOGY!!!!!!!
Future SLHC, 15 T?
Everything must be reshaped





INJECTION



Courtesy E. Métral - CERN

Trip of the LHC beam long the CERN injectors' chain

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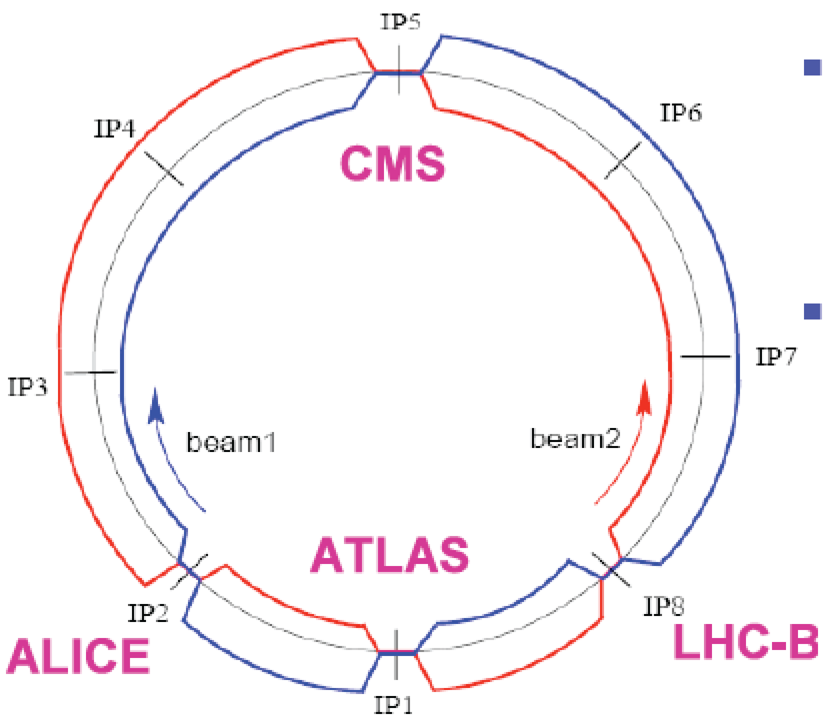
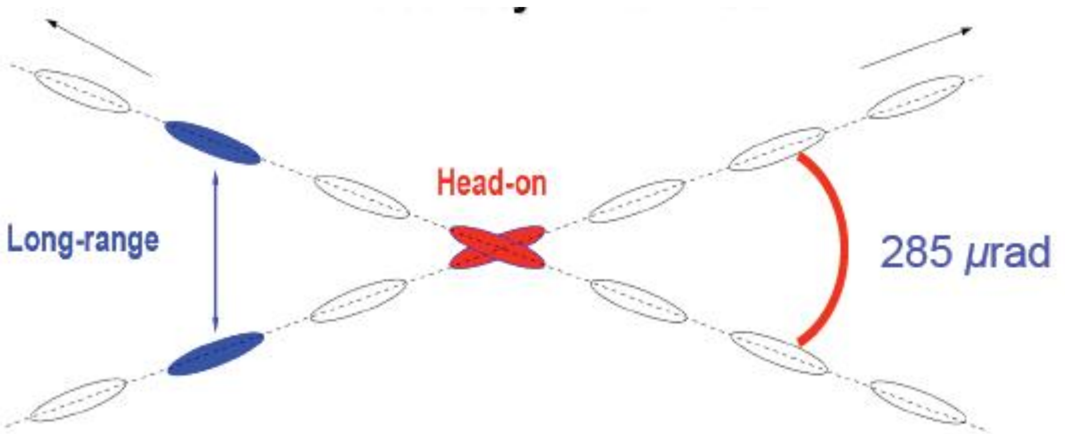
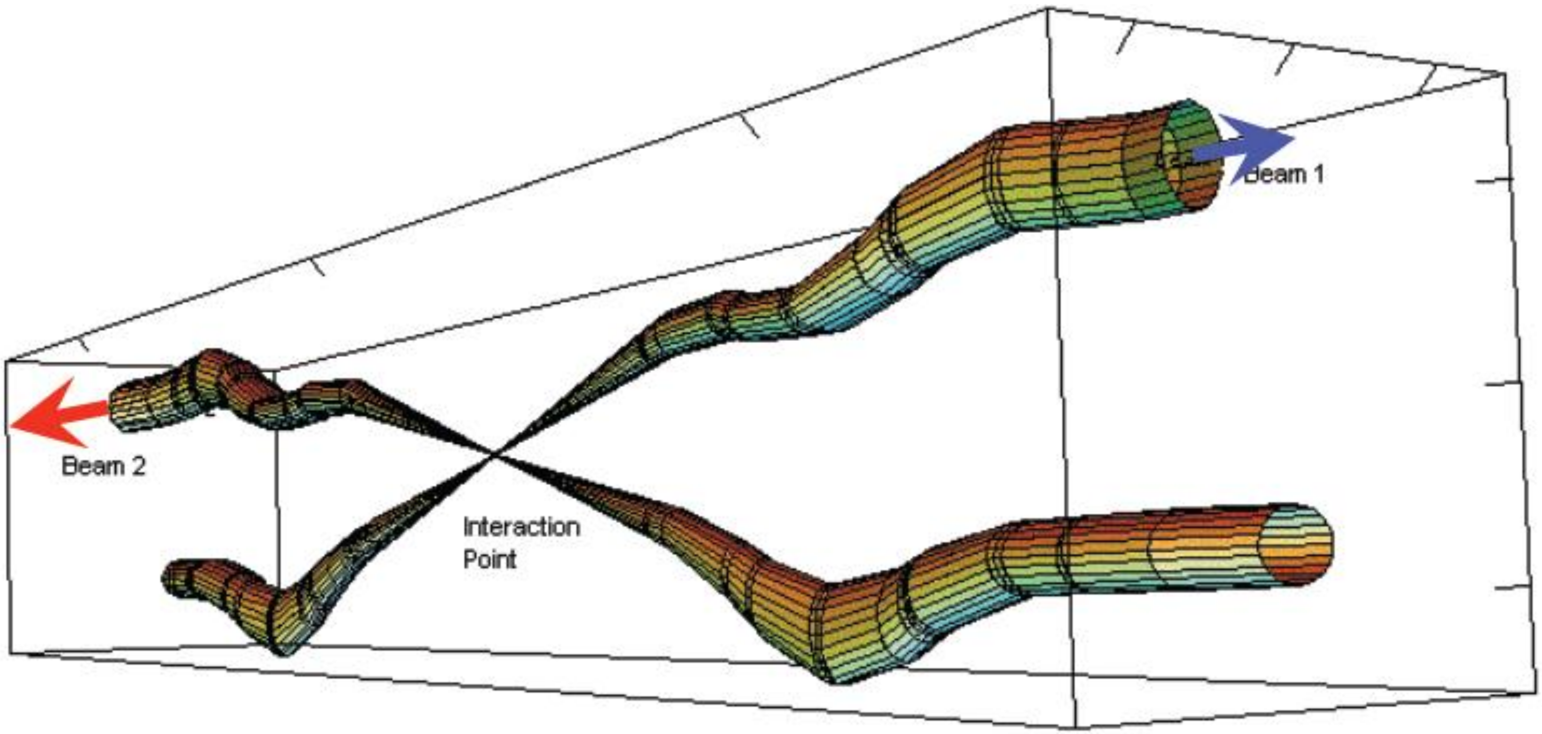
Layout



- ATLAS: High luminosity experiment. Search for the Higgs boson(s).
- A Large Ion Collider Experiment (ALICE): Ions. New phase of matter expected (Quark-Gluon Plasma).
- Compact Muon Solenoid (CMS): High luminosity experiment. Search for the Higgs boson(s). In this insertion is also located TOTEM for the measurement of the total proton-proton cross-section and study elastic scattering and diffractive physics.
- LHCb: Beauty quark physics " for precise measurements of CP violation and rare decays.

Collision region
The heart of the machine :
Luminosity is the game





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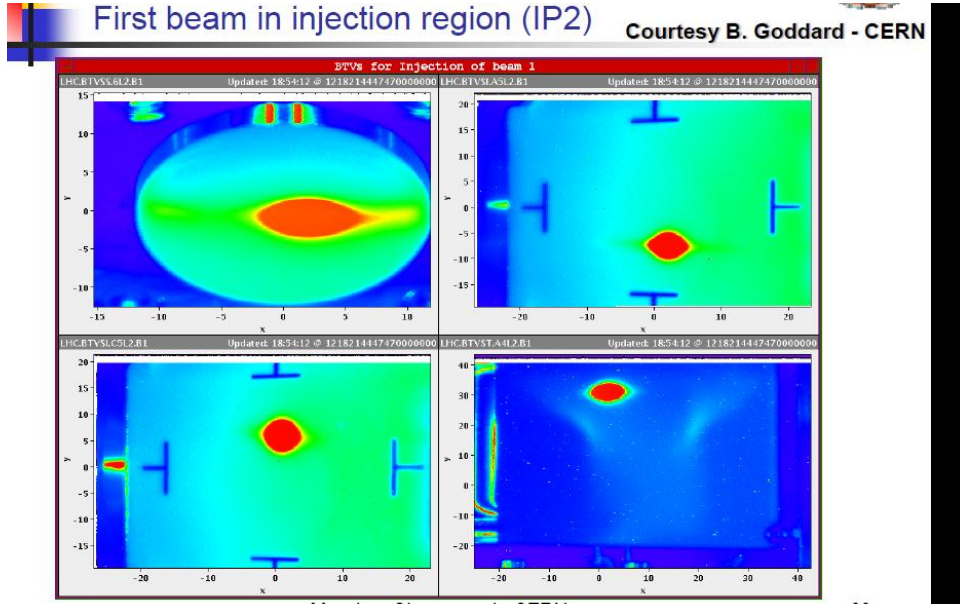
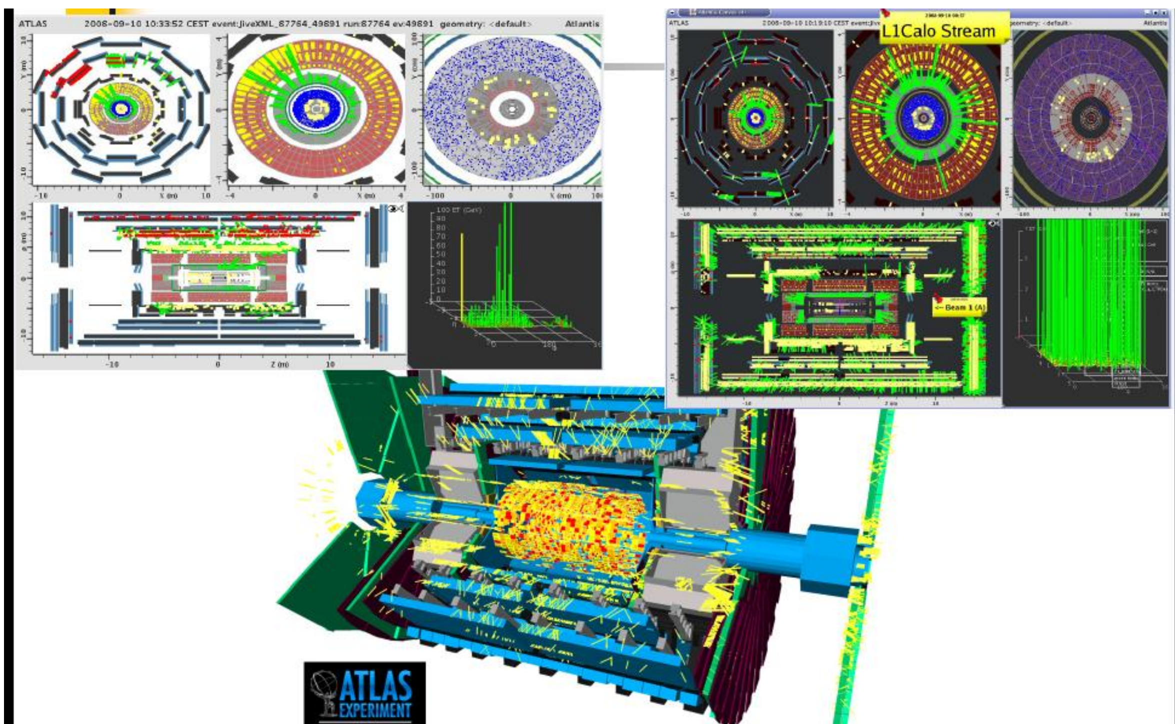
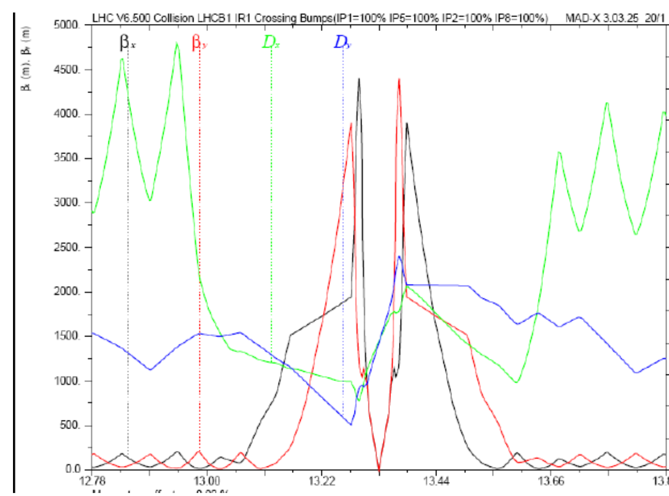

First beam in injection region (IP2)
Courtesy B. Goddard - CERN
BTVs for Injection of beam 1
LHC.BTVSS.6L2.B1
LHC.BTVSI.A5L2.B1
LHC.BTVSI.C5L2.B1
LHC.BTVST.A4L2.B1
Updated: 18:54:12 @ 1218214447470000000


L1Calo Stream
ATLAS EXPERIMENT


LHC V6.500 Collision LHCB1 IR1 Crossing Bumps(IP1=100% IP5=100% IP2=100% IP8=100%)
MAD-X 3.03.25
β_x
β_y
D_x
D_y
β_x (m), β_y (m)

LHC And SLHC

Not only the dipoles must be upgraded…but the performances, the technology and the systems of the whole complex

- Magnets
- Collimation
- Linac4
- SPS and PS
- Detectors
- Radiation
- Luminosity => IP
- Crab cavities ?

………………………………

Leptons

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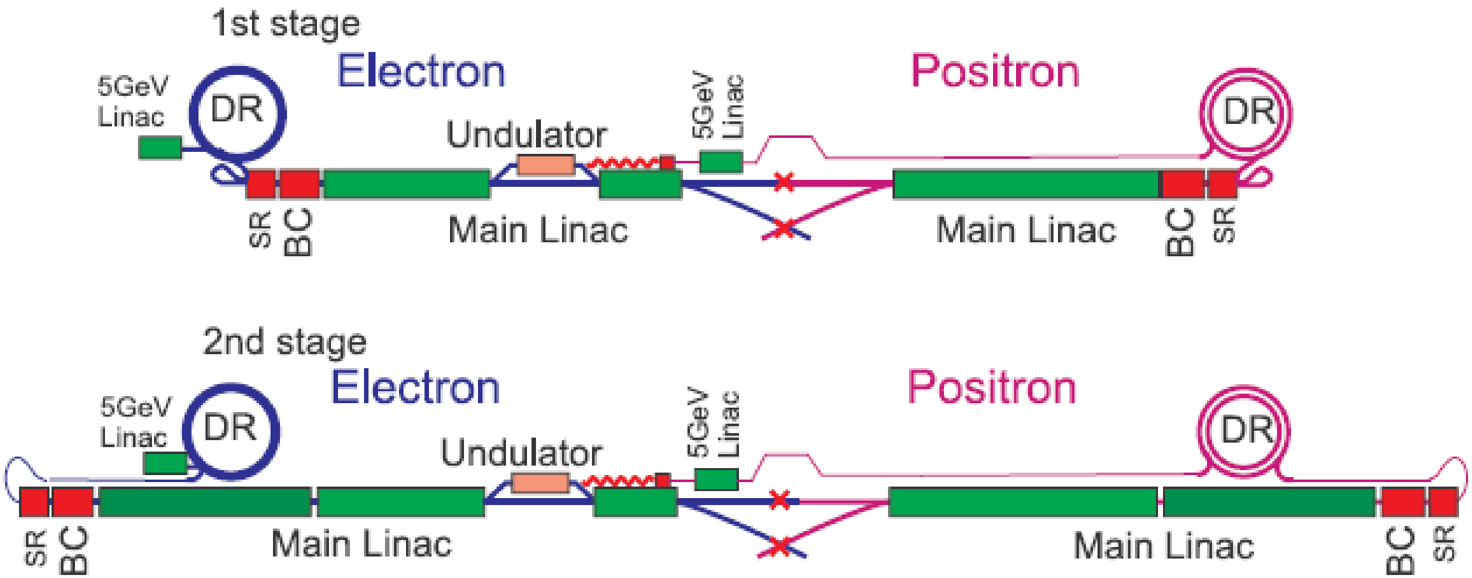
What's future for the leptons? Some preliminary considerations

- What's the problem for circular colliders?
- ENERGY : Synchrotron radiation!!!!
- LUMINOSITY : Re-use of the beam
- So for very high energy the future leptonic accelerator can only be a LINEAR COLLIDER

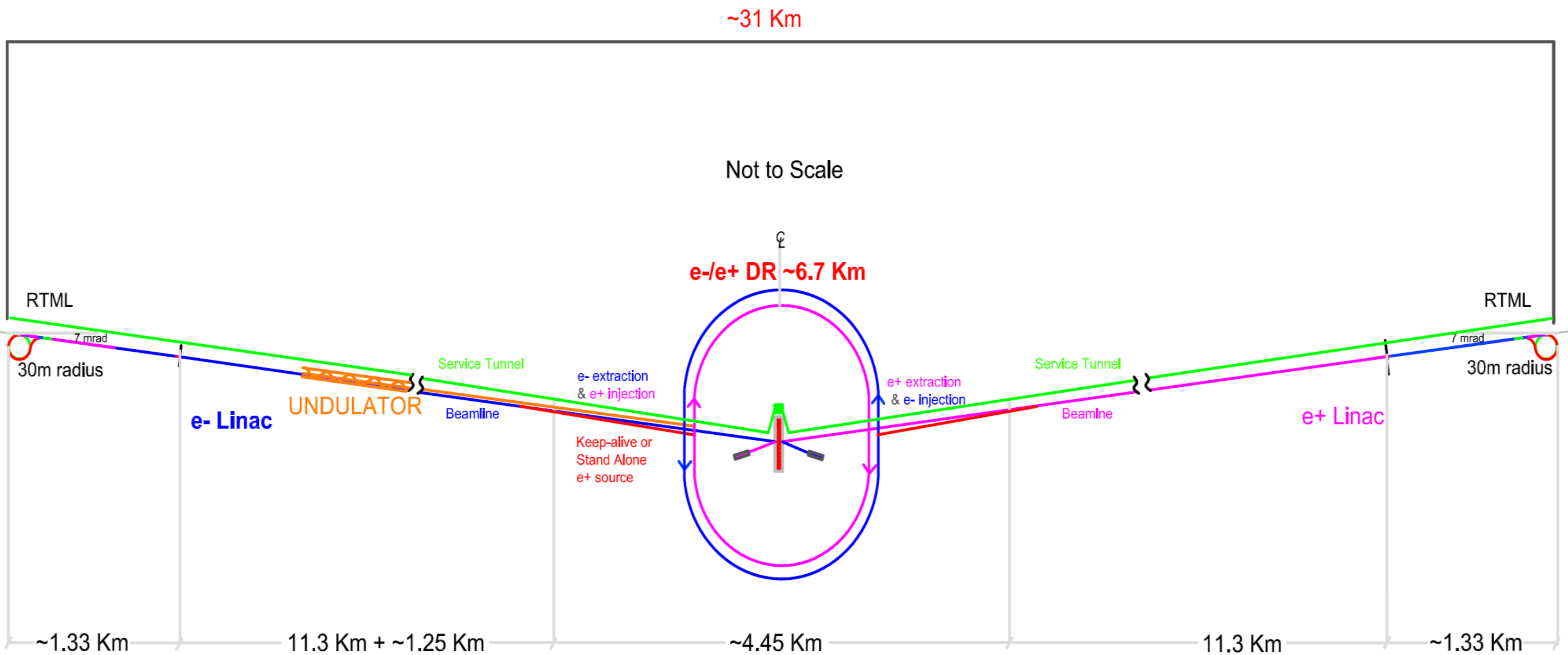
Linear colliders

- Scheme of principle:
- 1 Sources. Emittance will be damped in the Damping ring, but the timing (and so the Frep-luminosity) is always given by the source quality.
- 2 high current Damping Ring (1 e- / 1 e+) to damp the emittance by synchrotron radiation
- Accelerating Linac (low emittance transport)
- IP => Nanometric beam size
- Two technology proposed : COLD – ILC / Warm CLIC (relativistic Klystron)
- In this machines EVERYTHING must be pushed at the limit of our knowledge and beyond.....

Example ILC 1



Example : ILC 2



Schematic Layout of the 500 GeV Machine

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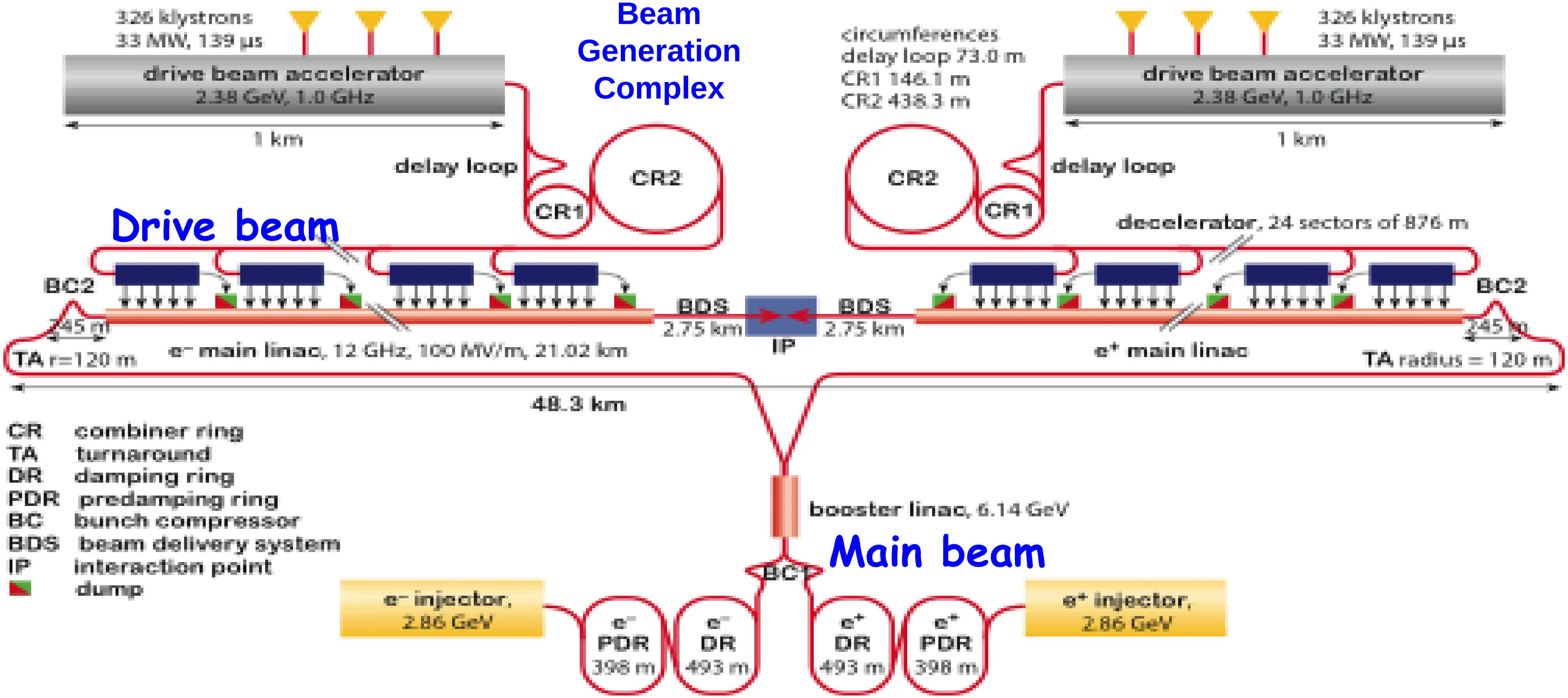
Drive Beam Generation Complex



Main Beam Generation Complex

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- ILC, the cold machine

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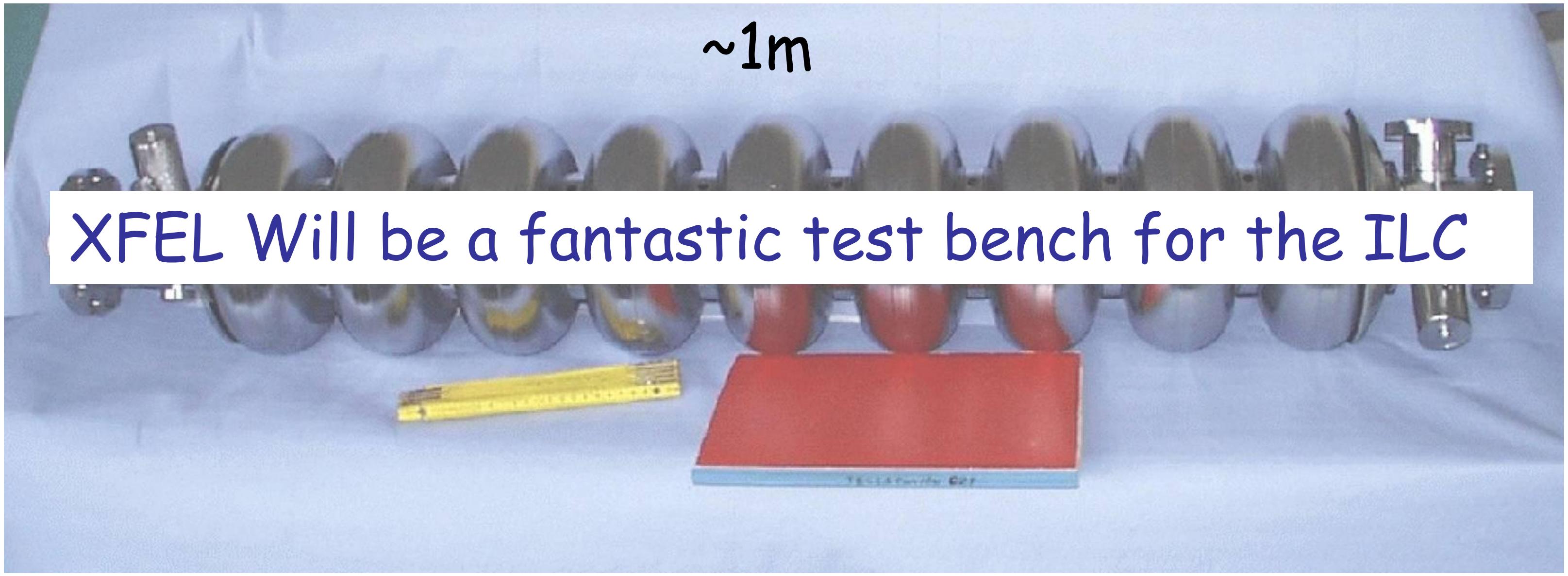
Technology : TESLA SCRF cavity



9-cell 1.3GHz Niobium Cavity

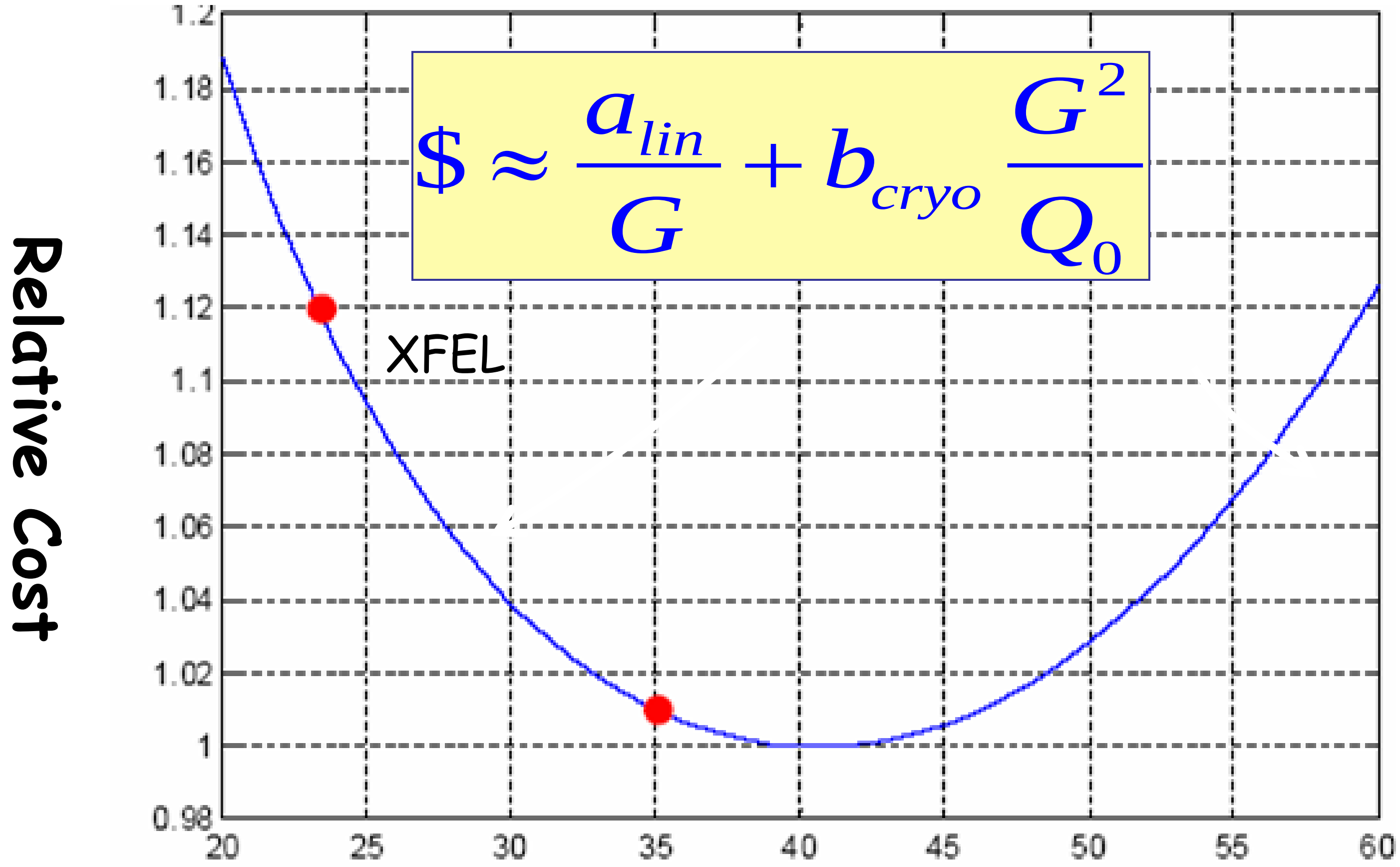
Reference design: has not been modified in 10 years

Cavities have been produced in industry & tested. World program

Challenge: produce in other parts of world in industry & develop critical processing procedures.

Major worldwide goal: make cleaning and resulting gradient consistent.

Why so important?
How Costs Scale with Gradient?



C. Adolphsen (SLAC)

Gradient MV/m

35MV/m is close to optimum

Japanese are still pushing for 40-45MV/m

30 MV/m would give safety margin

XFEL@DESY

XFEL project@ DESY:
-17.5 / 20 GeV beam for XFEL radiation
-SC Technology
-Gradient 23 MV/m
-1.3 GHz @ 10Hz, 1.4ms x 3000 bunches
-1 nC @ 1.4 mm mrad (normalised)

It is an incredible test facility for the ILC

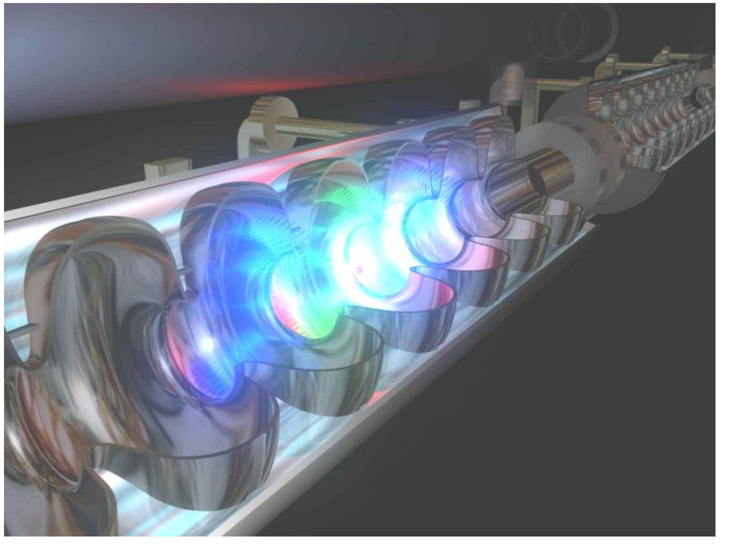
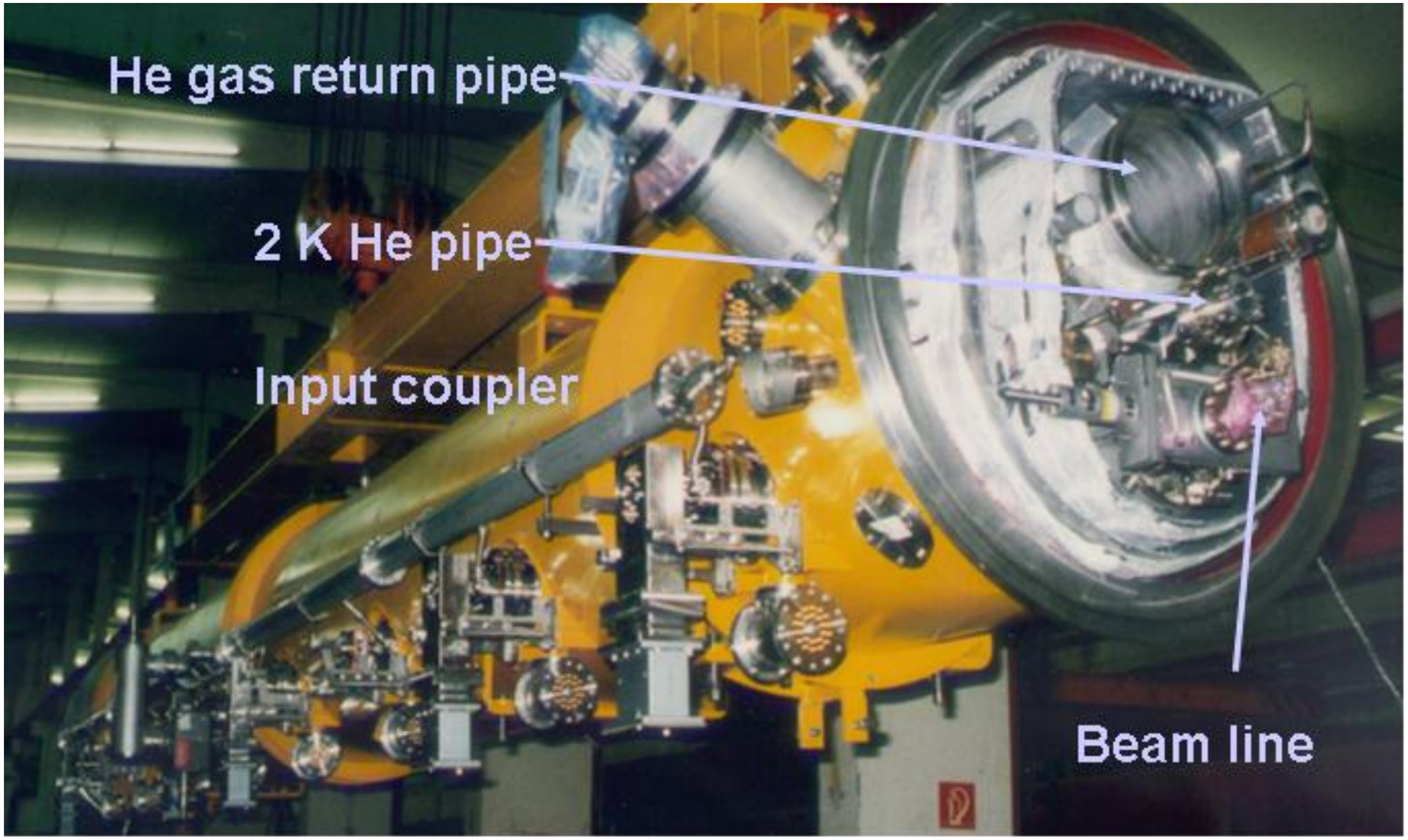


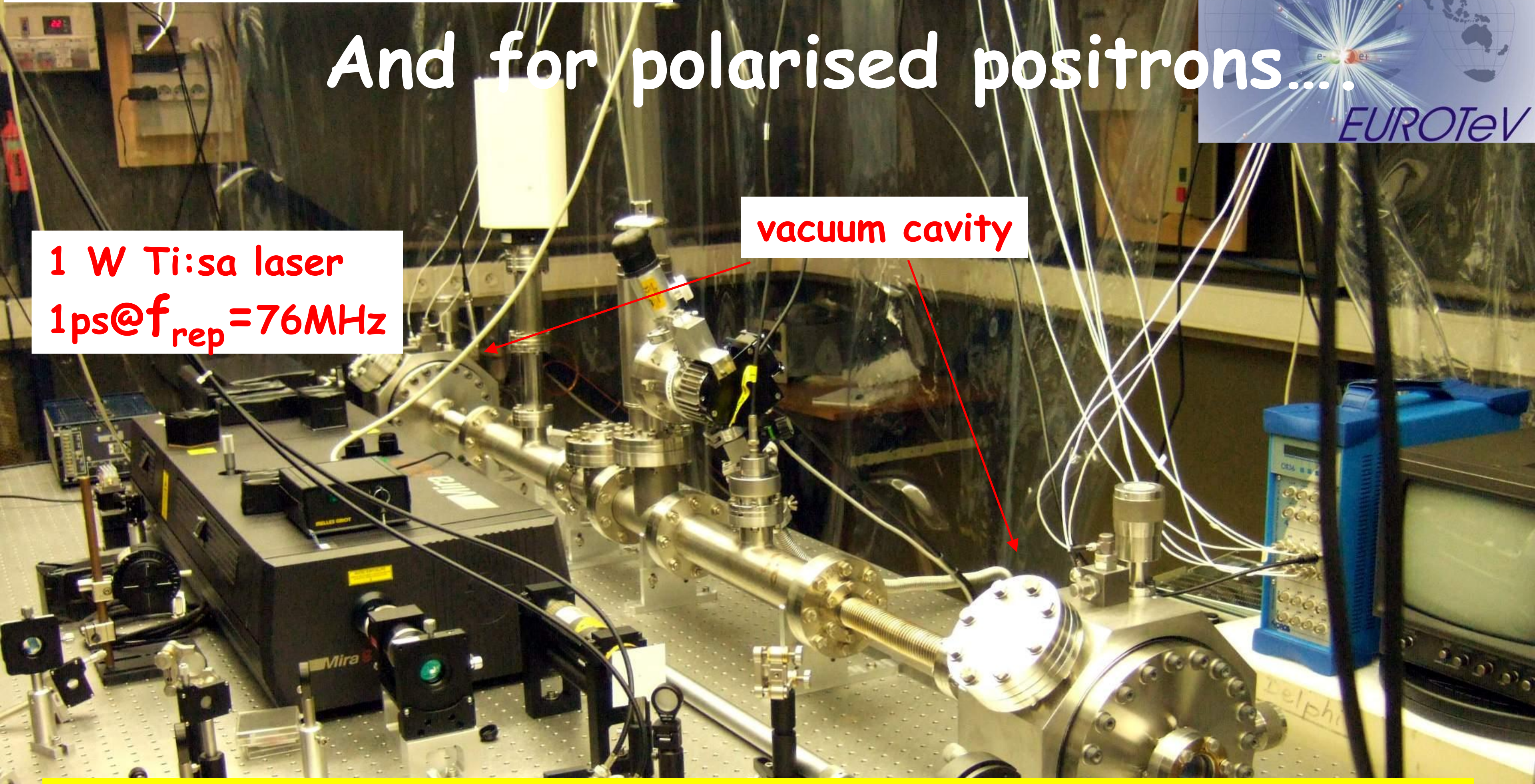
Image of a real cryomodule at DESY



Cryomodule with only 4 cavities. To tune the cavity : Tuners (CEA)

R&D setup at LAL/Orsay, F.ZOMER

And for polarised positrons….



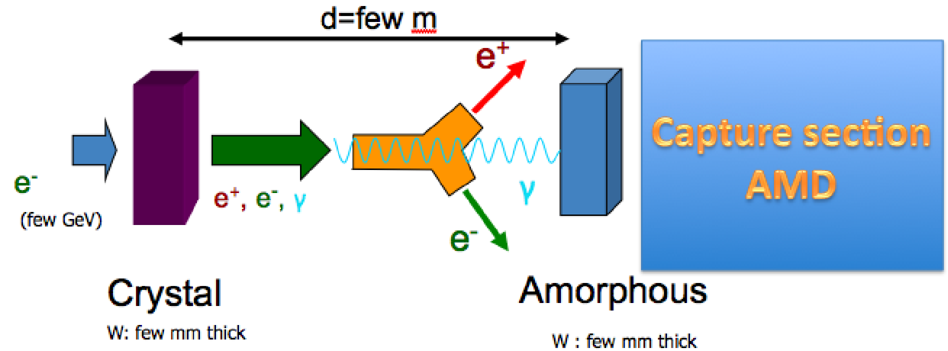
Status: cavity locked (low gain ~10000), world record!!!!

- **Digital feedback (VHDL programming) set up**
- **Already, stable $\Delta f_{rep}/f_{rep}=10^{-10}$ ➔ Δf_{rep}=30mHz for frep=76MHz**

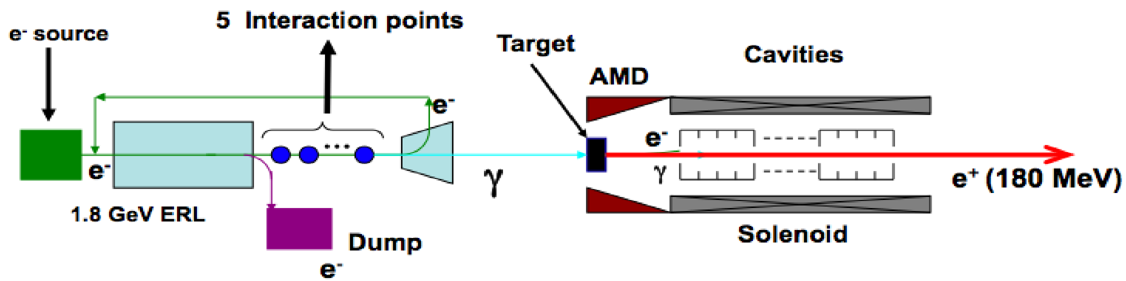
Positrons sources studies

Geant4 target simulation

- Hybrid : CLIC baseline



- Compton (polarized):ILC(alternative), CLIC&SuperB (baseline)

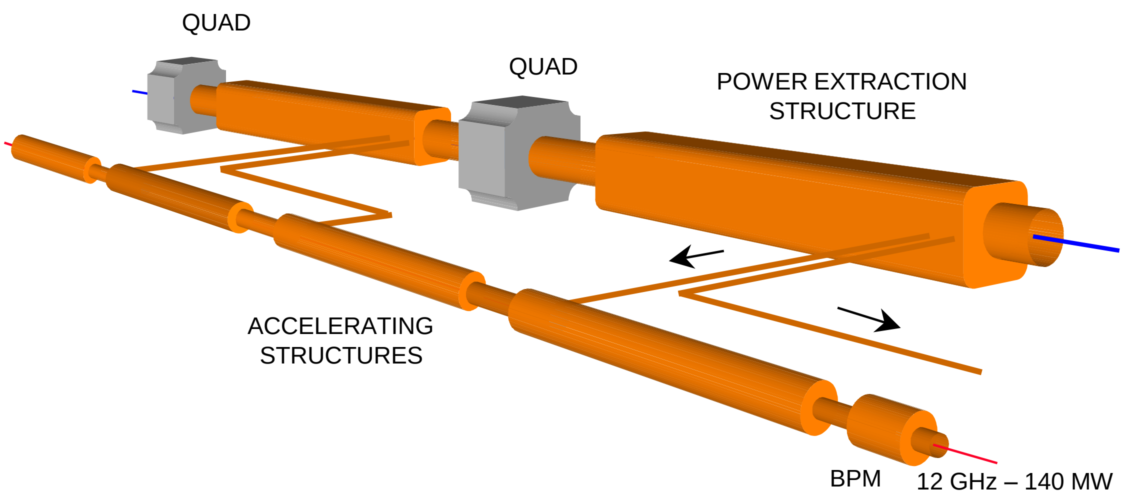


- Bremsstrahlung (polarized)
  - Polarized electron (E~50 MeV) impinging on a amorphous target to produce polarized positron
  - Start to study this alternative for SuperB

- CLIC : The warm technology…
- Relativistic klystron

CLIC

- needed to build multi-TeV linear collider:
- High acceleration gradient
  - "Compact" collider – total length < 50 km
  - Normal conducting acceleration structures
  - High acceleration frequency
- Two-Beam Acceleration Scheme
  - Cost effective, reliable, efficient
  - Simple tunnel, no active elements
  - Modular, easy energy upgrade in stages



Drive beam - 95 A, 300 ns
from 2.4 GeV to 240 MeV

Main beam – 1 A, 200 ns
from 9 GeV to 1.5 TeV

CLIC main parameters

Center-of-mass energy	CLIC 500 GeV		CLIC 3 TeV	
Beam parameters	Relaxed	Nominal	Relaxed	Nominal
Accelerating structure	502		G	
Total (Peak 1%) luminosity	$8.8(5.8)\cdot10^{33}$	$2.3(1.4)\cdot10^{34}$	$7.3(3.5)\cdot10^{33}$	$5.9(2.0)\cdot10^{34}$
Repetition rate (Hz)	50			
Loaded accel. gradient MV/m	80		100	
Main linac RF frequency GHz	12			
Bunch charge10^9	6.8		3.72	
Bunch separation (ns)	0.5			
Beam pulse duration (ns)	177		156	
Beam power/beam MWatts	4.9		14	
Hor./vert. norm. emitt ($10^{-6}/10^{-9}$)	7.5/40	4.8/25	7.5/40	0.66/20
Hor/Vert FF focusing (mm)	4/0.4	4 / 0.1	4/0.4	4 / 0.1
Hor./vert. IP beam size (nm)	248 / 5.7	202 / 2.3	101/3.3	40 / 1
Hadronic events/crossing at IP	0.07	0.19	0.28	2.7
Coherent pairs at IP	10	100	$2.5\ 10^7$	$3.8\ 10^8$
BDS length (km)	1.87		2.75	
Total site length km	13.0		48.3	
Wall plug to beam transfert eff	7.5%		6.8%	
Total power consumption MW	129.4		415	

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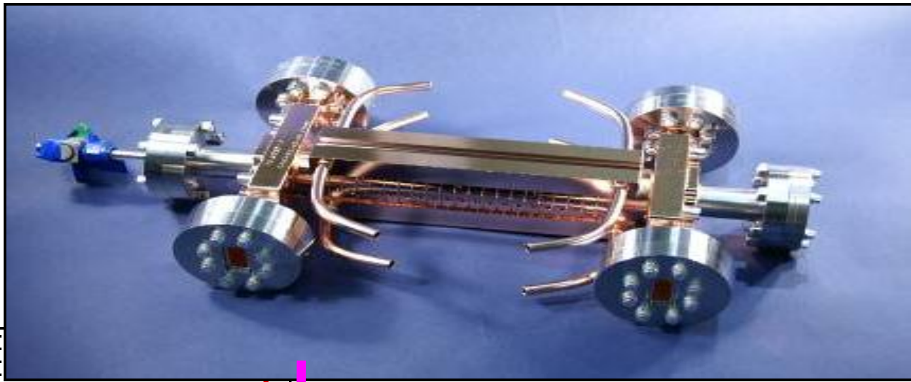
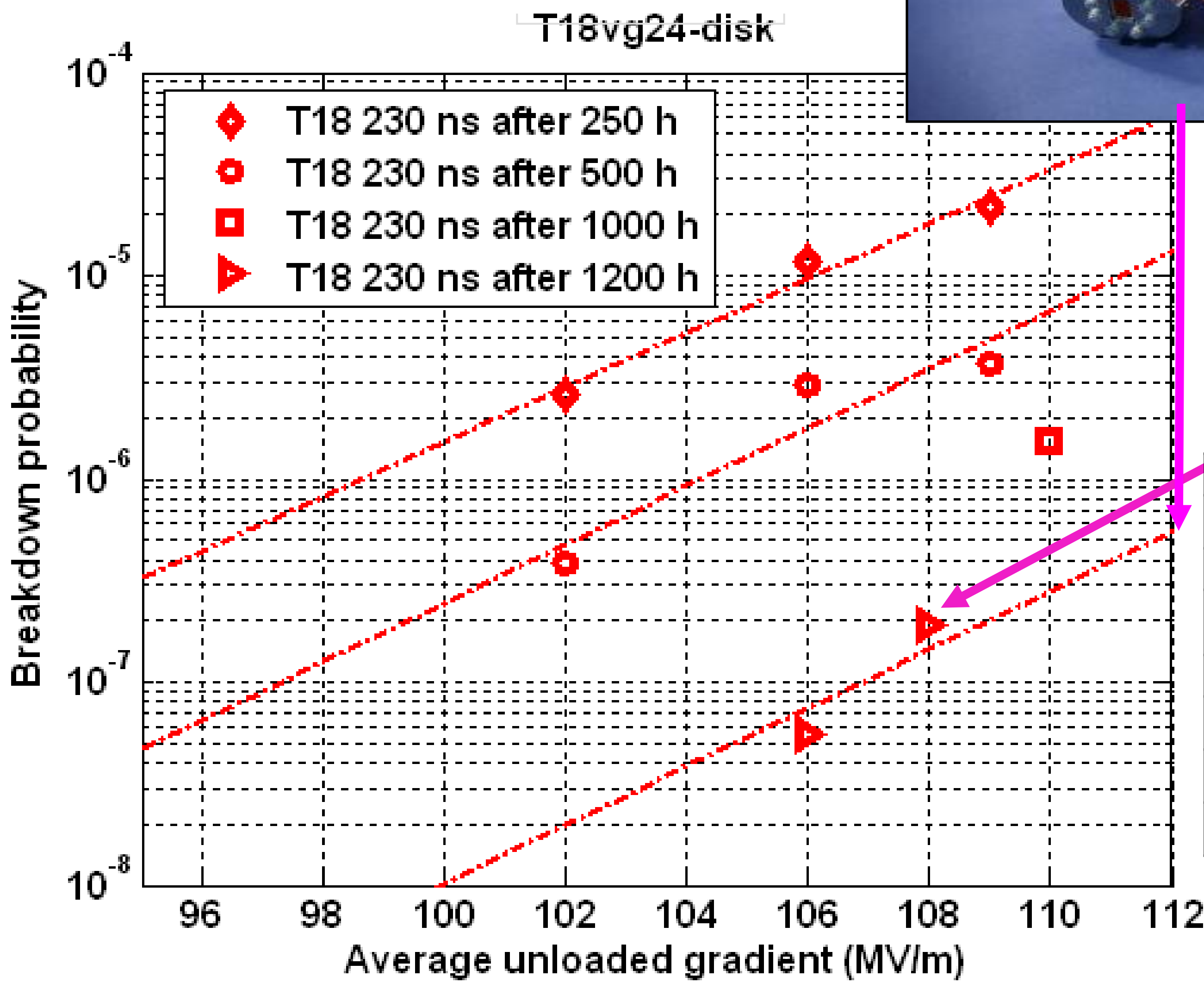
Nominal Structure Performance demonstrated

T18_VG2.4_disk: (without damping) *Designed at CERN, Built at KEK, RF Tested at SLAC*





Improvement by RF conditionning

CLIC nominal

Frequency:	11.424 GHz
Cells:	18+2 matching cells
Filling Time:	36 ns
Length: active acceleration	18 cm
Iris Dia. a/λ	0.155~0.10
Group Velocity: vg/c	2.6-1.0 %
Phase Advace Per Cell	2π/3
Power for <Ea>=100MV/m	55.5 MW

W.Wuensch & S.Doebert

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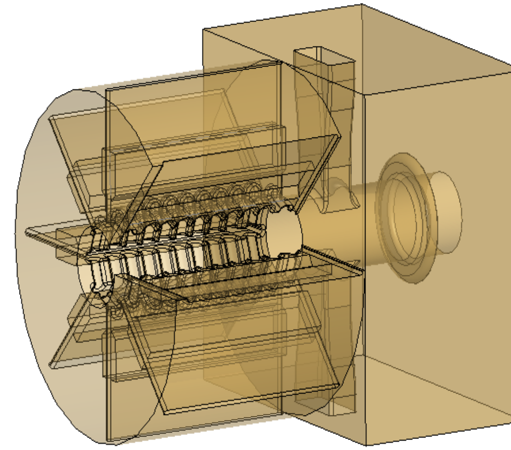
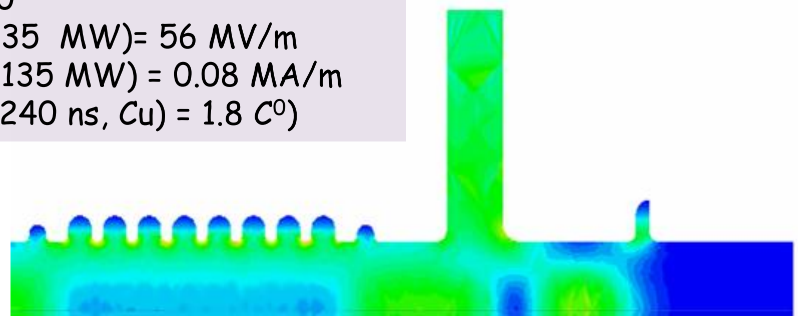
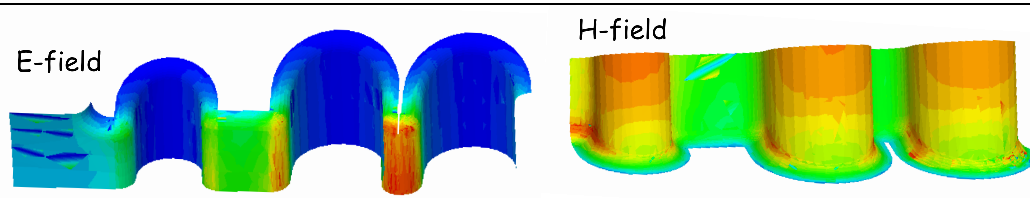
CLIC Power Extraction and Transfer Structure (PETS)

PETS parameters:
- Aperture = 23 mm
- Period = 6.253 mm (90^0/cell)
- Iris thickness = 2 mm
- R/Q = 2258 Ω
- V group= 0.453
- Q = 7200
- E surf. (135 MW)= 56 MV/m
- H surf. (135 MW) = 0.08 MA/m

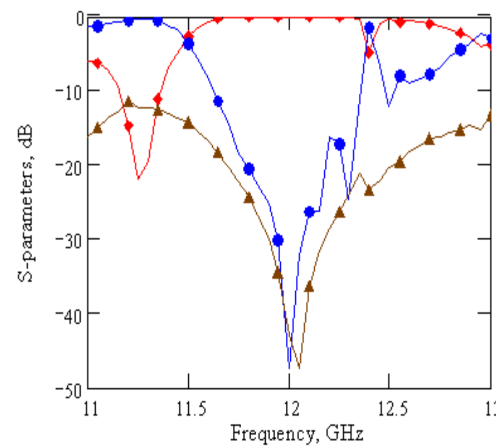
(ΔT max (240 ns, Cu) = 1.8 C^0)

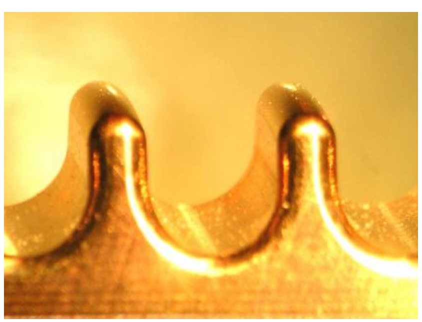






To reduce the surface field concentration in the presence of the damping slot, the special profiling of the iris was adopted.





PETS at 11.4 GHz
L = 300 mm
Tested at SLAC

PETS at 12 GHz
L = 1000 mm
Tested in the CTF3/TBTS

Another example of French technology. Nanometer Stabilisation LAPP Annecy (A.Jeremie)

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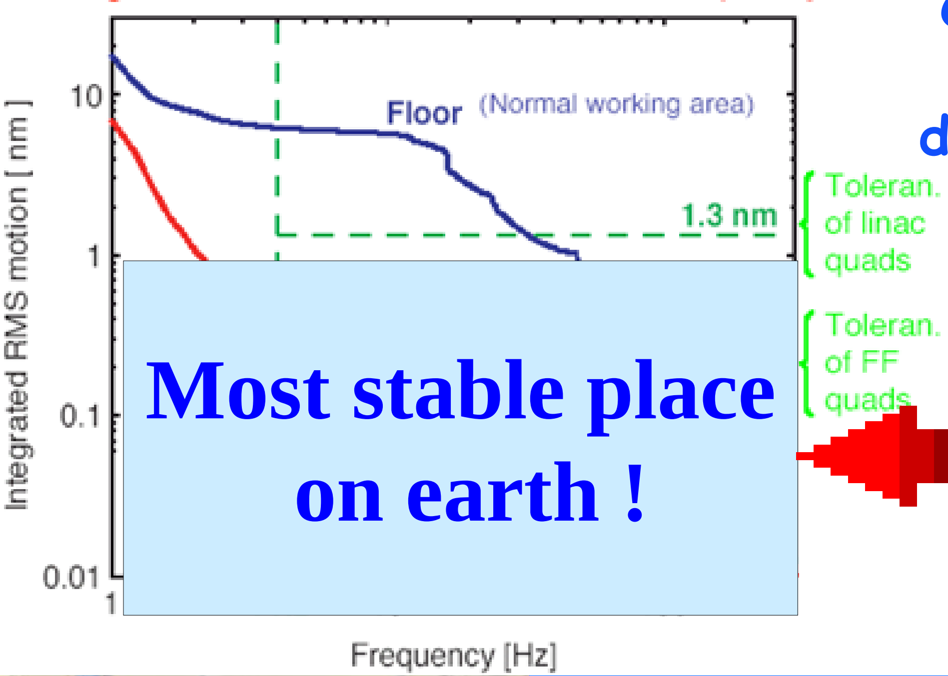
Integrated *vertical* RMS motion versus frequency



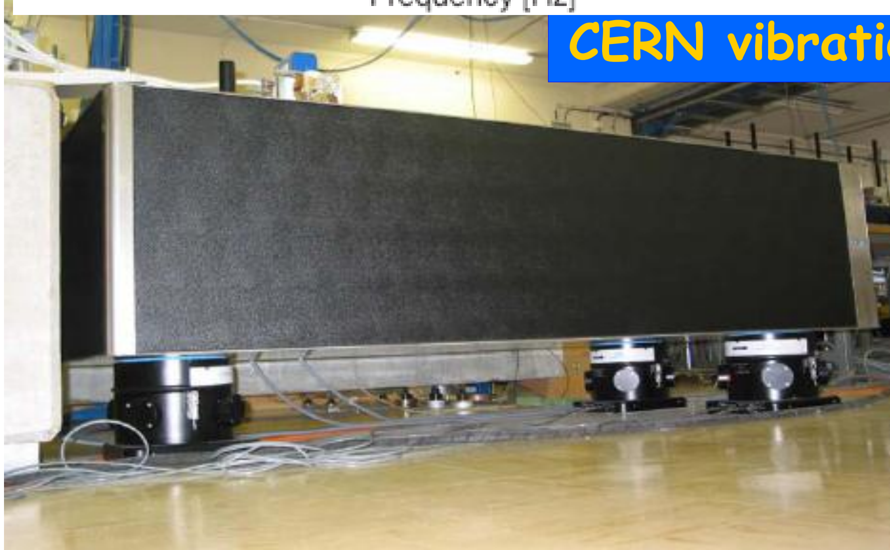
Most stable place on earth !

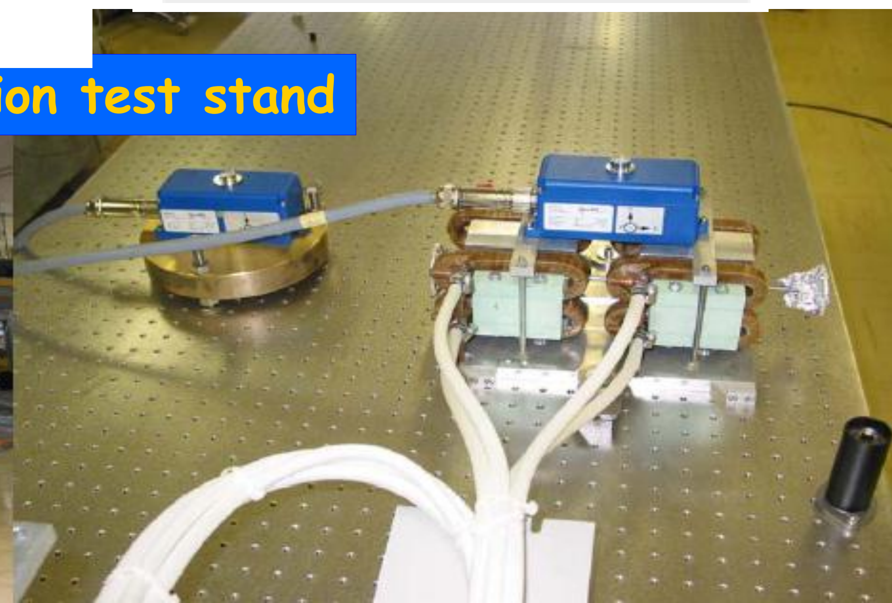
CLIC small quadrupole stabilised to nanometer level by active damping of natural floor vibration

RMS vibrations above 4 Hz

	Quad [nm]	Ground [nm]
Vertical	0.43	6.20
Horizontal	0.79	3.04
Longitud.	4.29	4.32

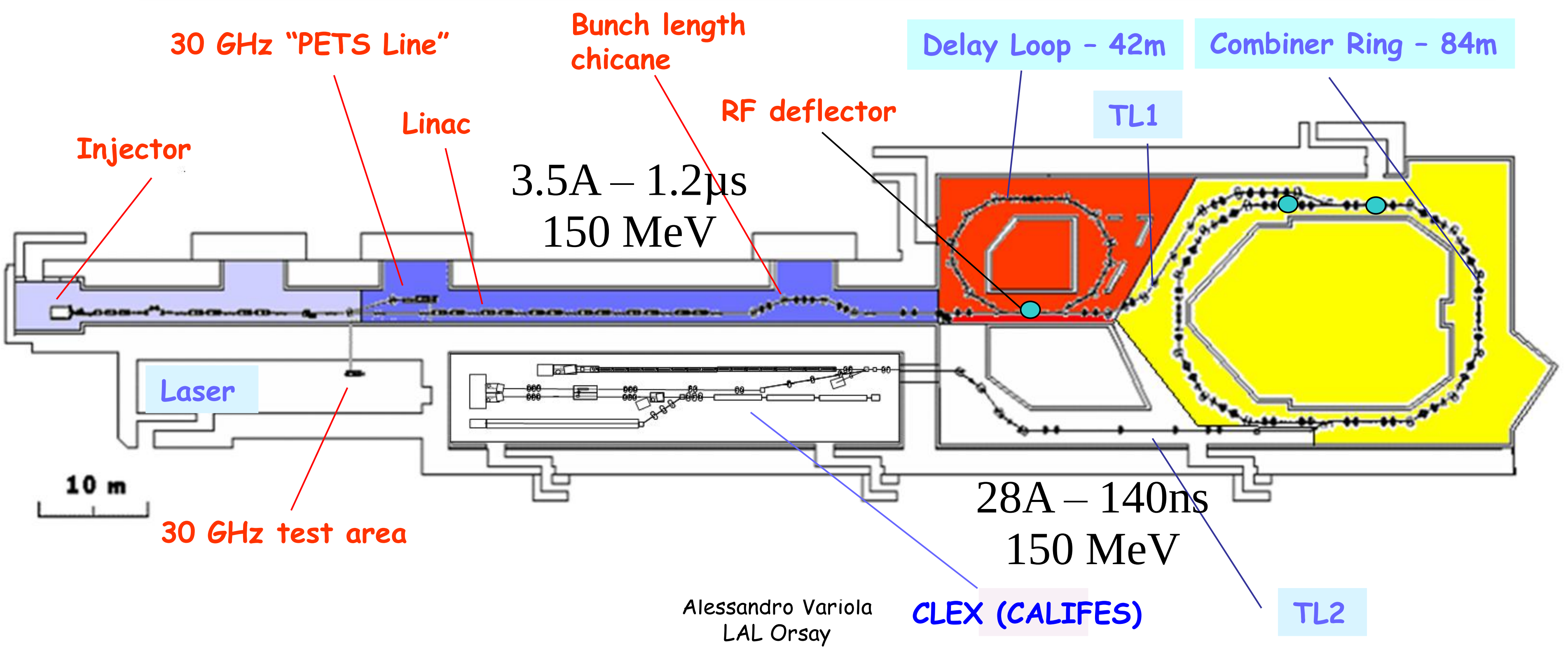
CERN vibration test stand





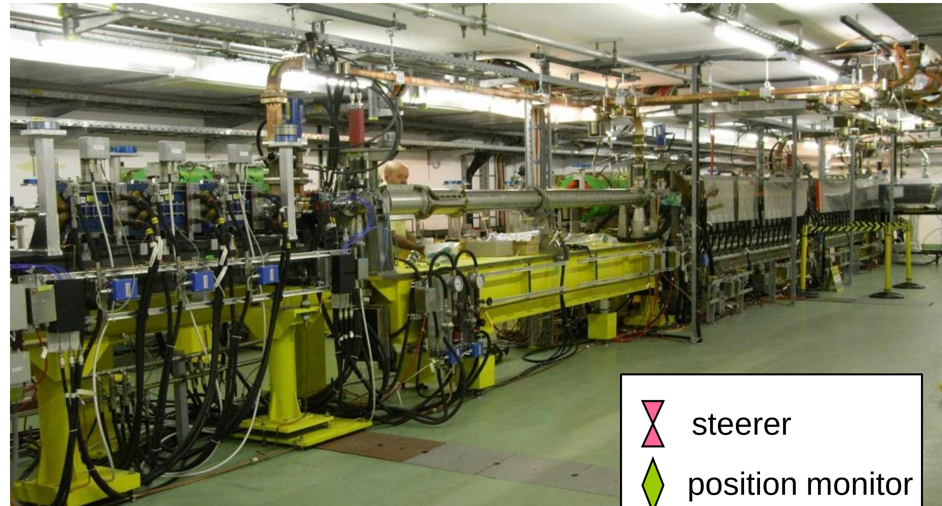
CTF 3 - CLIC Test Facility

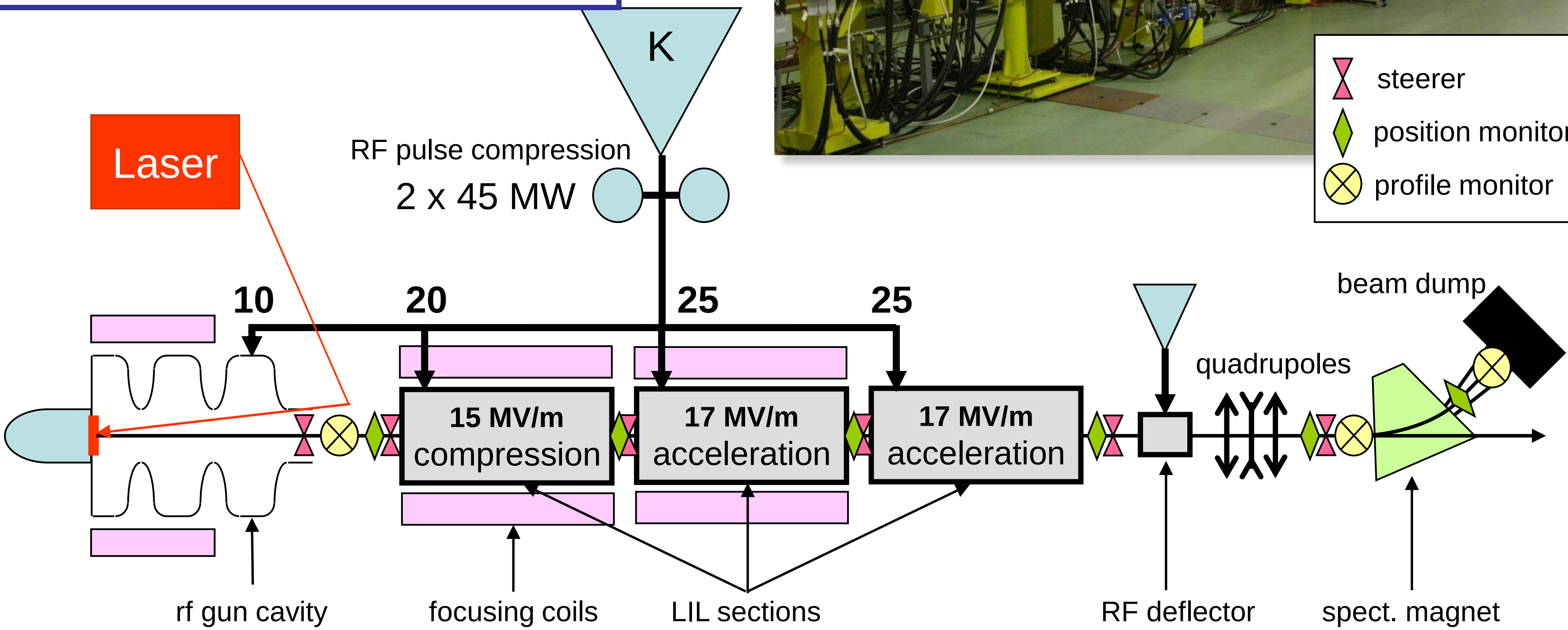
- demonstrate CLIC RF power source Drive Beam generation (fully loaded acceleration, bunch frequency multiplication 8x)
- Test CLIC accelerating structures
- Test power production structures (PETS)



Probe Beam - CALIFES

180 MeV
bunch charge 0.6 nC
number of bunches 1 – 32, 226





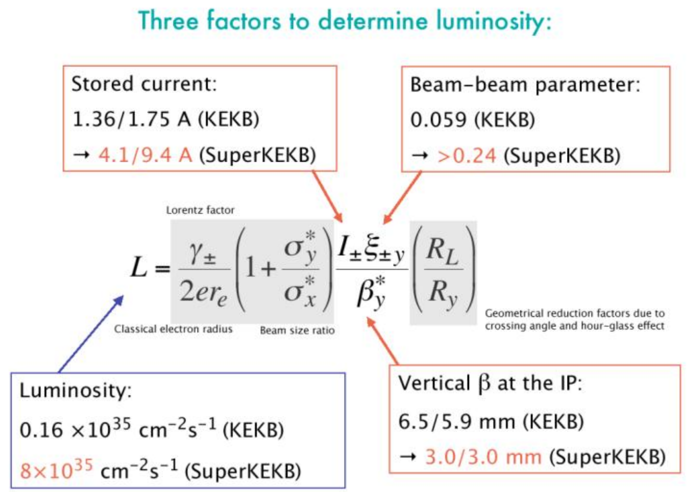
BY LAL

Alessandro Variola
LAL Orsay

- The luminosity Frontier
- SuperB factory and Dafne tests

Basic concepts

- B-factories already attain very high luminosity (~10^{34} s^{-1} cm^{-2}).
- To increase it by ~ two orders of magnitude (KeKB-SuperKeKB) it is possible to extrapolate the requirements from the current machines:

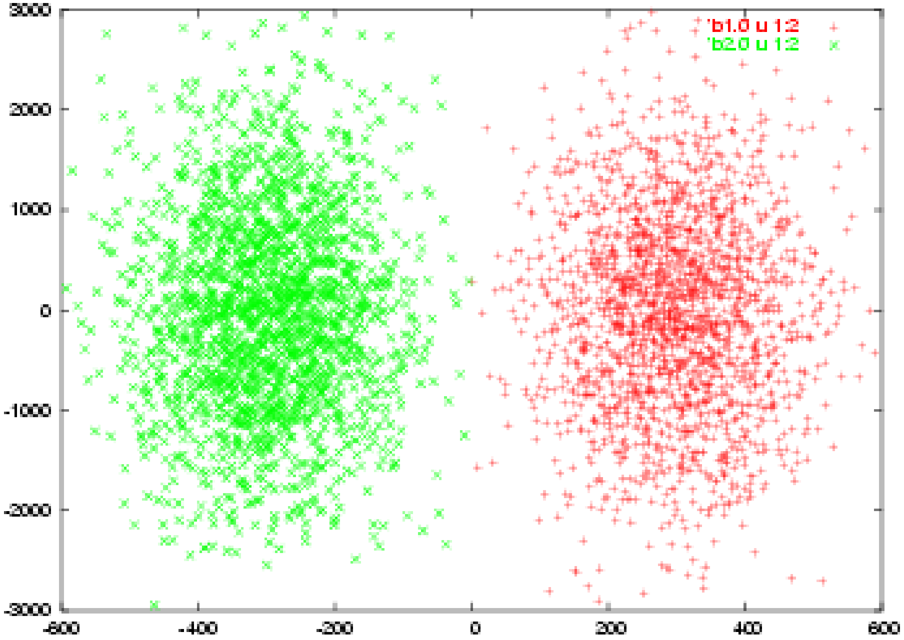


Parameters :

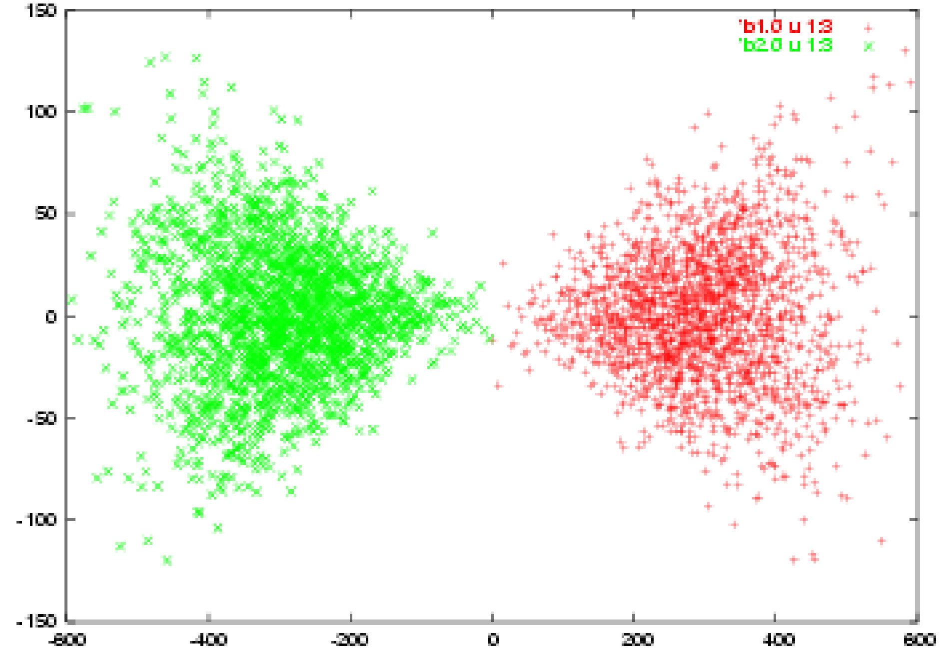
- Higher currents
- Smaller damping time (f(exp1/3))
- Shorter bunches
- Crab collision
- Higher Disruption
- Higher power
- SuperKeKB Proposal is based on these concepts

Increase in plug power ($$$$$..) and hard to operate (high current, short bunches)

Look for alternatives keeping constant the luminosity => new IP scheme: CRAB WAIST (P.Raimondi)



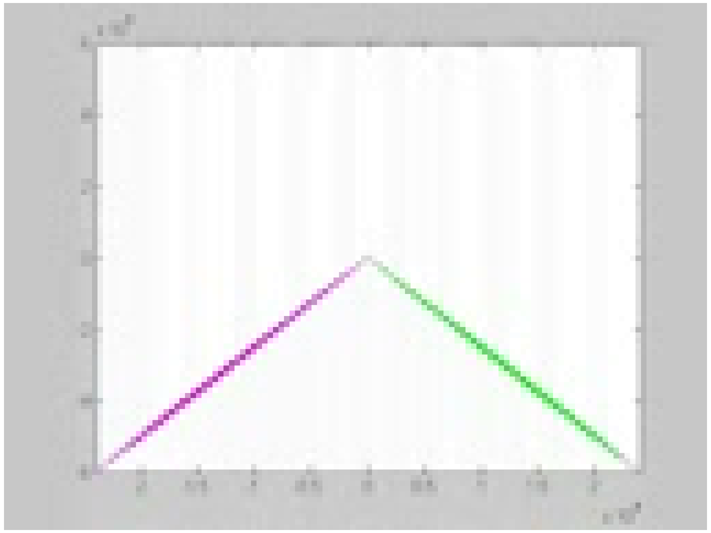
Horizontal Collision

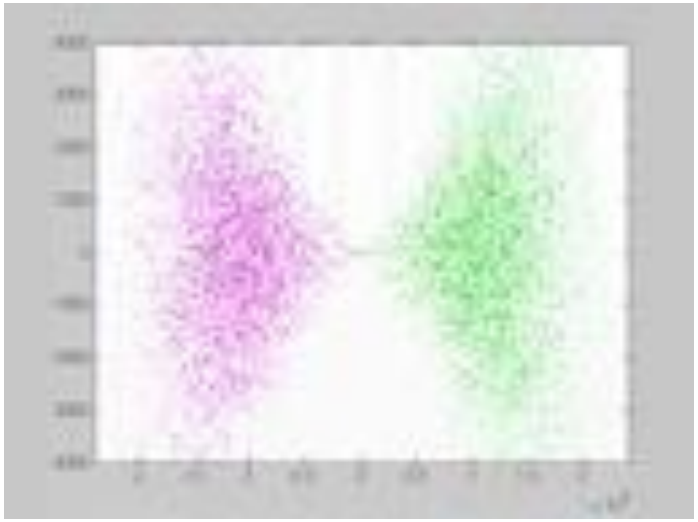


Vertical collision

First attempt without crab waist.
Relative Emittance growth per collision about 2.5*10-3
$\varepsilon_{yout}/\varepsilon_{yin}$= 200y/10x

Simulation by D.Schulte





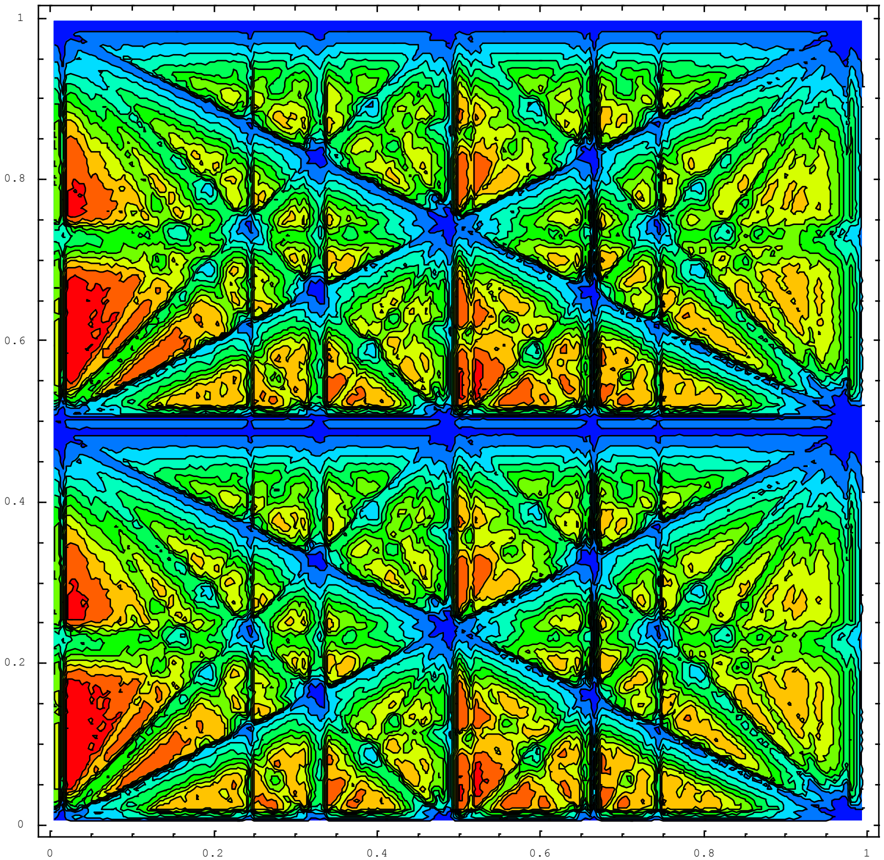
Horizontal Plane **Vertical Plane**

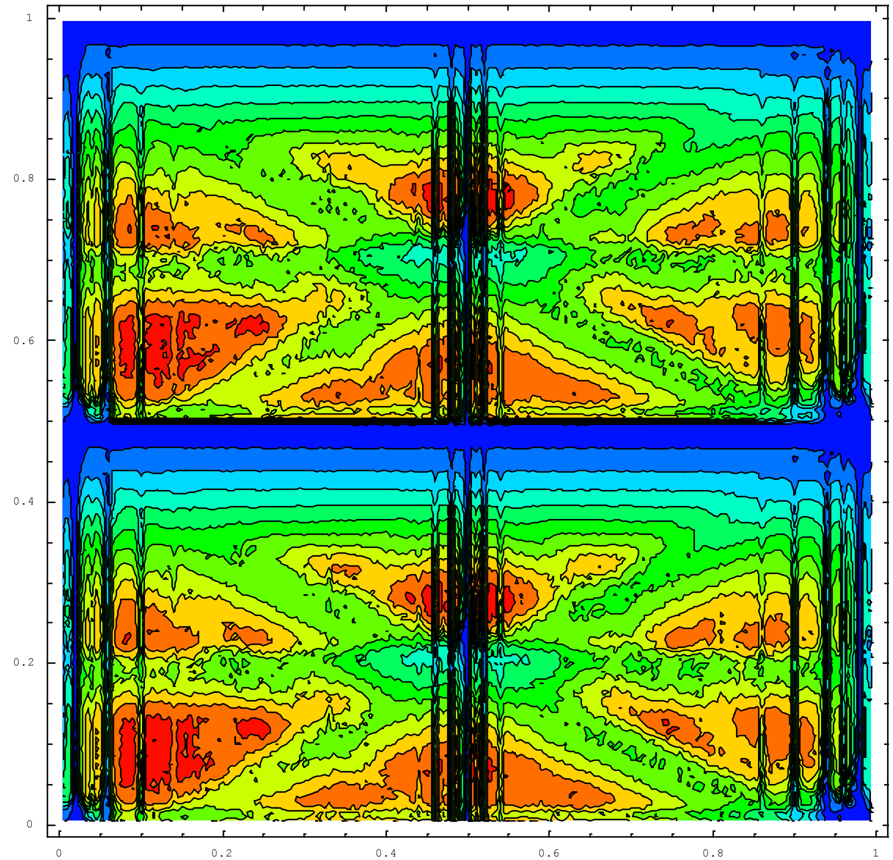
Another example: Collisions with uncompressed beams
Crossing angle = 2*25mrad.
Relative Emittance growth per collision about $2.5 \cdot 10^{-3}$
$\varepsilon_{yout}/\varepsilon_{yin}=1.0025$

Suppression x-y in LPA&CW

D.Shatilov's (BINP), ICFA08 Workshop

HIgh luminosity





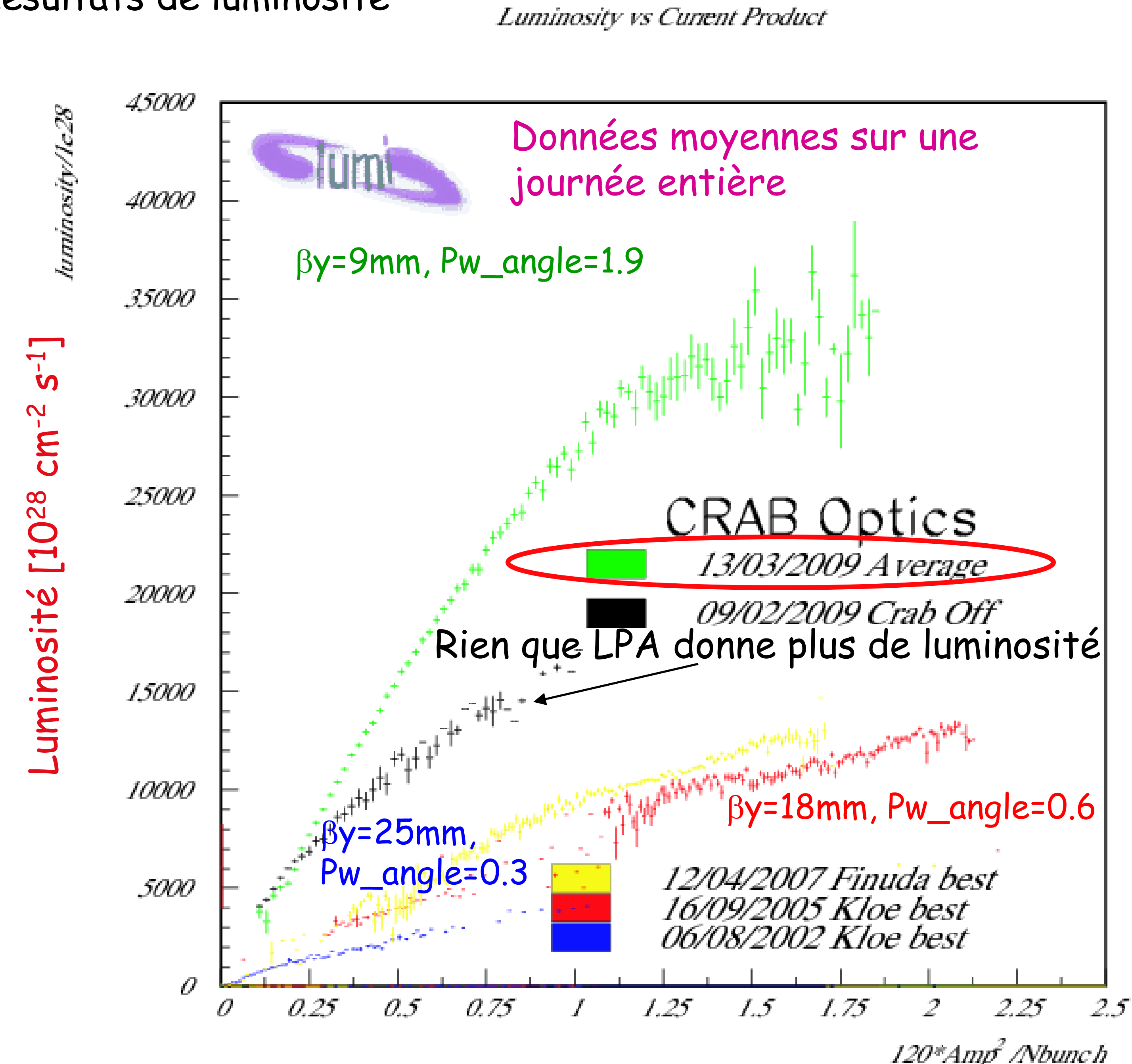
(KEKB, DAΦNE):

1. Low Piwinski angle $\Phi < 1$
2. $\beta_y \sim \sigma_z$

Avec Crab Waist :

1. Big Piwinski angle $>> 1$
2. $\beta_y \sim \sigma_x/\theta$

Résultats de luminosité

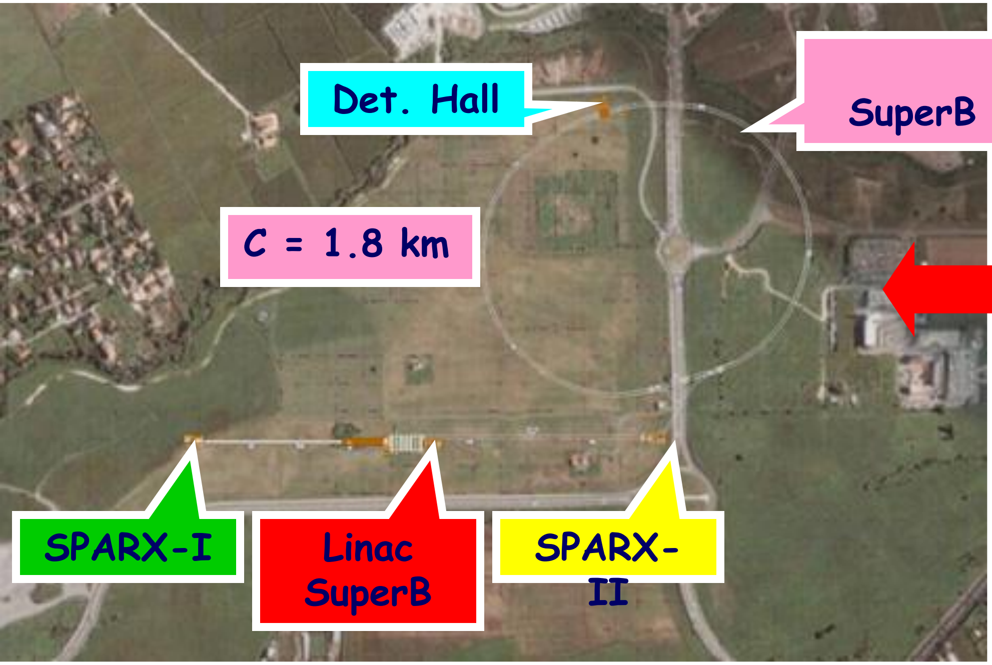


SuperB parameters flexibility

LER/HER	Unit	Juin 2008	Jan. 2009	Mars 2009	Version LNF
E+/E-	GeV	4/7	4/7	4/7	4/7
L	$cm^{-2}\ s^{-1}$	$1x10^{36}$	$1x10^{36}$	$1x10^{36}$	$1x10^{36}$
I^+/I^-	Amp	1.85 /1.85	2.00/2.00	2.80/2.80	2.70/2.70
N_{part}	$x10^{10}$	5.55 /5.55	6/6	4.37/4.37	4.53/4.53
N_{bun}		1250	1250	2400	1740
I_{bunch}	mA	1.48	1.6	1.17	1.6
$\theta/2$	mrad	25	30	30	30
β_x*	mm	35/20	35/20	35/20	35/20
β_y*	mm	0.22 /0.39	0.21 /0.37	0.21 /0.37	0.21 /0.37
ε_x	nm	2.8/1.6	2.8/1.6	2.8/1.6	2.8/1.6
ε_y	pm	7/4	7/4	7/4	7/4
σ_x	μm	9.9/5.7	9.9/5.7	9.9/5.7	9.9/5.7
σ_y	nm	39/39	38/38	38/38	38/38
σ_z	mm	5/5	5/5	5/5	5/5
ξ_x	X tune shift	0.007/0.002	0.005/0.0017	0.004/0.001 3	0.004/0.0013
ξ_y	Y tune shift	0.14 /0.14	0.125/0.126	0.091/0.092	0.094/0.095
Stations RF	LER/HER	5/6	5/6	5/8	6/9
Puissance RF	MW	16.2	18	25.5	30.
Circonférence	m	1800	1800	1800	1400

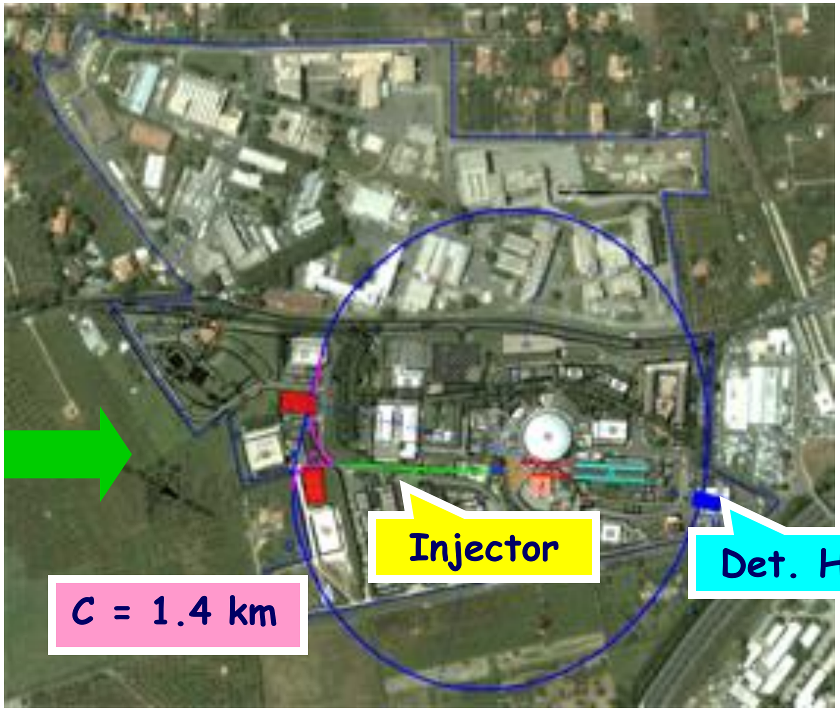
S. Tomassini

SuperB site



Tor Vergata :
- zone verte
- synergies with SPARX-FEL

LNF :
- infrastructures
- synergies with the SPARX-FEL

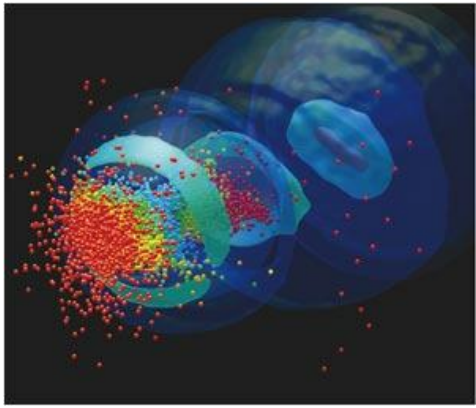


- WHAT'S NEXT?

Plasma acceleration

- If the e.m. cavity is replaced by something that can not be damaged, much higher accelerating gradients can be reached.
- This can be done by creating a wakefield in a plasma.
- Different tools are used to create such plasma accelerator:
  - Lasers (Tajima and Dawson, PRL, 1979)
  - Electron beams (Hogan et al., PRL, 2005)
  - Proton beams (Caldwell et al., Nature Phys., 2009)

Example of wakefield
Source: http://www.arwenmarine.com

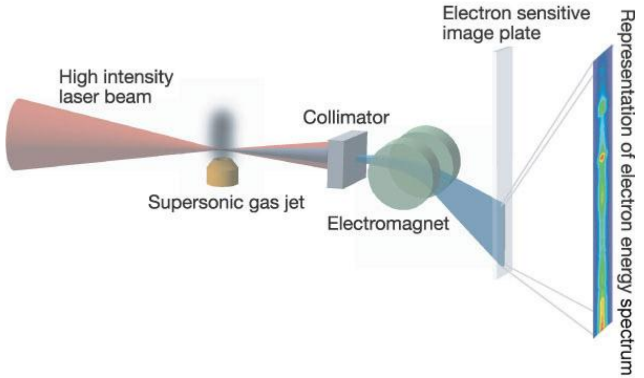


Wakefield in a plasma
Source: CERN Courier

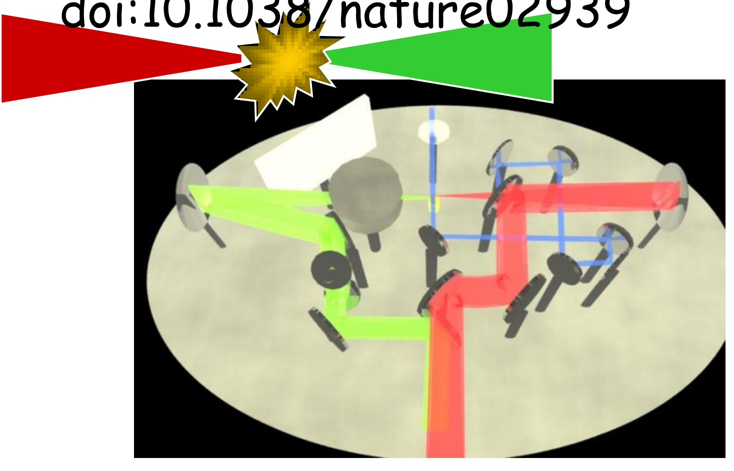
Laser-driven plasma acceleration

- First proposed in 1979 (Tajima and Dawson)
- In the 90s LULI demonstrated that injected electrons can be accelerated from 3 MeV to 4.5 MeV (Amarinoff et Al., PRL, 1998).
- Significant progress in 2004: Nature: "dream beam"
  - RAL/IC/UK: Mangles et al.
  - LOA/France: Faure et al.
  - LBNL/USA: C.G.R. Geddes et al.

Laser-driven plasma acceleration: "dream beam"



Mangles et al, doi:10.1038/nature02939

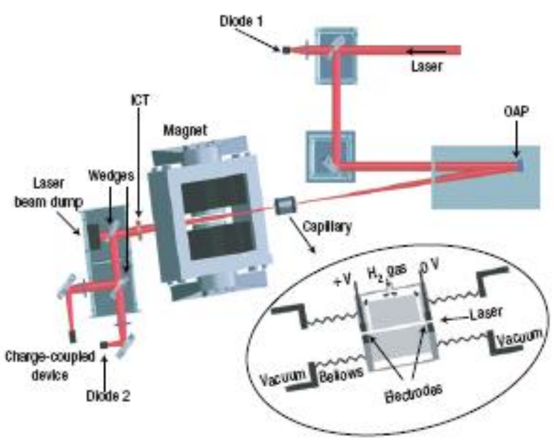


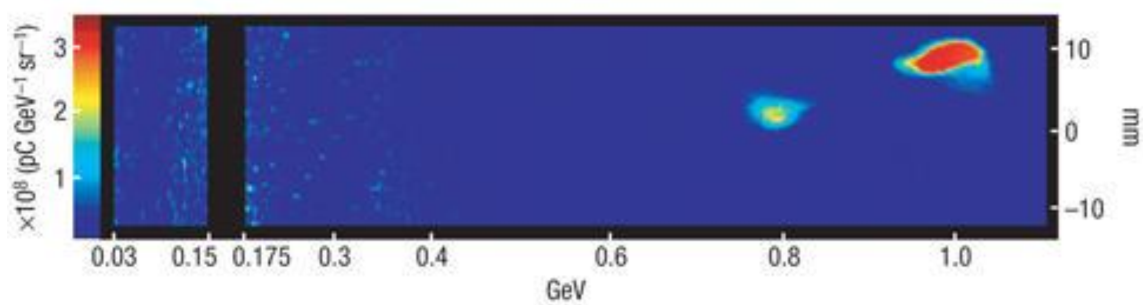
Faure et al., doi:10.108/nature05393

- In the "dream beam" experiments the plasma was created in a gas jet.
- In this case the electrons are taken from the ions inside the plasma.
- In 2008 a beam of 800 MeV was produced using this technique

GeV LPA beam

- Another breakthrough occurred in 2005 when a Berkeley + Oxford collaboration reached an energy of 1 GeV.
- To do so they used a 33mm long capillary to extend the length over which the plasma has the right properties to accelerate electrons.
- The field created during this experiment was of the order of 100 GV/m!

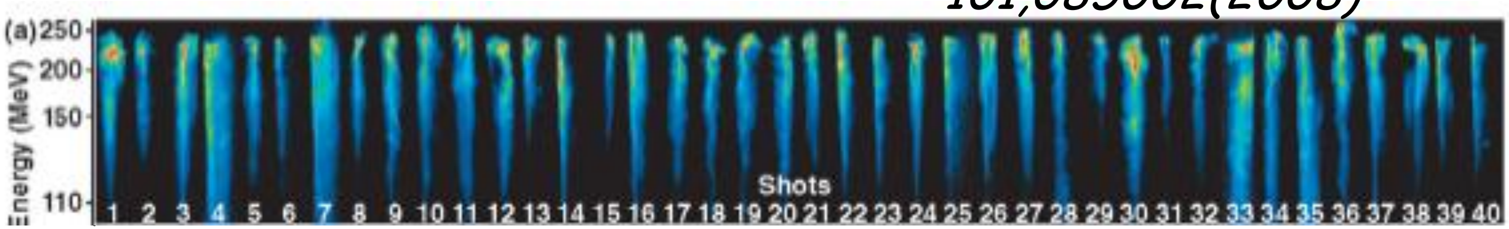




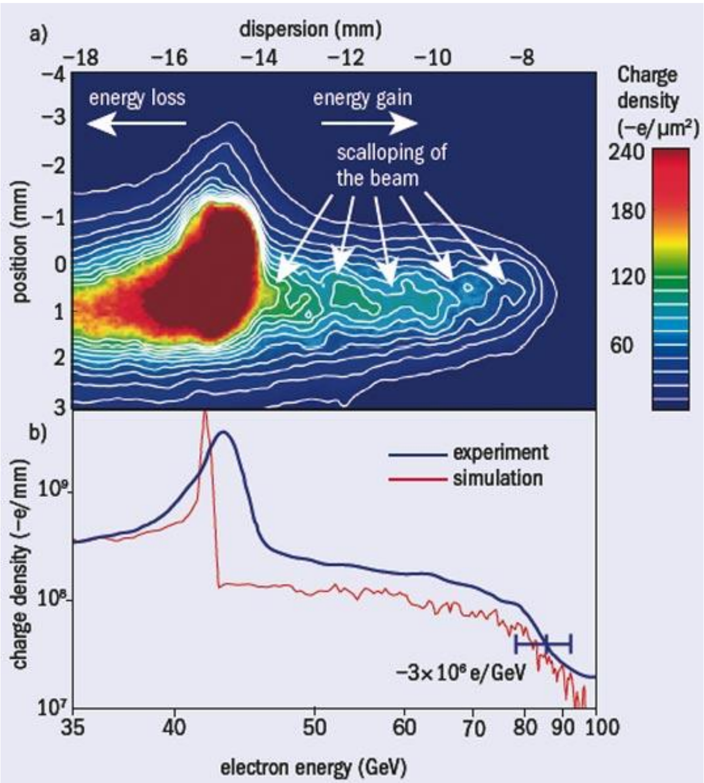
Typical features of LPA beams achieved so far

- Energy 50 MeV – 1 GeV
- Energy spread: from very large to a few percent
- Low repetition rate: 1Hz and less
  (eg: 1 shot every 20s at GEMINI)
- Low charge: 10-50pC
- Ultra-short pulses: 5-30fs (measure very difficult)
  => High peak current
- Shot to shot reproducibility is poor.
- Very small footprint for the "accelerator", laser included (few rooms).
- Simulations are difficult (particle in cell on large computers)
- Not all plasma acceleration experiments produce the beam predicted/expected…

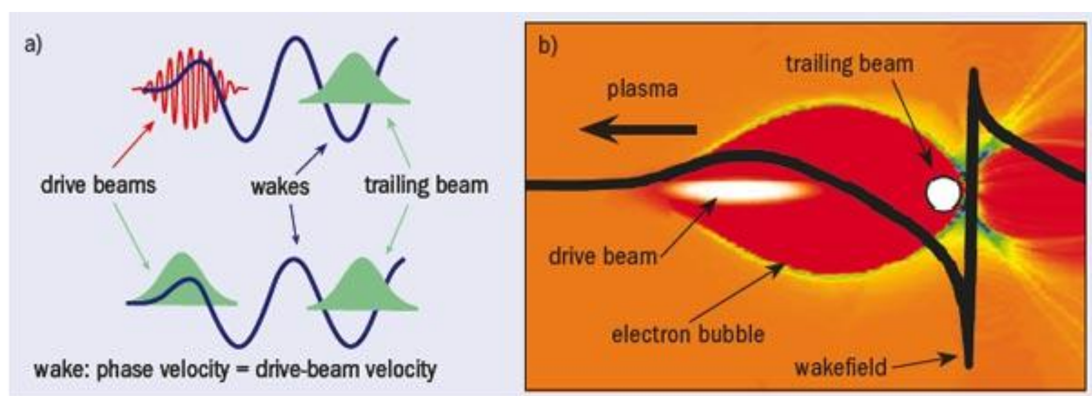
J.Osterhoff et al., PRL 101,085002(2008)



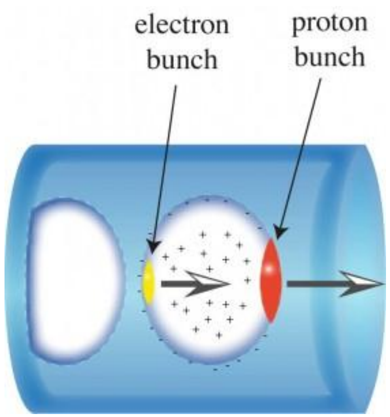
Electron driven plasma acceleration



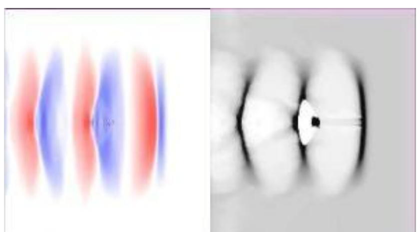
- Electrons can also be used to generate the wakefield required to accelerate other electrons.
- This has been demonstrated using the SLAC LINAC when the energy of some electrons of a bunch was doubled from 42 to 85 GeV.
- The field was about 50 GV/m.

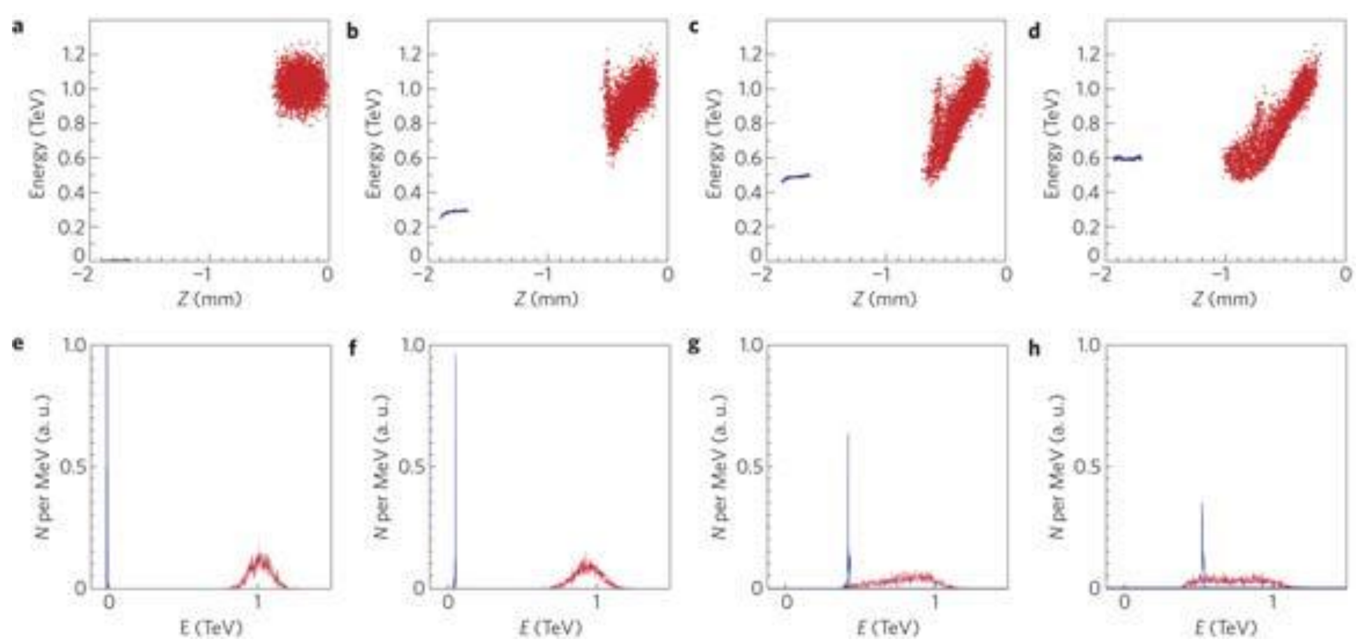


Proton driven plasma acceleration



- More recently there has been a proposal to use protons as drive beam to accelerate electrons.
- Simulations indicate that the CERN SPS beam could be used to accelerate electrons to 600 GeV.

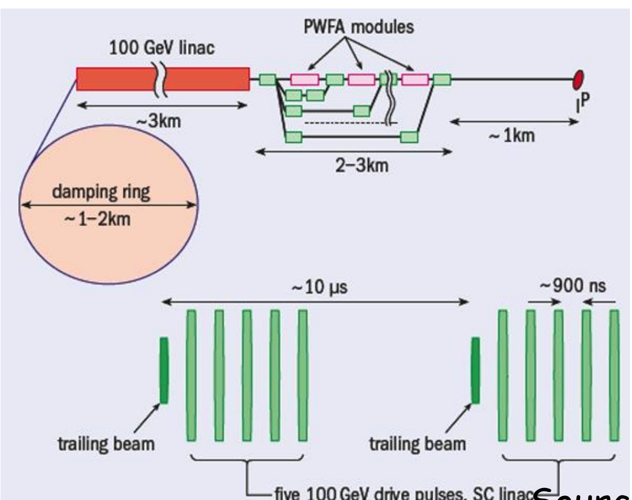




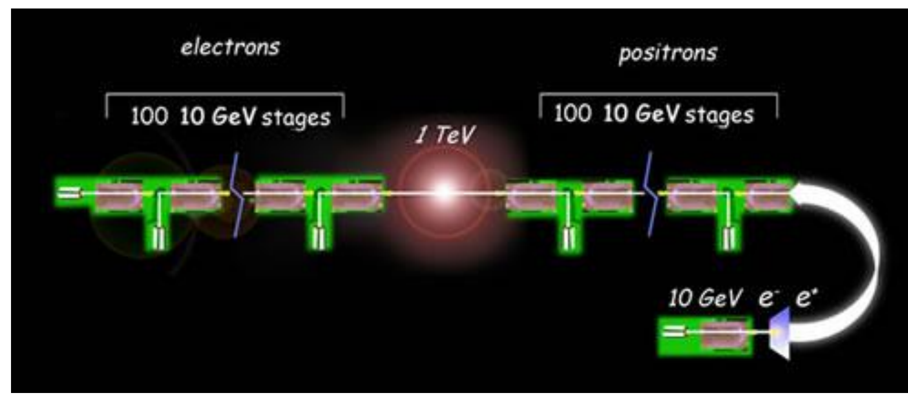
Caldwell et al., Nature Physics 5, 363 - 367 (2009)

Toward a plasma-based collider

- The next electron collider will require beams with an energy of between 500 GeV and a TeV.
- The production of such beam by a plasma-based collider has not yet been demonstrated, however there are proposal to stage several "accelerating sections" to achieve this.



Source:CERN Courier



Source:LBL

Limits

- Several important steps need to be made before such collider can be built.
- Plug to beam power efficiency is very low. In the case of laser-driven accelerators, fibre lasers may improve this but it may not be enough.
- Beam stability is another issue: at the moment each shot is different and goes in a slightly different direction…
- Very little is know about the quality (emittance) of such beam.

- Summary
- The future is wide and complex
- Based on technology but also ideas (crab waist docet)
- Amazing science
- Performances are at the limit of what we can imagine
- Accelerator will push the physics limits and discovery frontiers.
- THANK YOU

- Thanks to M Giovannozzi, J Brossard, F Zomer and N Delerue for the transparencies