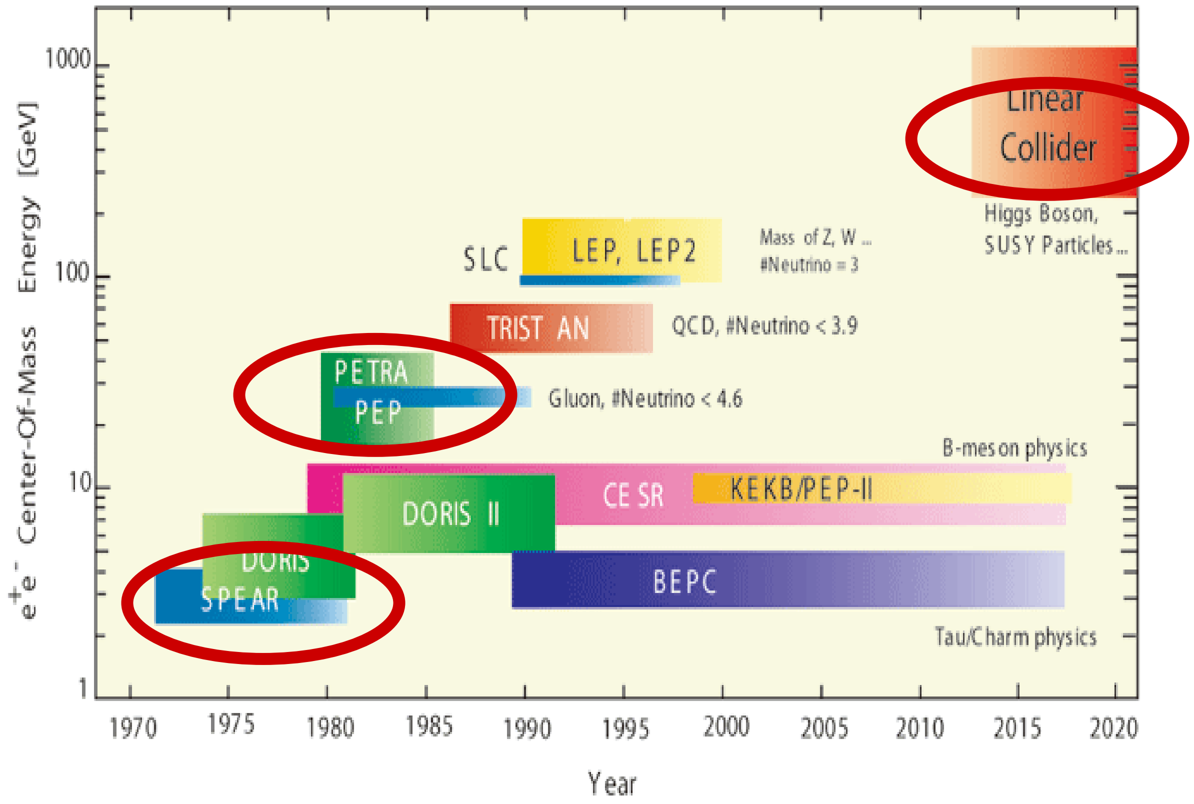
High Energy Frontier

Orsay Jan,30 2006

P. Raimondi

- ILC
- CLIC
- LHC Upgrade
- Muon Collider

Electron Positron Colliders
The Energy Frontier



Parameters for the ILC

- E_{cm} adjustable from 200 – 500 GeV
- Luminosity → $\int L dt$ = 500 fb^{-1} in 4 years
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarization of at least 80%

- The machine must be upgradeable to 1 TeV

A TeV Scale e^+e^- Accelerator?

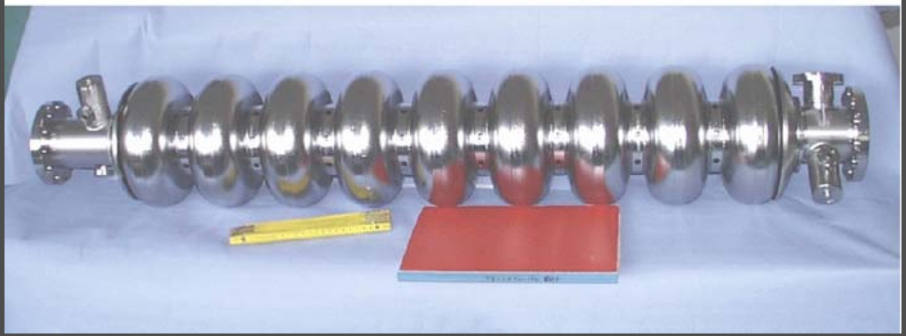
- Two parallel developments over the past few years (the science & the technology)

  - Two alternate designs -- “warm” and “cold” had come to the stage where the show stoppers had been eliminated and the concepts were well understood.

  - A major step toward a new international machine requires uniting behind one technology, and then make a unified global design based on the recommended technology.

The ITRP Recommendation

- We recommend that the linear collider be based on superconducting rf technology



  - This recommendation is made with the understanding that we are recommending a technology, not a design. We expect the final design to be developed by a team drawn from the combined warm and cold linear collider communities, taking full advantage of the experience and expertise of both (from the Executive Summary).

SCRF Technology Recommendation

- The recommendation of ITRP was presented to ILCSC & ICFA on August 19, 2004 in a joint meeting in Beijing.

- ICFA unanimously endorsed the ITRP's recommendation on August 20, 2004

Start of the Global Design Initiative

INTERNATIONAL ILC WORKSHOP

First ILC Workshop

Towards an International Design of a Linear Collider

November 13th (Sat) through 15th (Mon), 2004

KEK, High Energy Accelerator Research Organization
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Program Committee:
Kaoru Yokoya (KEK), Hitoshi Hayano (KEK),
Kenji Saito (KEK), David Burke (SLAC),
Steve Holmes (FNAL), Gerald Dugan (Cornell),
Nick Walker (DESY), Jean-Pierre Delahaye (CERN),
Olivier Napoly (CEA/Saclay)

Nov 13-15, 2004

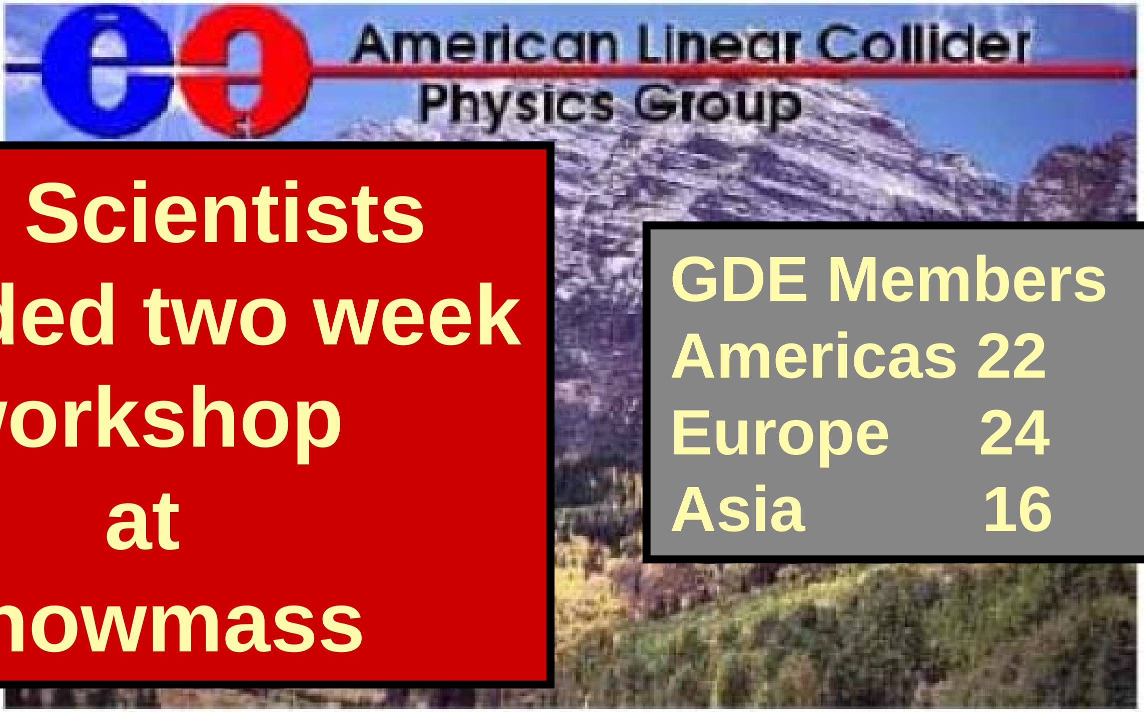
~ 220 participants from 3 regions, most of them accelerator experts

The Mission of the GDE

Produce a design for the ILC that includes a detailed design concept, performance assessments, reliable international costing, an industrialization plan , siting analysis, as well as detector concepts and scope.

Coordinate worldwide prioritized proposal driven R & D efforts (to demonstrate and improve the performance, reduce the costs, attain the required reliability, etc.)

GDE Begins at Snowmass



670 Scientists attended two week workshop at Snowmass

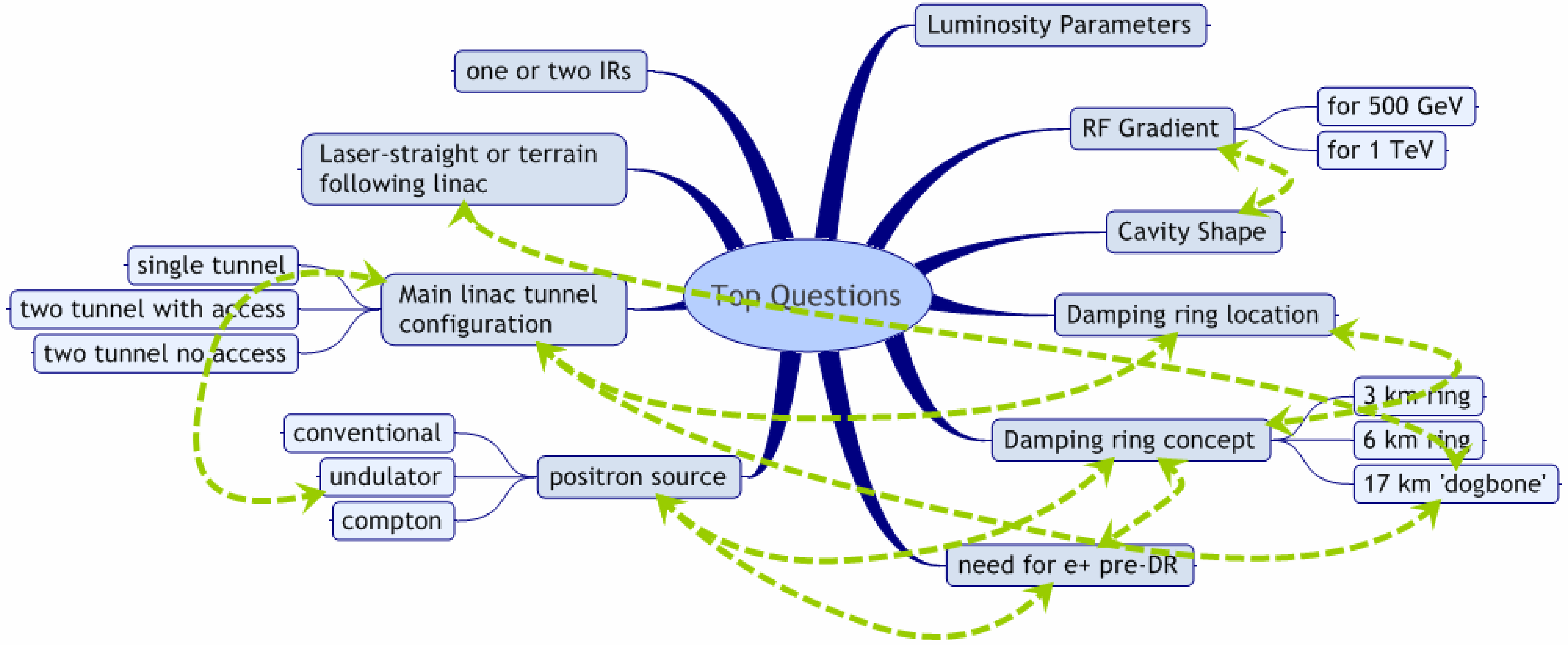
GDE Members	
Americas	22
Europe	24
Asia	16

2005 International Linear Collider Physics and Detector Workshop
and Second ILC Accelerator Workshop
Snowmass, Colorado, August 14-27, 2005

Design Approach

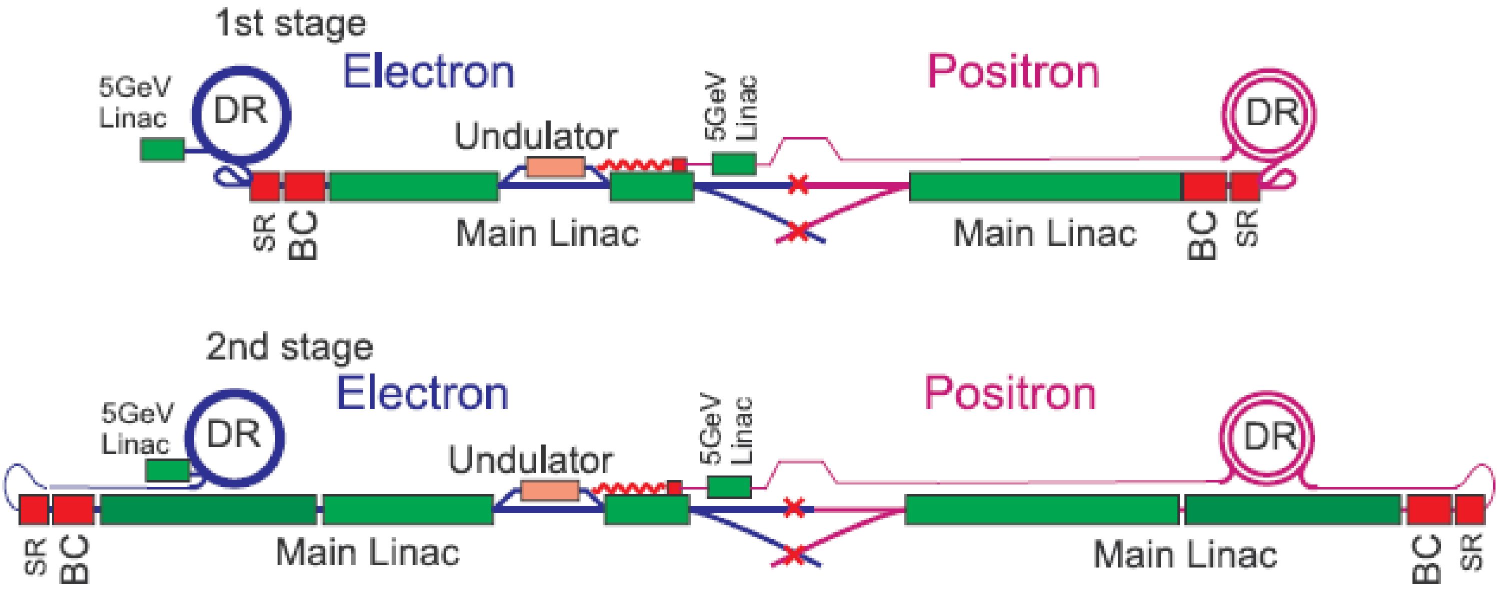
- Create a baseline configuration for the machine
  - Document a concept for ILC machine with a complete layout, parameters etc. defined by the end of 2005
  - Make forward looking choices, consistent with attaining performance goals, and understood well enough to do a conceptual design and reliable costing by end of 2006.
  - Technical and cost considerations will be an integral part in making these choices.
  - Baseline will be put under "configuration control," with a defined process for changes to the baseline.
  - A reference design will be carried out in 2006. We are using a "parametric" design and costing approach.
  - Technical performance and physics performance will be evaluated for the reference design

Making Choices – The Tradeoffs



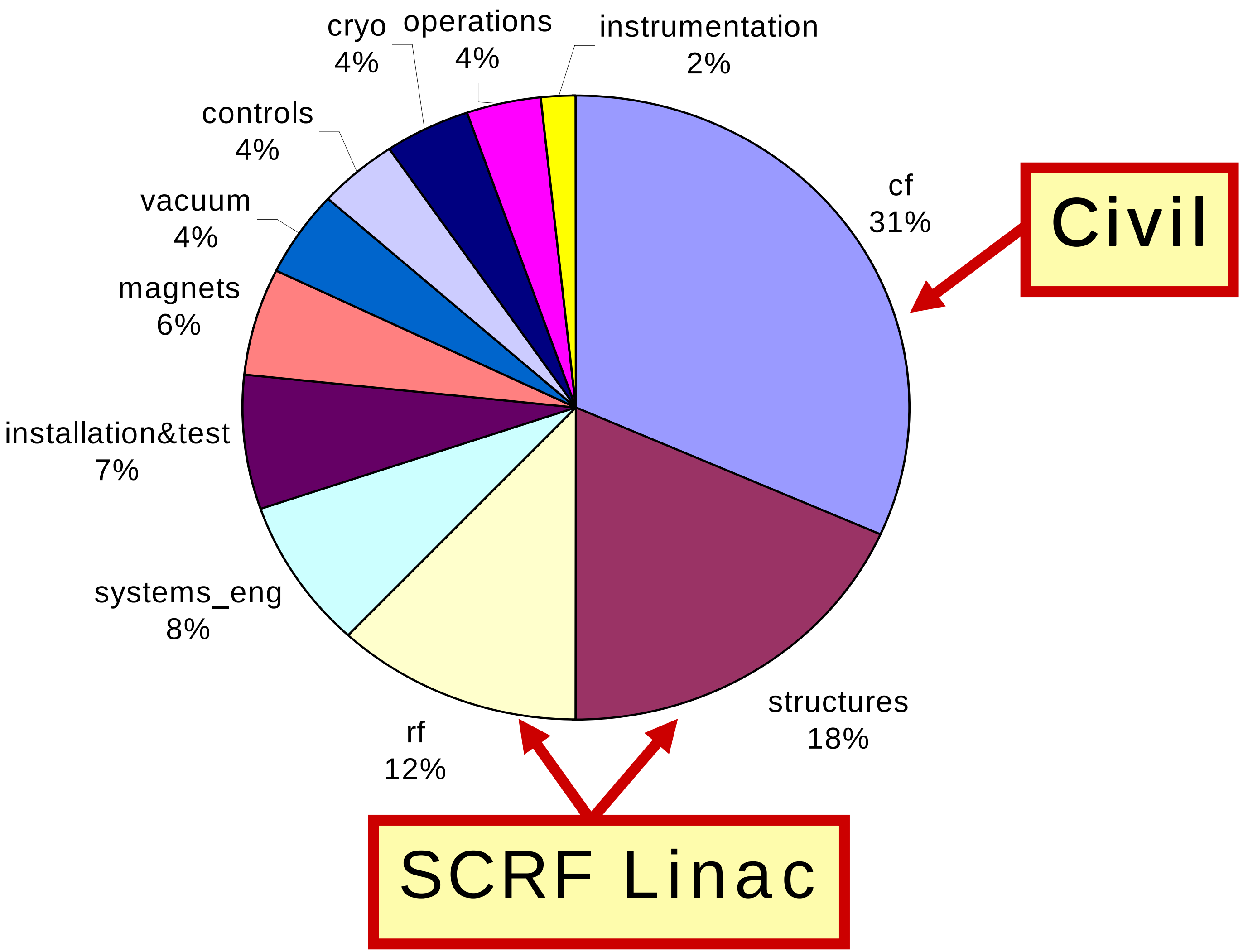
Many decisions are interrelated and require input from several WG/GG groups

ILC Baseline Configuration

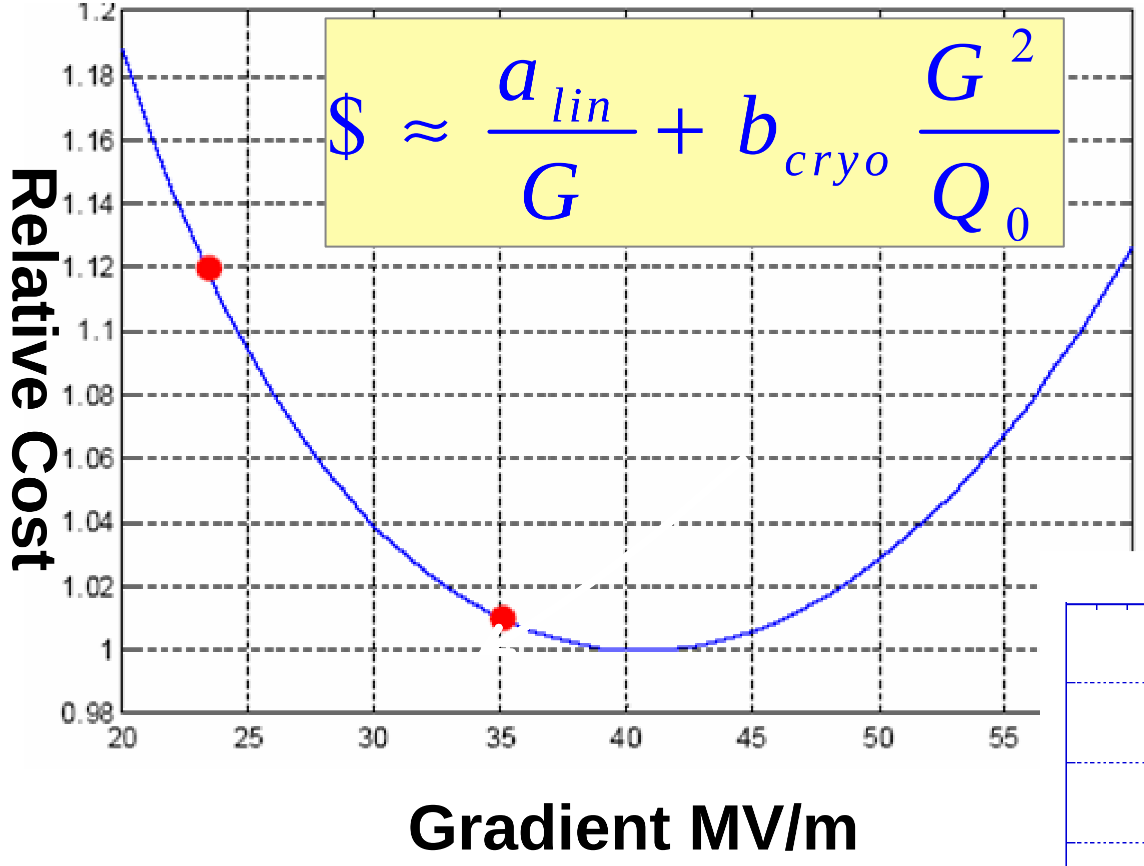


- Configuration for 500 GeV machine with expandability to 1 TeV
- Some details – locations of low energy acceleration; crossing angles are not indicated in this cartoon.

Cost Breakdown by Subsystem



How Costs Scale with Gradient?



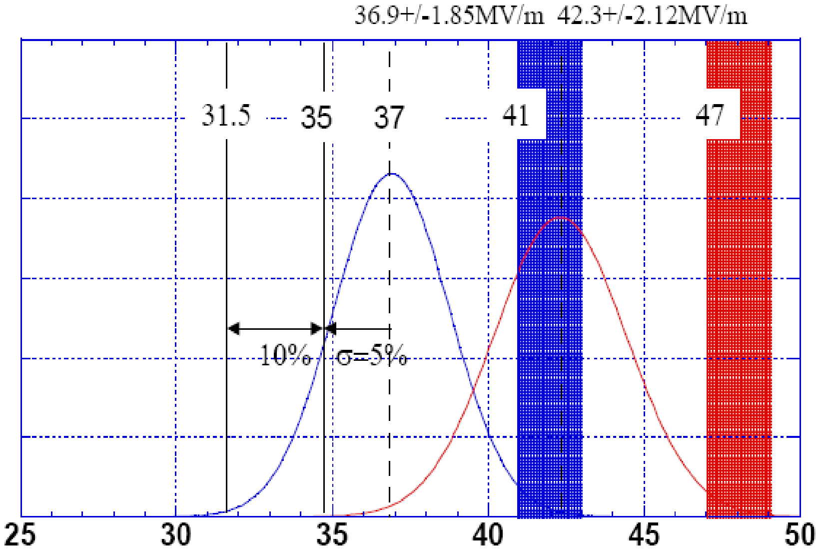
$$\$ \approx \frac{a_{lin}}{G} + b_{cryo} \frac{G^{2}}{Q_{0}}$$

35MV/m is close to optimum

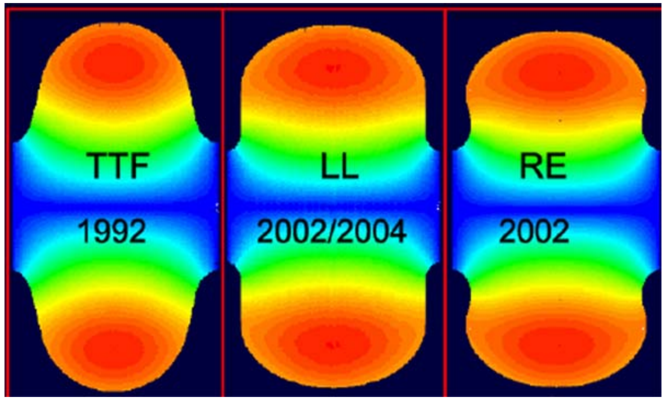
Japanese are still pushing for 40-45MV/m

30 MV/m would give safety margin

Baseline Gradient

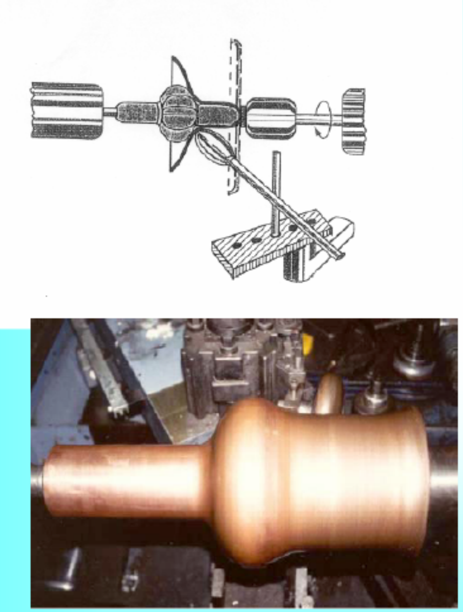


Superconducting RF Cavities

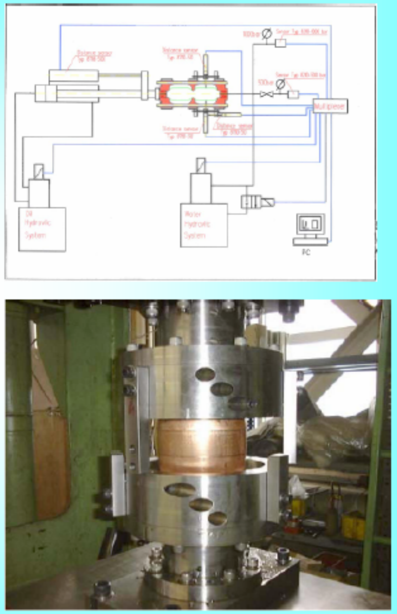


High Gradient Accelerator
35 MV/meter -- 40 km linear collider

Spinning (V.Palmieri, INFN Legnaro)



Hydroforming, DESY, KEK



Improved Fabrication

Improved Processing Electropolishing

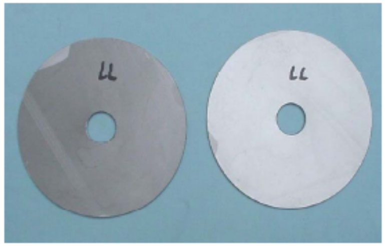
KEK / Nomura EP

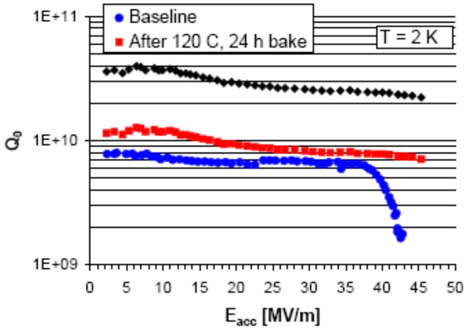
DESY EP

Chemical Polish

Electro Polish

Nb Discs





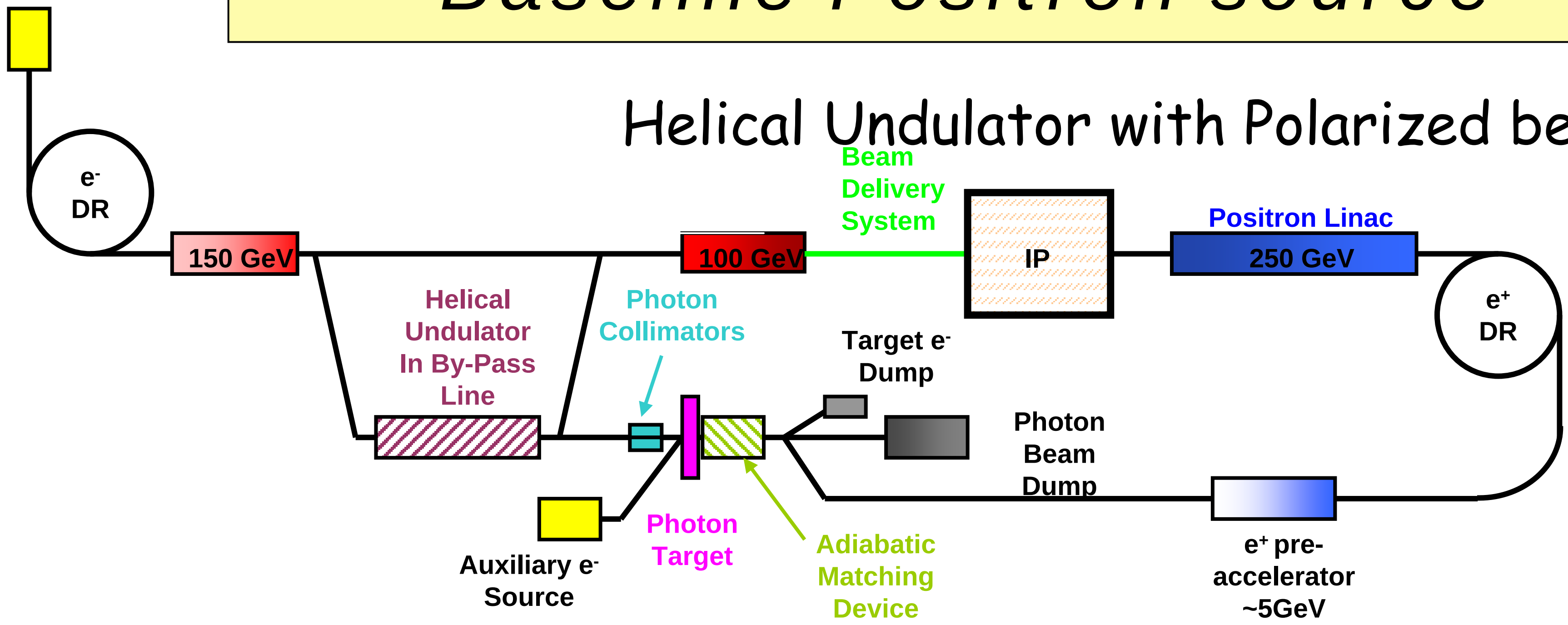
$E_{peak}/E_{acc} = 2.072$

$H_{peak}/E_{acc} = 3.56$ mT/MV/m

Large Grain
Single Crystal Nb Material

Baseline Positron source

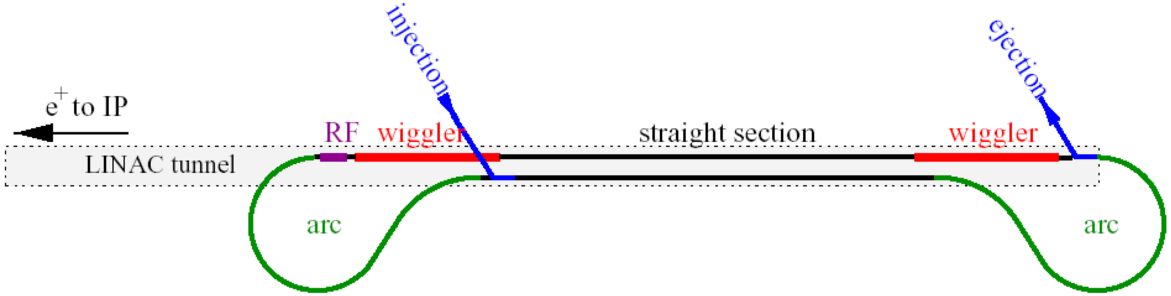
Helical Undulator with Polarized beams

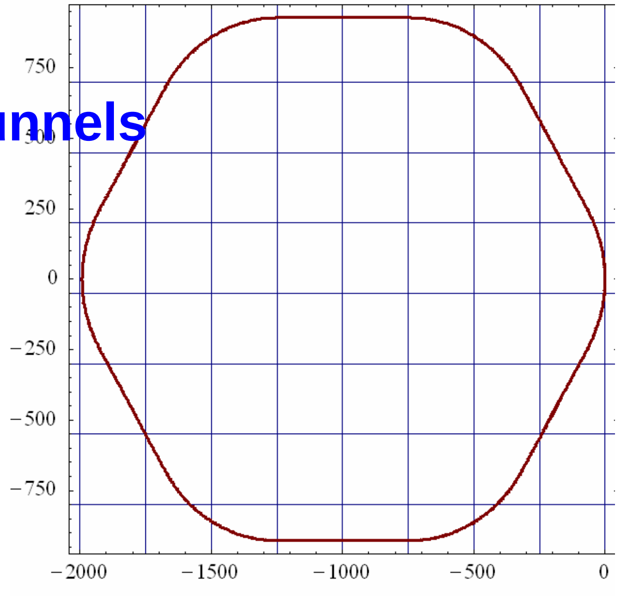


Damping Ring Options

2 stacked 6 km rings can be built in independent tunnels

“dogbone” straight sections share linac tunnel





ILC Siting and Conventional Facilities

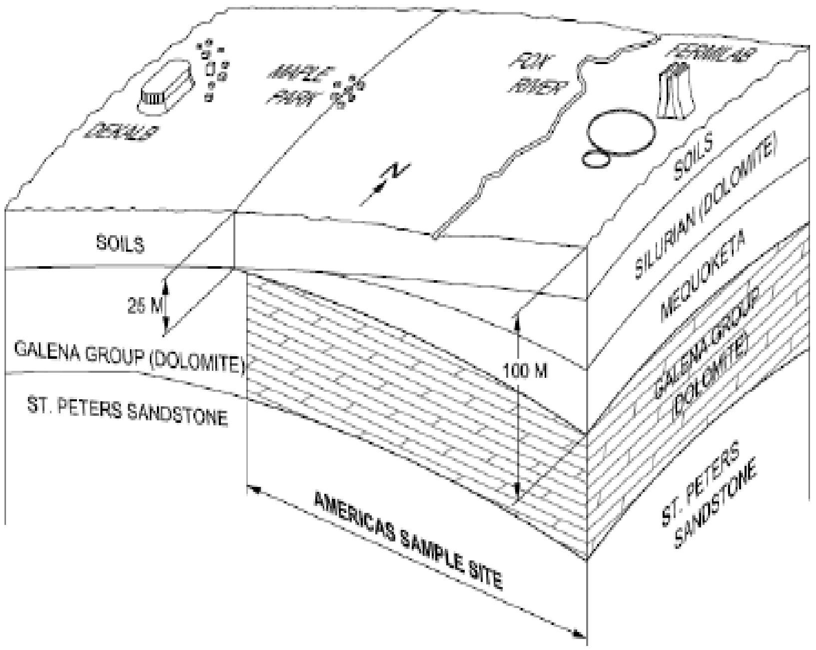
- The design is intimately tied to the features of the site
  - 1 tunnels or 2 tunnels?
  - Deep or shallow?
  - Laser straight linac or follow earth’s curvature in segments?

- GDE ILC Design will be done to samples sites in the three regions
  - North American sample site will be near Fermilab
  - Japan and Europe are to determine sample sites by the end of 2005

- Design to “sample sites” from each region
  - Americas – near Fermilab
  - Japan
  - Europe – CERN & DESY

- Illinois Site – depth 135m
  - Glacially derived deposits overlaying Bedrock. The concerned rock layers are from top to bottom the Silurian dolomite, Maquoketa dolomitic shale, and the Galena-Platteville dolomites.

Americas Sample Plan / Section



Accelerator Physics Challenges

- Develop High Gradient Superconducting RF systems
  - Requires efficient RF systems, capable of accelerating high power beams (~MW) with small beam spots(~nm).
- Achieving nm scale beam spots
  - Requires generating high intensity beams of electrons and positrons
  - Damping the beams to ultra-low emittance in damping rings
  - Transporting the beams to the collision point without significant emittance growth or uncontrolled beam jitter
  - Cleanly dumping the used beams.
- Reaching Luminosity Requirements
  - Designs satisfy the luminosity goals in simulations
  - A number of challenging problems in accelerator physics and technology must be solved, however.

Euro Collaborations

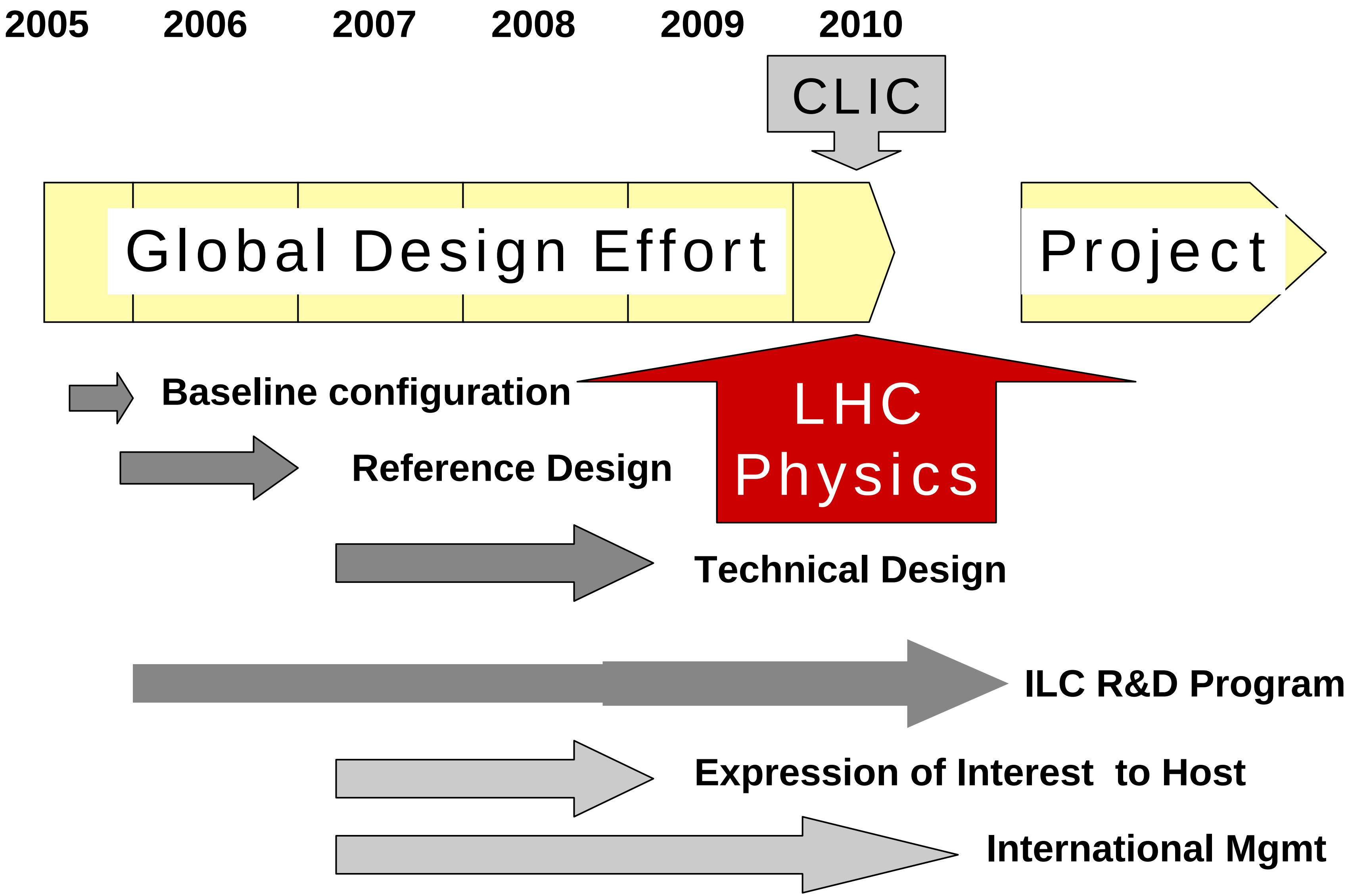
- TESLA (wider than Europe alone)
- European XFEL
- Coordinated Accelerator Research in Europe
- EuroTeV - LC research programme

EU Funded -> 2008

- UK Linear Collider Accelerator & Beam Delivery LCABD – PPARC & CCLRC-funded

Other funding via national agencies (i.e. many soruces)

The GDE Plan and Schedule



Baseline configuration

Reference Design

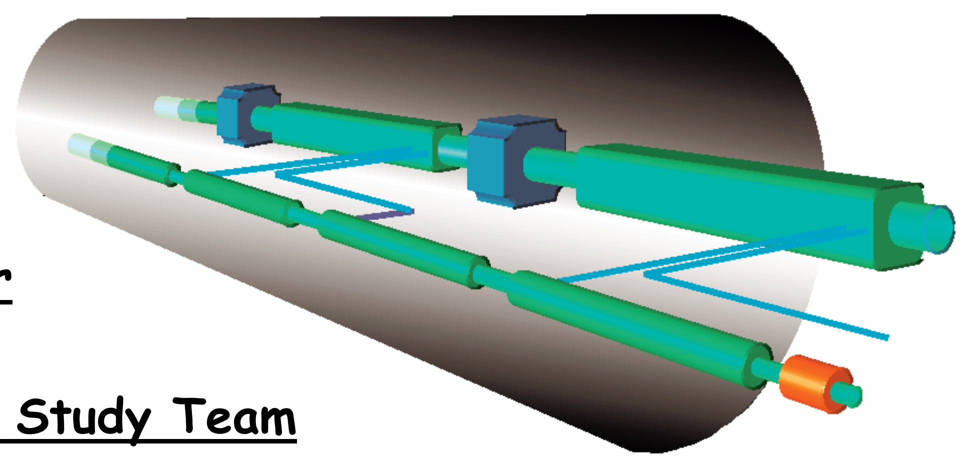
Technical Design

ILC R&D Program

Expression of Interest to Host

International Mgmt

THE COMPACT LINEAR COLLIDER (CLIC) STUDY



J.P.Delahaye for

The Compact LInear Collider Study Team

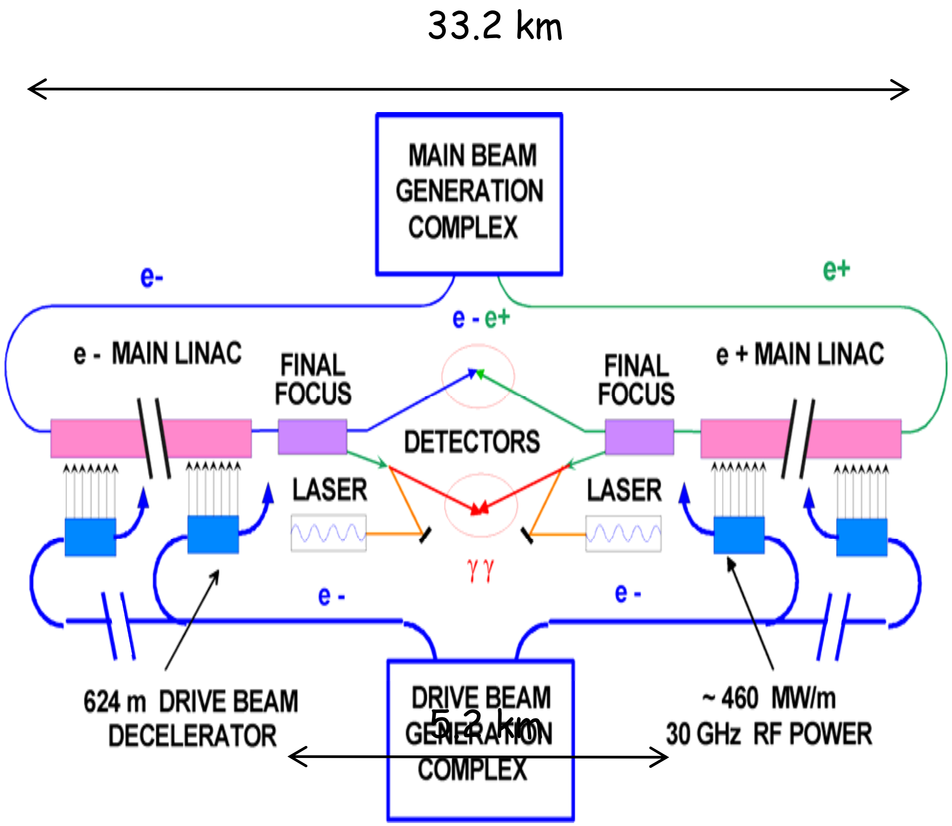
The CLIC study is a site independent feasibility study aiming at the development of a realistic technology at an affordable cost for an e± Linear Collider in the post-LHC era for Physics in the multi-TeV center of mass colliding beam energy range.

CLIC = Complementary to ILC = CILC

http://clic-study.web.cern.ch/CLIC-Study/

CERN 2000-008, CERN 2003-007, CERN 2004-005

CLIC technology for Multi-TeV Linear Colliders



Overall layout for a center of mass energy of 3 TeV/c

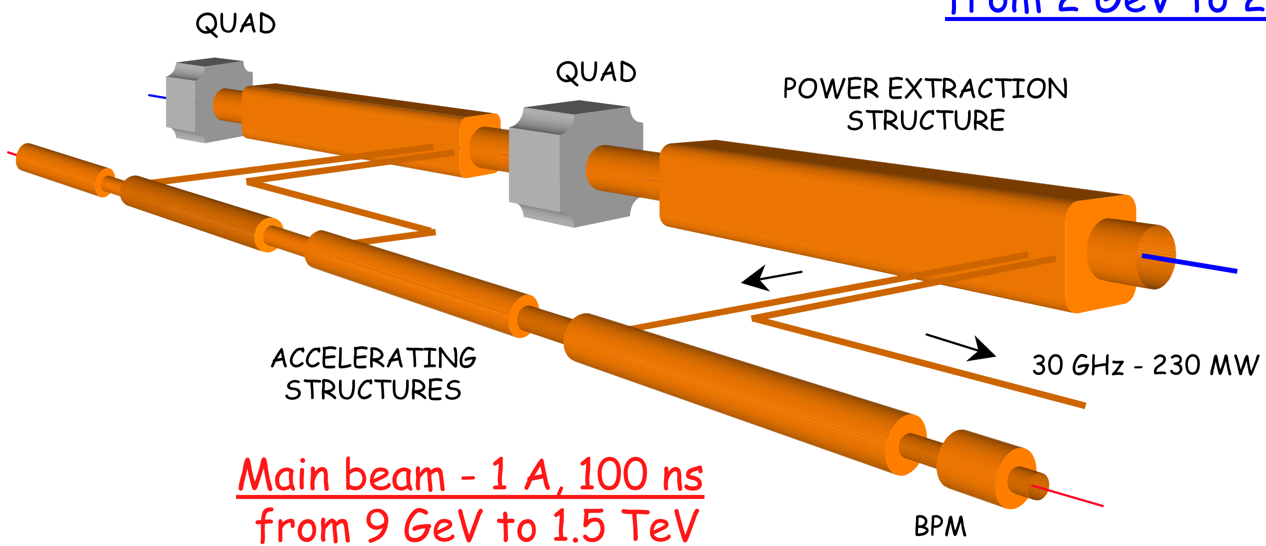
- High acceleration gradient (150 MV/m)

- "Compact" collider-overall length≈33 km
  - Normal conducting accelerating structures
  - High acceleration frequency (30 GHz)

- Two-Beam Acceleration Scheme
  - RF power generation at high frequency
  - Cost-effective & efficient (~ 10% overall)
  - Simple tunnel, no active elements
  - "modular" design, can be built in stages
  - Easily expendable in energy

CLIC Two-Beam scheme

Drive beam - 150 A, 130 ns
from 2 GeV to 200 MeV

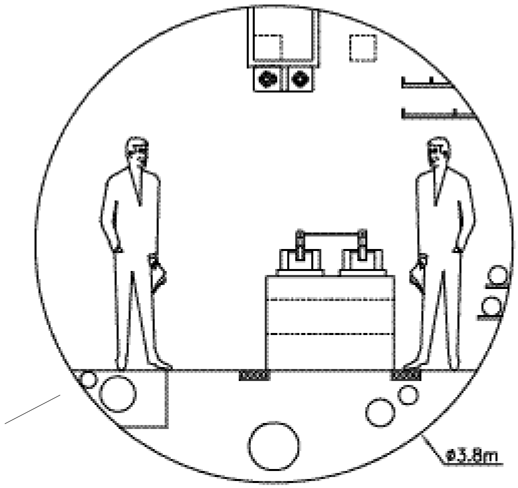


Main beam - 1 A, 100 ns
from 9 GeV to 1.5 TeV

CLIC MODULE

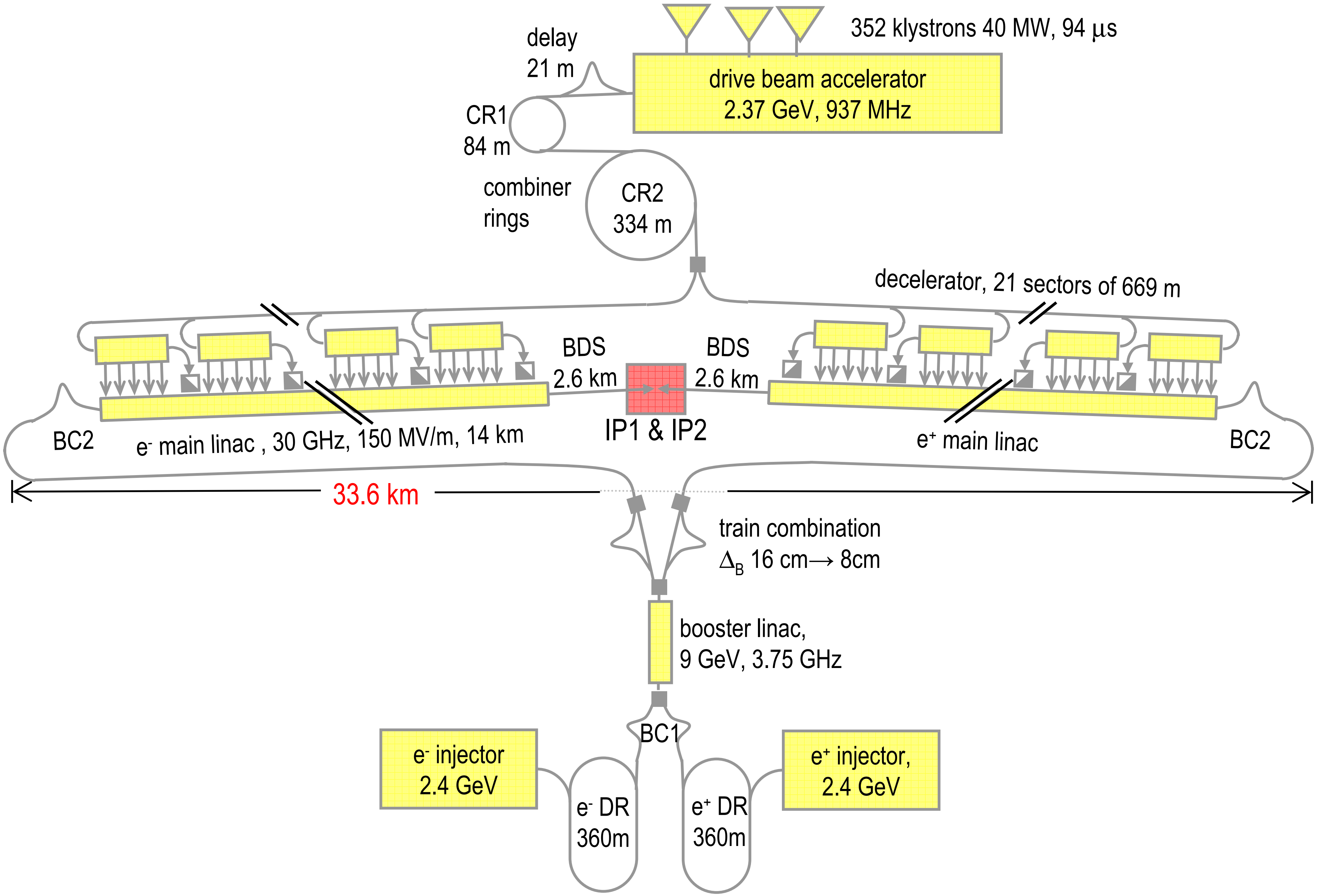
(6000 modules/linac at 3 TeV)

CLIC TUNNEL
CROSS-SECTION



3.8 m diameter

CLIC 3 TeV layout



352 klystrons 40 MW, 94 µs

delay
21 m

drive beam accelerator
2.37 GeV, 937 MHz

CR1
84 m

combiner
rings

CR2
334 m

decelerator, 21 sectors of 669 m

BDS
2.6 km

BDS
2.6 km

BC2

e$^-$ main linac , 30 GHz, 150 MV/m, 14 km

IP1 & IP2

e$^+$ main linac

BC2

33.6 km

train combination
Δ_B 16 cm→ 8cm

booster linac,
9 GeV, 3.75 GHz

BC1

e$^-$ injector
2.4 GeV

e$^-$ DR
360m

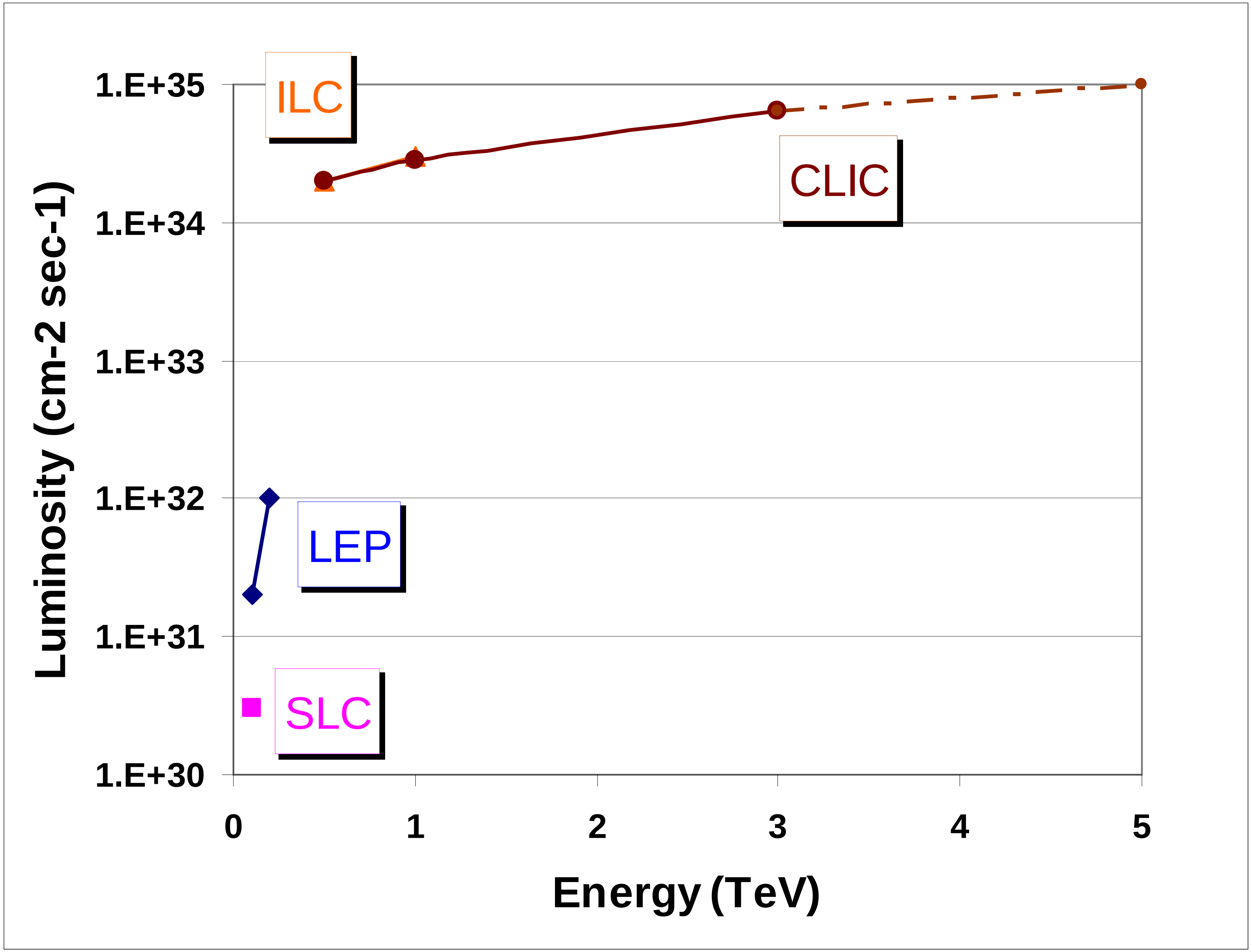
e$^+$ DR
360m

e$^+$ injector,
2.4 GeV

The CLIC main parameters

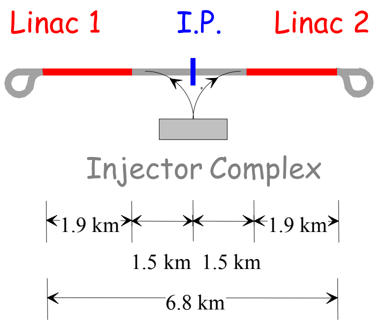
Center of mass Energy (TeV)	1.0 TeV	3 TeV
Luminosity (10^{34} $cm^{-1}s^{-1}$)	2.8	6.5
Mean energy loss (%)	4.4	16
Photons / electron	0.75	1.1
Coherent pairs per X	700	$5\ 10^7$
Rep. Rate (Hz)	150	150
10^9 $e^{\pm}$ / bunch	2.56	2.56
Bunches / pulse	220	220
Bunch spacing (cm)	8	8
H/V ε_n (10^{-8} rad.m)	66/1	66/1
Beam size (H/V) (nm)	94/1	60/0.7
Bunch length (µm)	30.8	30.8
Accelerating gradient (MV/m)	150	150
Overall length (km)	7.7	33.2
Power / section (MW)	150	150
RF to beam efficiency (%)	30.9	30.9
AC to beam efficiency (%)	12.5	12.5
Total AC power for RF (MW)	106	319
Total site AC power (MW)	175	418

Performances of Lepton Colliders

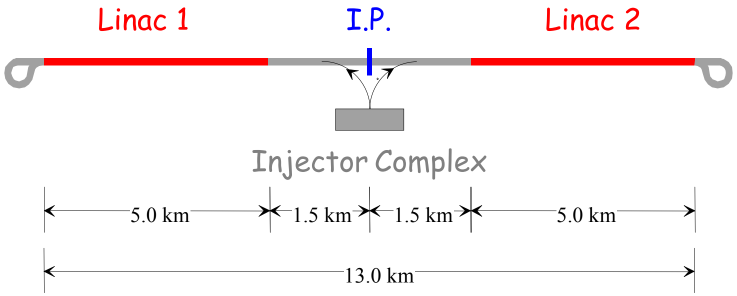


CLIC Layout at various energies

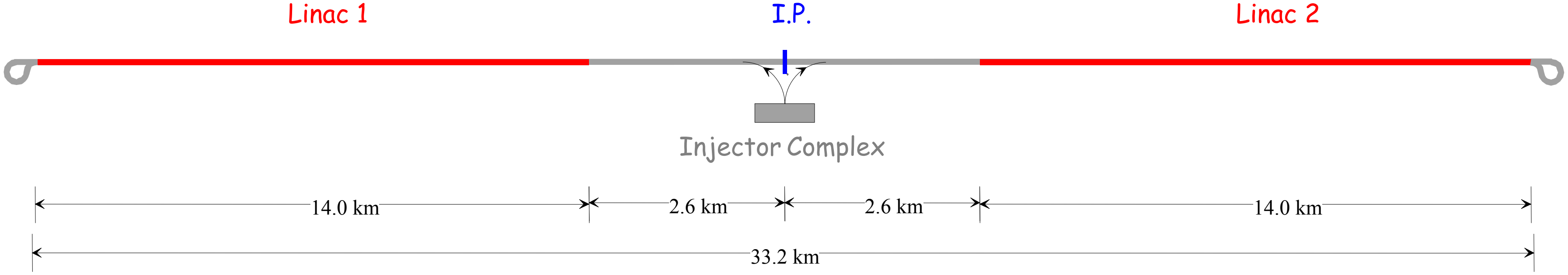
0.42 TeV Stage



1 TeV Stage



3 TeV Stage



Strategy to address key issues

- Key issues common to all Linear Collider studies independently of the chosen technology in close collaboration with:
  - International Linear Collider (ILC) study
  - The Accelerator Test Facility (ATF@KEK)
  - European Laboratories in the frame of the Coordinated Accelerator Research in Europe (CARE) and of a "Design Study" (EUROTeV) funded by EU Framework Programme (FP6)

- Key issues specific to CLIC technology:
  - Focus of the CLIC study
  - All R1 (feasibility) and R2 (design finalisation) key issues addressed in test facilities: CTF@CERN

    except the Multi-Beam Klystron (MBK) which does not require R&D but development by industry (feasibility study already done)

CLIC technology-related key issues (ILC-TRC 2003

Covered by CTF3

R1: Feasibility

- R1.1: Test of damped accelerating structure at design gradient and pulse length
- R1.2: Validation of drive beam generation scheme with fully loaded linac operation
- R1.3: Design and test of damped ON/OFF power extraction structure

R2: Design finalisation

- R2.1: Developments of structures with hard-breaking materials (W, Mo…)
- R2.2: Validation of stability and losses of drive beam decelerator;
  Design of machine protection system
- R2.3: Test of relevant linac sub-unit with beam

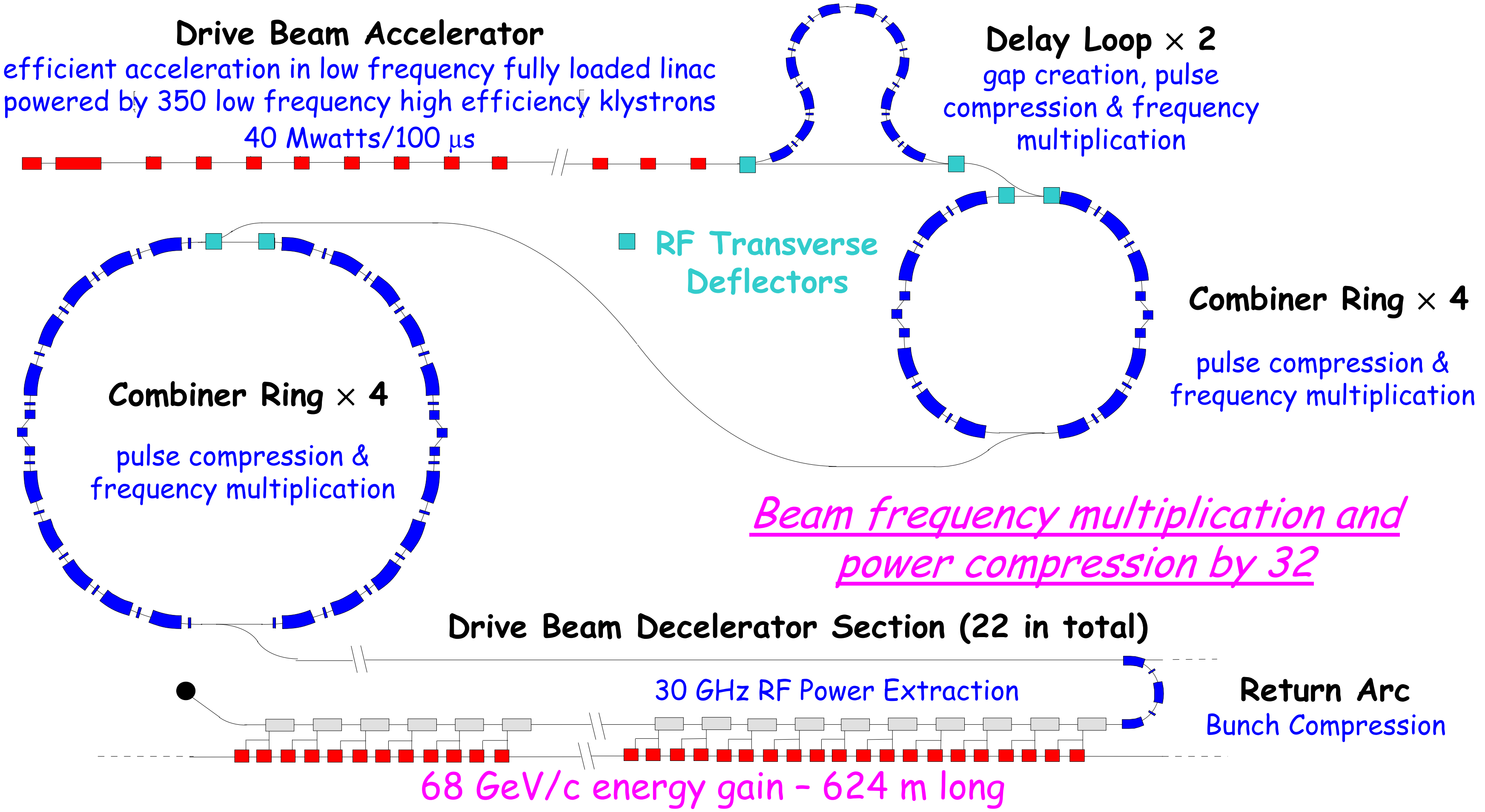
Industrial development

- R2.4: Validation of drive beam 40 MW, 937 MHz Multi-Beam Klystron with long RF pulse

- R2.5: Effects of coherent synchrotron radiation in bunch compressors
- R2.6: Design of an extraction line for 3 TeV c.m.

Covered by EUROTeV

The CLIC RF Power Source



Drive Beam Accelerator

efficient acceleration in low frequency fully loaded linac
powered by 350 low frequency high efficiency klystrons
40 Mwatts/100 µs

Delay Loop × 2

gap creation, pulse
compression & frequency
multiplication

■ RF Transverse
Deflectors

Combiner Ring × 4

pulse compression &
frequency multiplication

Combiner Ring × 4

pulse compression &
frequency multiplication

Beam frequency multiplication and power compression by 32

Drive Beam Decelerator Section (22 in total)

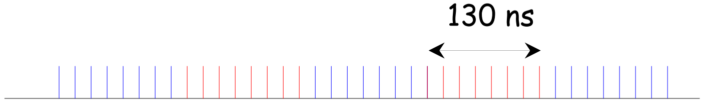
30 GHz RF Power Extraction

Return Arc

Bunch Compression

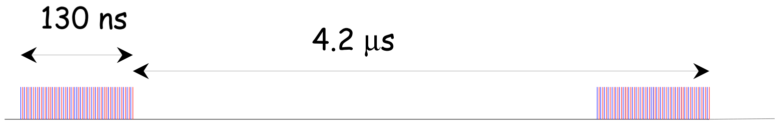
68 GeV/c energy gain – 624 m long

Drive beam time structure - initial



100 µs train length - 32 × 22 sub-pulses – **4.6 A**
2 GeV - 64 cm between bunches

Drive beam time structure - final



22 pulses - **147 A** - 2 cm between bunches

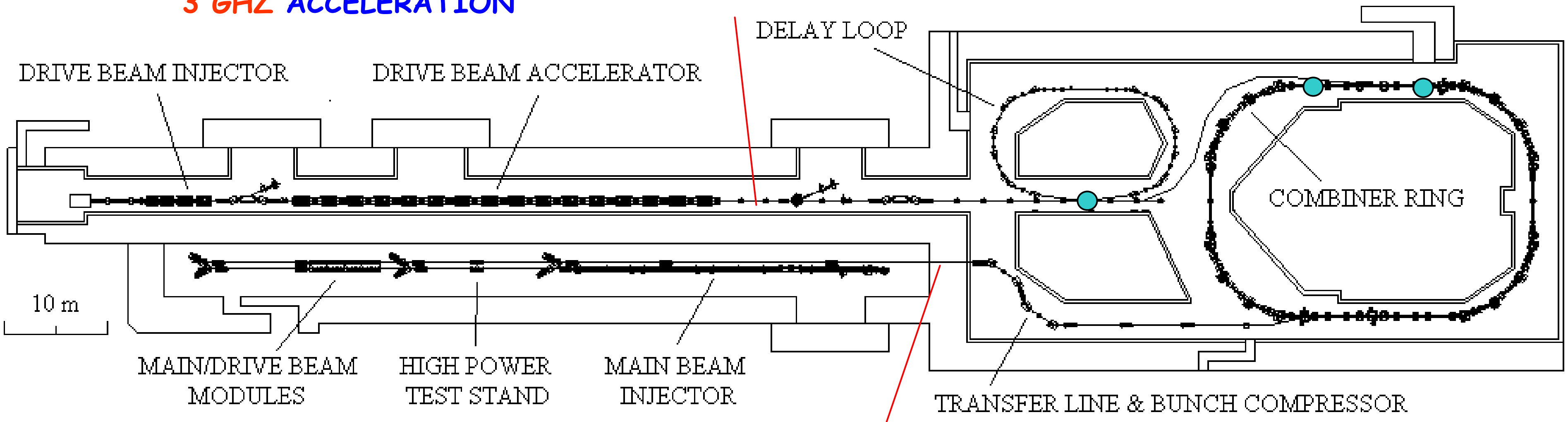
All feasibility CLIC key issues addressed in CLIC Test Facility (CTF3)

Test of Drive Beam Generation, Acceleration & RF Multiplication by a factor 10
Two Beam RF power generation & component tests with nominal fields & pulse length

FULLY LOADED
3 GHZ ACCELERATION

3.5 A - 1.4 μs

PULSE COMPRESSION
FREQUENCY MULTIPLICATION



30 GHz - ≥ 200 MW - 140 ns

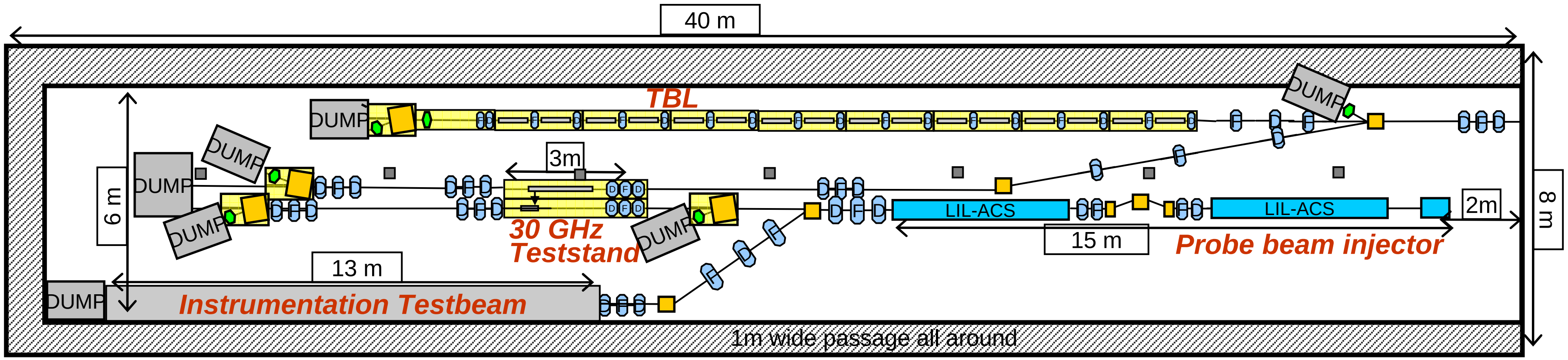
30 GHZ POWER EXTRACTION
& COMPONENTS TEST

35 A - 140 ns

● *RF DEFLECTORS*

CLIC experimental area (CLEX)

- ***Test beam line (TBL) to study RF power production (5 TW at 30 GHz) and drive beam decelerator dynamics, stability & losses***
- ***Two Beam Test Stand to study probe beam acceleration with high fields at high frequency and the feasibility of Two Beam modules***



Layout for CLEX floor space

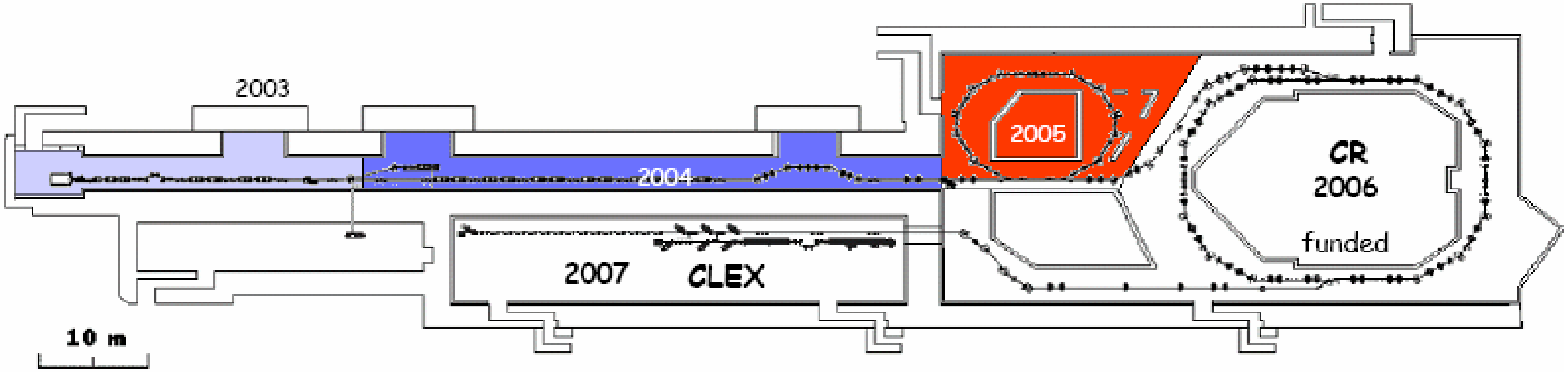
CTF3 Collaboration

- World-wide Institutes have been invited to contribute to this programme by:
  - ✓ taking full responsibility for part, complete of one or several work-packages
  - ✓ providing voluntary contributions “a la carte” in cash, in kind and/or in man-power

- Multilateral collaboration network of volunteer institutes (from which CERN is one of them) participating jointly to the technical coordination and management of the project.

CTF3 collaboration meeting held at CERN on 30/11/05
MoU being signed by 14 Institutes from 9 Countries

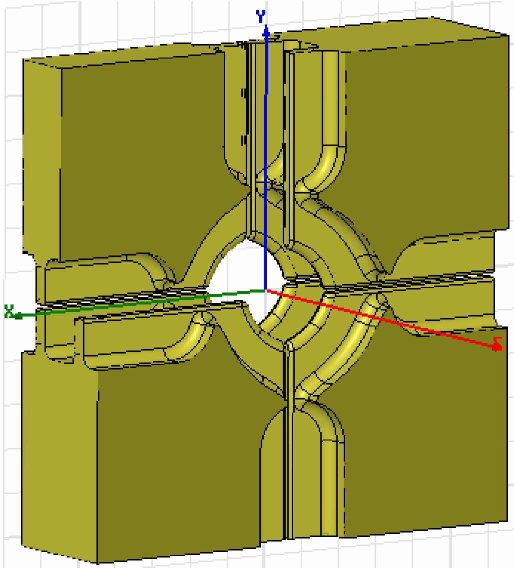
CTF3 project & schedule

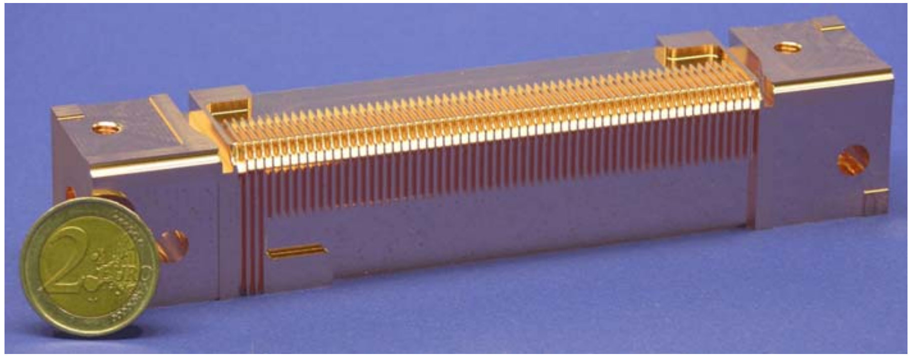


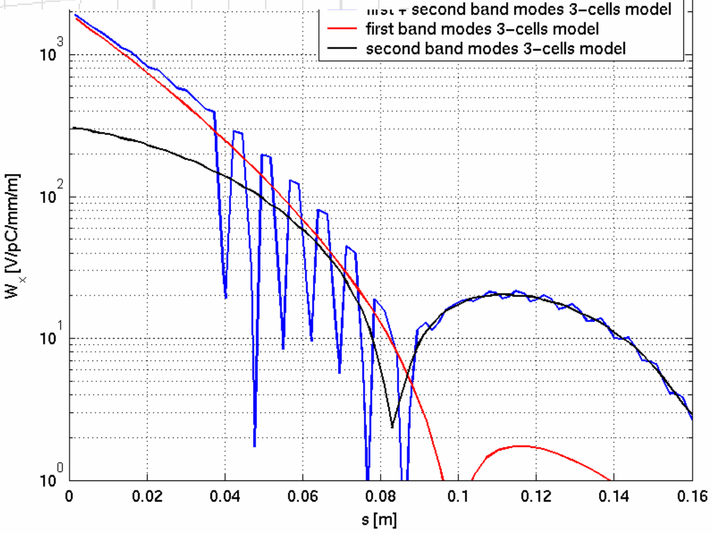
SCHEDULE WITH EXTRA RESOURCES	2004	2005	2006	2007	2008	2009
Drive Beam Accelerator	🟦					
30 GHz power test stand in Drive Beam accelerator	🟦	🟦				
30 GHz power testing (4 months per year)		🟦	🟦	🟦	🟦	🟦
R1.1 feasibility test of CLIC structure				🟪		
Delay Loop	🟦	🟦				
Combiner Ring	🟦	🟦	🟦			
R1.2 feasibility test of Drive beam generation				🟪		
CLIC Experimental Area (CLEX)		🟦	🟦			
R1.3 feasibility test PETS				🟪		
Probe Beam			🟦	🟦		
R2.2 feasibility test representative CLIC linac section					🟪	
Test beam line		🟦	🟦	🟦	🟦	
R2.1 Beam stability bench mark tests					🟪	🟪

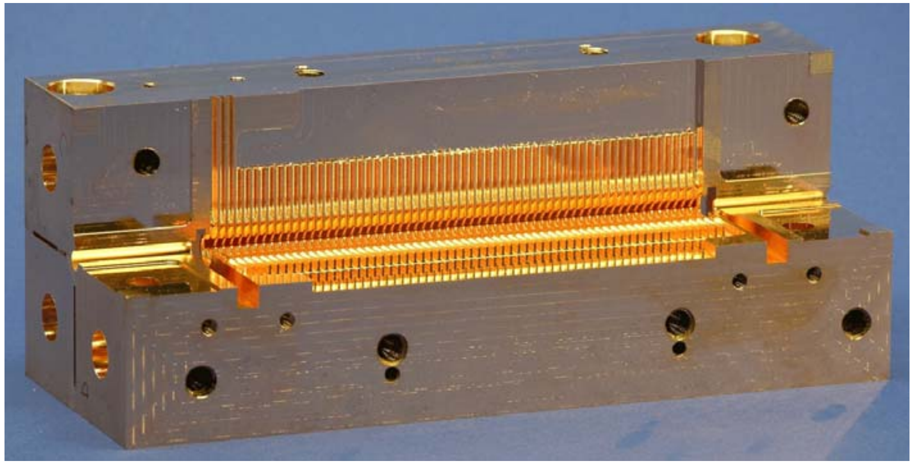
CLIC Accelerating structure:
New concept HDS

- ***Damping waveguides + slotted iris for improved wakefield damping***
- ***Geometry optimized to reduced surface electric and magnetic fields***
- ***First high power test early 2006***



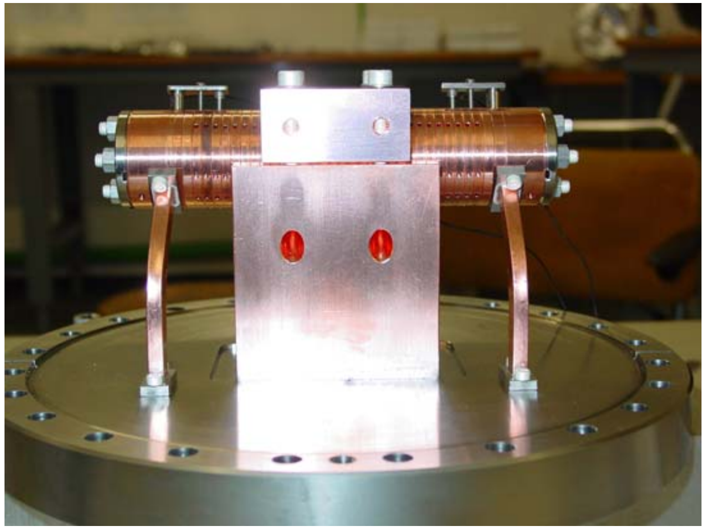




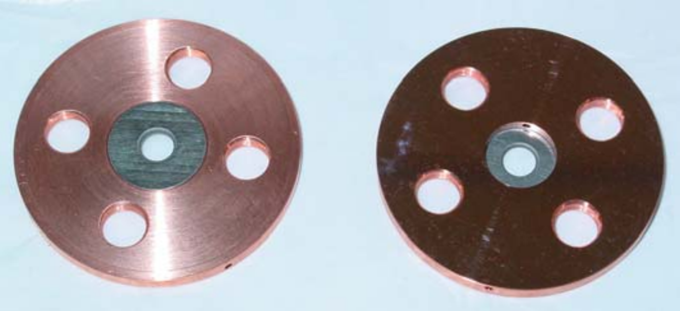


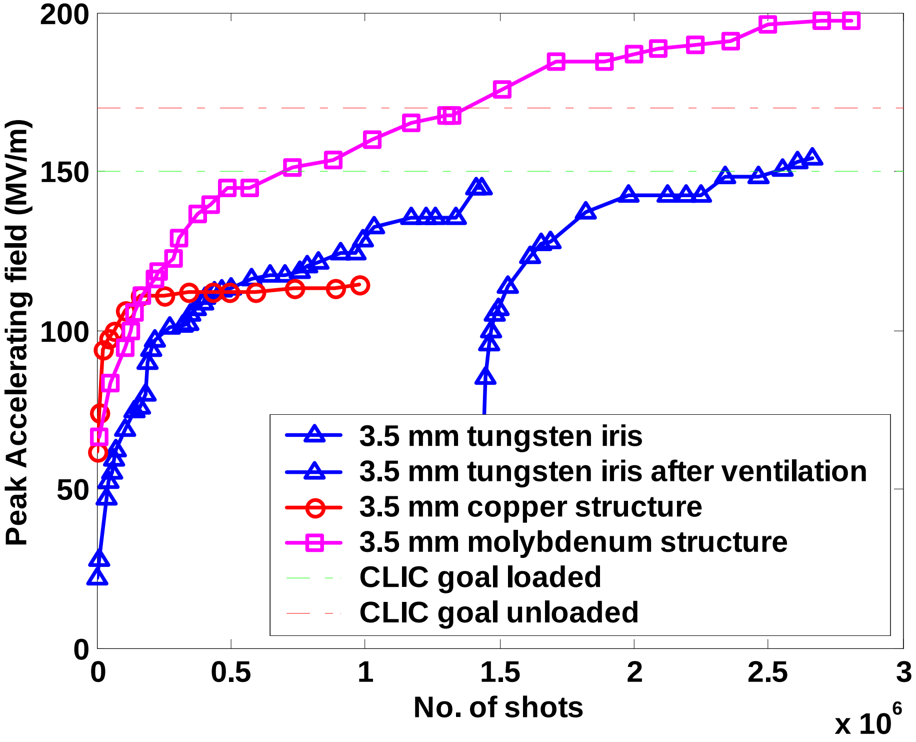
Achieved accelerating fields in CTF2

High gradient tests of new structures with molybdenum irises reached 190 MV/m peak accelerating gradient without any damage well above the nominal CLIC accelerating field of 150 MV/m but with RF pulse length of 16 ns only (nominal 70 ns)



30 cell clamped tungsten-iris structure



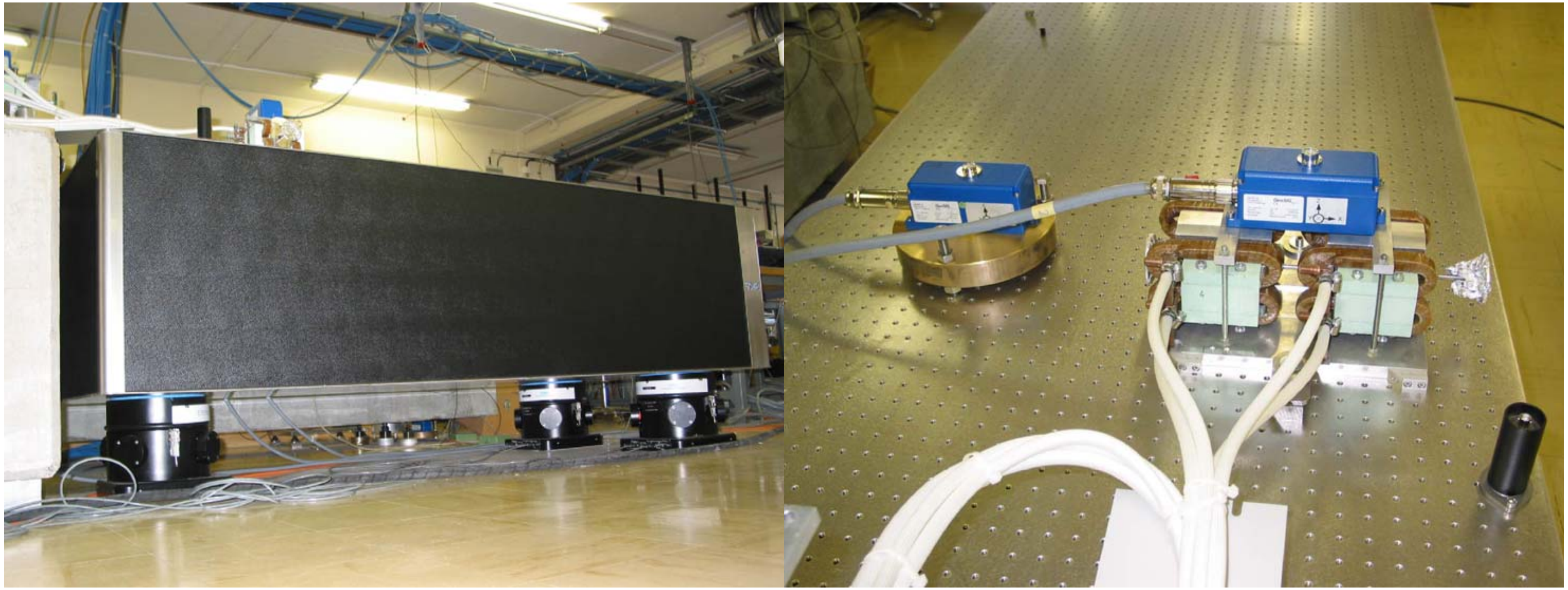


A world record !!!

Nanometer stabilisation

Latest stabilization technology applied to the accelerator field

The most stable place on earth!!!



Stabilizing quadrupoles to the **0.5 nm** level!

(up to 10 times better than supporting ground, above 4 Hz)

- CLIC only possible scheme to extend Linear Collider energy into the Multi-TeV range
- CLIC technology not mature yet, requires challenging R&D
- A development:
  - ✓complementary to Super-Conducting technology of the International Linear Collider (ILC) in the TeV energy range
  - ✓necessary in order to extend energy range of Linear Colliders in the future
- Very promising performances already demonstrated in CTF2/CTF3
- Remaining key issues clearly identified (ILC-TRC)
- L.C. Key-issues independent of the technology studied by 2008 in a wide collaboration of European Institutes (Design Study submitted to EU FP6 funding)
- CLIC-related key-issues addressed in CTF3 (feasibility by 2007 and design finalisation by 2009) built in multi-lateral collaboration

- Provides the High Energy Physics community with the information about the feasibility of CLIC technology for Linear Collider in due time when Physics needs will be fully determined following LHC results
- Safety net to the Super-Conducting technology in case sub-TeV energy range is not considered attractive enough for Physics
- Possible construction in stages starting with low energy applications
- A lot still to be done before the CLIC technology can be made operational;
- Novel Ideas and Challenging work in world-wide collaborations still needed

Scenarios for the LHC Luminosity Upgrade: Interaction Region Upgrade

- **Report from the CARE-HHH-APD LHC-LUMI-2005 workshop (Arcidosso, 31 Aug–3 Sep 2005)**
- **Luminosity upgrade paths and IR design: dipole-first vs quadrupole-first, energy deposition, minimum crossing angle and beam-beam compensation, Crab cavities or early beam separation, flat beams**
- **Highlights from the US-LARP mini-workshop IR-2005 (Fermilab, 3–4 Oct 2005) and recent developments**
- **Tentative conclusions: R&D, milestones, convergence towards a Reference Design Report**

WORKSHOP

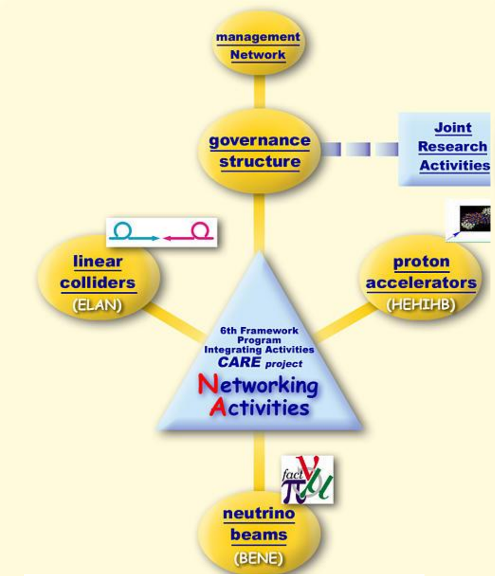
Scientific Research and Society during the last fifty years

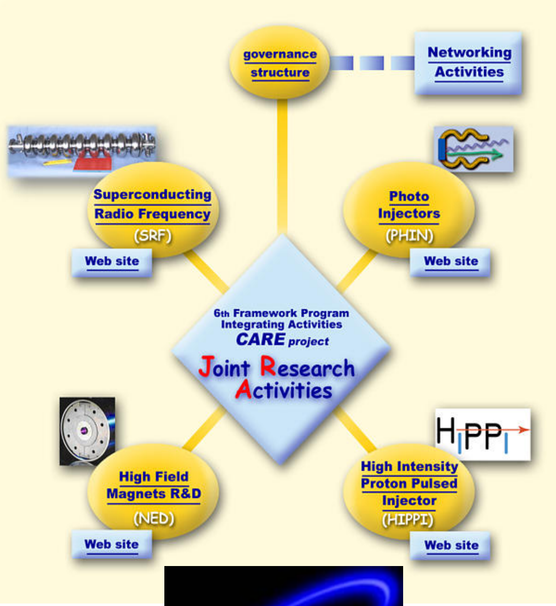
Joint Meeting: Care HHH-APD workshop about "Scenarios for the LHC luminosity upgrade"

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395).

ARCIDOSSO
ITALY
Castello Aldobrandesco
August 31 - September 3,
2005

SCIENTIFIC AND ORGANIZING COORDINATION:
Paola Cerrai, Dipartimento di Matematica Università di Pisa
e-mail: cerrai@dm.unipi.it





LHC-LUMI-2005 WORKSHOP PROGRAMME

Opening Session, convener E. Tsesmelis helped by F. Zimmermann

- Physics Motivation for an LHC Luminosity Upgrade, M. Mangano
- Machine-Detector Interface, F. Palla (INFN)
- LHC beam parameters and IR upgrade options, F. Ruggiero
- Fast pulsed High Energy injectors, W. Scandale

Session 1: Optics & Layout, convener P. Raimondi (INFN) helped by R. Tomas

- Progress of US-LARP activities on LHC IR Upgrade, T. Sen (FNAL)
- Possible Dipole-First Options and Challenges, O. Brüning
- Optics Design for Dipole-First Options, R. De Maria
- Possible Quadrupole-First Options with $\beta^* \leq 0.25$ m, J.-P. Koutchouk
- Magnetic lattice for the High Energy injectors, G. Arduini

Session 2: High-Intensity Effects, convener F. Ruggiero helped by G. Rumolo

- Progress of Beam-Beam compensation schemes, F. Zimmermann
- High brilliance and closer bunches from the LHC injectors, E. Shaposhnikova
- Beam collimation and control in the High Energy injectors, N. Catalan
- New RF systems for the Super-ISR and Super-SPS, J. Tuckmantel

WG 1 on LHC IR Upgrade, convener O. Brüning helped by E. Todesco

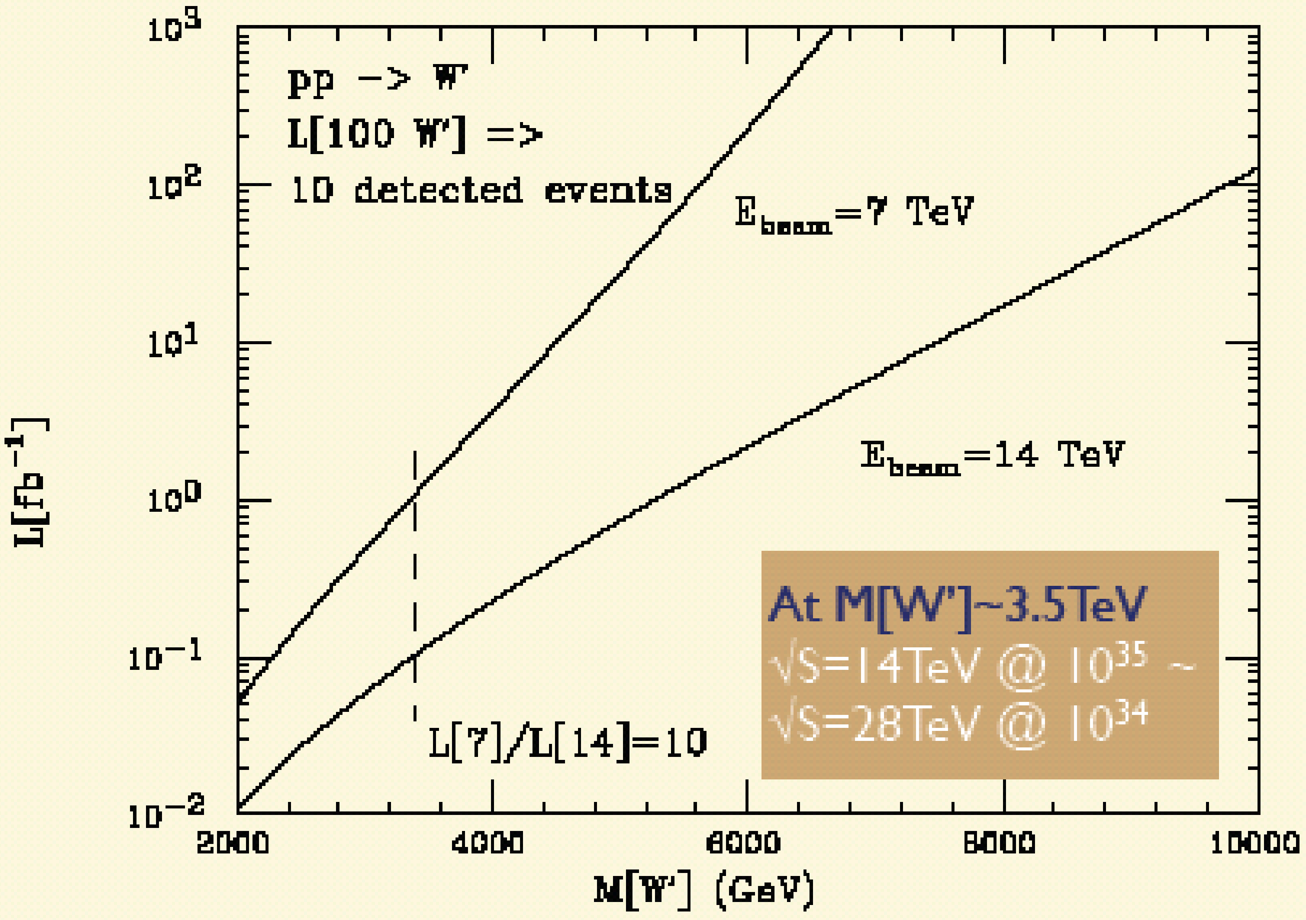
WG 2 on High Energy Injectors, convener W. Scandale helped by G. Arduini

Closing Session, Summary talks by the Sessions and WG's conveners

luminosity versus energy upgrade

Courtesy of Michelangelo Mangano

At low mass, the energy-dependence of the cross section is weaker, and a factor x10 in Lum is better than a factor of x2 in Ebeam



At M[W']~3.5TeV
√S=14TeV @ 10^{35} ~
√S=28TeV @ 10^{34}

At high masses, the E upgrade is essential

Nominal LHC parameters

collision energy	E_{cm}	2x7	TeV
dipole peak field	B	8.3	T
injection energy	E_{inj}	450	GeV
protons per bunch	N_b	1.15	10^{11}
bunch spacing	Δt	25	ns
average beam current	I	0.58	A
stored energy per beam		362	MJ
radiated power per beam		3.7	kW
normalized emittance	ε_n	3.75	µm
rms bunch length	σ_z	7.55	cm
beam size at IP1&IP5	σ^*	16.6	µm
beta function at IP1&IP5	β^*	0.55	m
full crossing angle	θ_c	285	µrad
luminosity lifetime	τ_L	15.5	h
peak luminosity	L	10^{34}	$cm^{-2}s^{-1}$
events per bunch crossing		19.2	
integrated luminosity	$\int L\, dt$	66.2	fb^{-1}/year

Various LHC upgrade options

parameter	symbol	nominal	ultimate	shorter bunch	longer bunch
no of bunches	n_b	2808	2808	5616	936
proton per bunch	N_b $[10^{11}]$	1.15	1.7	1.7	6.0
bunch spacing	Δt_{sep}[ns]	25	25	12.5	75
average current	I [A]	0.58	0.86	1.72	1.0
normalized emittance	ε_n [μm]	3.75	3.75	3.75	3.75
longit. profile		Gaussian	Gaussian	Gaussian	flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
β^* at IP1&IP5	β^* [m]	0.55	0.50	0.25	0.25
full crossing angle	θ_c [μrad]	285	315	445	430
Piwinski parameter	$\theta_c\, \sigma_z/(2\sigma^*)$	0.64	0.75	0.75	2.8
peak luminosity	L $[10^{34}$ $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	1.0	2.3	9.2	8.9
events per crossing		19	44	88	510
luminous region length	σ_{lum} [mm]	44.9	42.8	21.8	36.2

- Peak luminosity at the beam-beam limit *L~ I/b**
- Total beam intensity *I* limited by electron cloud, collimation, injectors
- Minimum crossing angle depends on beam intensity: limited by triplet aperture
- Longer bunches allow higher bb-limit for *Nb/en*: limited by the injectors
- Less ecloud and RF heating for longer bunches: ~50% luminosity gain for flat bunches longer than *b**
- Event pile-up in the physics detectors increases with *Nb*
- Luminosity lifetime at the bb limit depends only on *b**

Expected factors for the LHC luminosity upgrade

The peak LHC luminosity can be multiplied by:

- **factor 2.3** from nominal to ultimate beam intensity (0.58 ⇒ 0.86 A)
- **factor 2** (or more?) from new low-beta insertions with $\beta^* = 0.25$ m

$T_{\text{turnaround}} \sim 10$ h ⇒ $\int L dt \sim 3 \times$ nominal ~ 200/(fb*year)

Major hardware upgrades (LHC main ring and injectors) are needed to exceed ultimate beam intensity. The peak luminosity can be increased by:

- **factor 2** if we can double the number of bunches (maybe impossible due to electron cloud effects) or increase bunch intensity and bunch length

$T_{\text{turnaround}} \sim 10$ h ⇒ $\int L dt \sim 6 \times$ nominal ~ 400/(fb*year)

Increasing the LHC injection energy to 1 TeV would potentially yield:

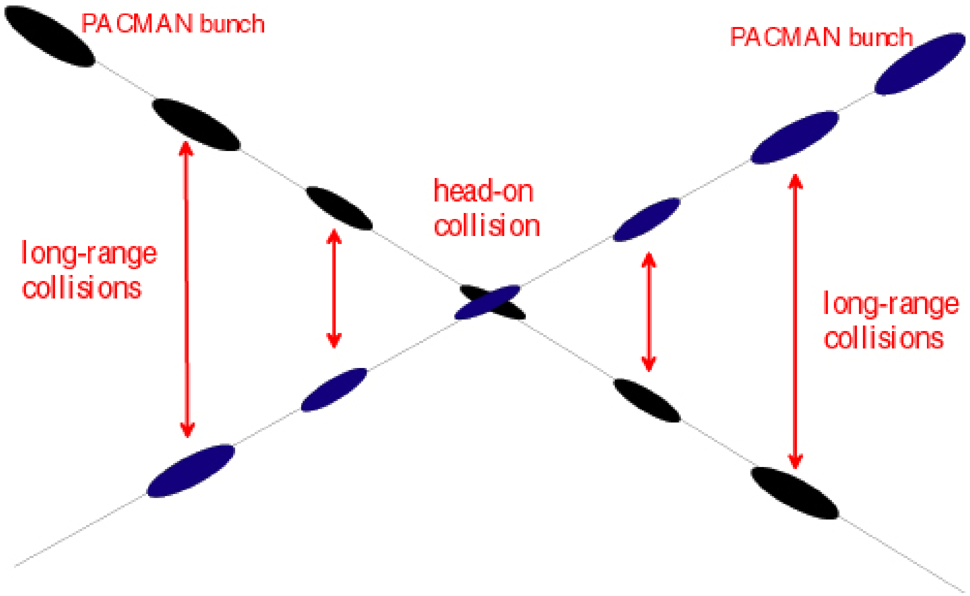
- **factor ~2** in peak luminosity (2 x bunch intensity and 2 x emittance)
- **factor 1.4** in integrated luminosity from shorter $T_{\text{turnaround}} \sim 5$ h

thus ensuring $L \sim 10^{35}$ cm^{-2} s^{-1} and $\int L dt \sim 9 \times$ nominal ~ 600/(fb*year)

Minimum crossing angle

Beam-Beam Long-Range collisions:

- perturb motion at large betatron amplitudes, where particles come close to opposing beam
- cause 'diffusive' (or dynamic) aperture, high background, poor beam lifetime
- increasing problem for SPS, Tevatron, LHC, i.e., for operation with larger # of bunches



dynamic aperture caused by n_{par} parasitic collisions around two IP's

$$\frac{d_{da}}{\sigma} \approx \frac{\theta_c}{\sigma_\theta} - 3\sqrt{\frac{n_{par}}{32}\frac{N_b}{10^{11}}\frac{3.75\mu m}{\varepsilon_n}} \Rightarrow \frac{\theta_c}{\sigma_\theta} \approx 6 + 3\sqrt{\frac{I}{0.5A}\frac{3.75\mu m}{\varepsilon_n}}$$

$$\sigma_\theta = \sqrt{\frac{\varepsilon}{\beta^*}}$$ angular beam divergence at IP

higher beam intensities or smaller β^* require larger crossing angles to preserve dynamic aperture and shorter bunches to avoid geometric luminosity loss

⇒ baseline scaling: $\theta_c \sim 1/\sqrt{\beta^*}$, $\sigma_z \sim \beta^*$

Alternative ways to avoid luminosity loss

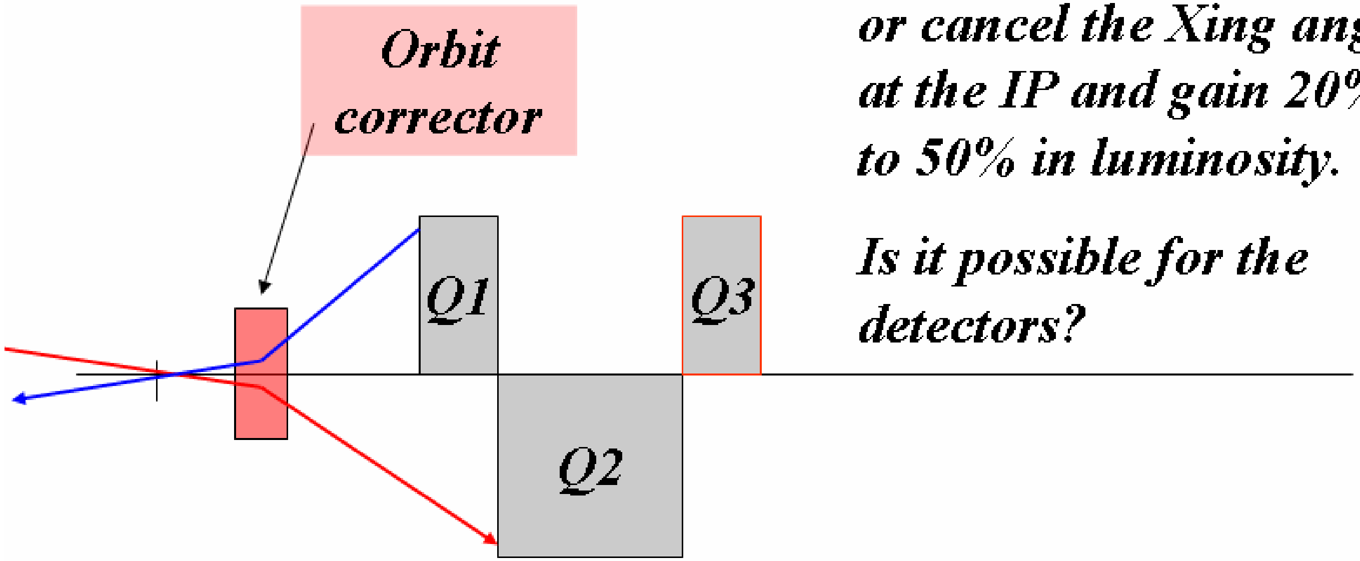
1) **Reduce crossing angle and apply "wire" compensation of long range beam-beam effects**

2) **Crab cavities ⇒ large crossing angles to avoid long range bb effects w/o luminosity loss.** Potential of boosting the beam-beam tune shift (factor 2-3 predicted for KEKB, what about LHC?)

3) **Early beam separation by a "D0" dipole located a few metres away from the IP, as recently suggested by JPK at the LHC-LUMI-05 workshop.** The same effect could be obtained by tilted experimental solenoids, but the experiments don't seem to like the idea.

A potential drawback of 2) and 3) is that ΔQ_{bb} is no longer reduced by the geometric factor F ⇒ lower beam-beam limit?

- Cheap and elegant solution to increase luminosity
- No need of a new bunch shortening RF system
- Cleans collision debris from Q1?
- Reduced separation at first few parasitic encounters?
- Collision debris and background in the experiments?
- Compatibility with detector layout and integration into the experiments



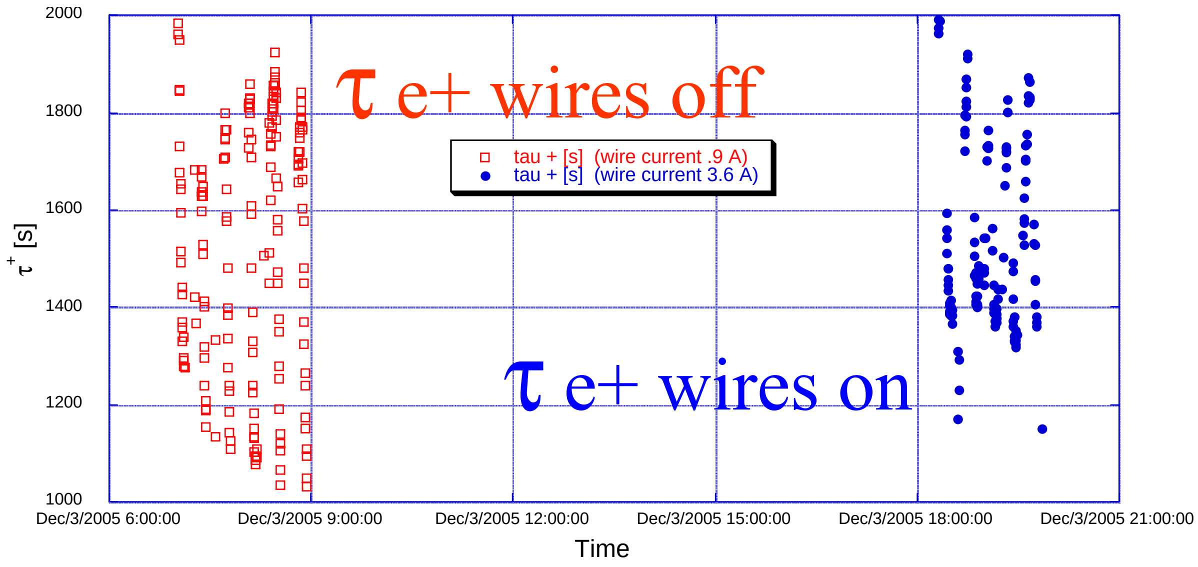
An "easy" way to reduce or cancel the Xing angle at the IP and gain 20% to 50% in luminosity.

Is it possible for the detectors?

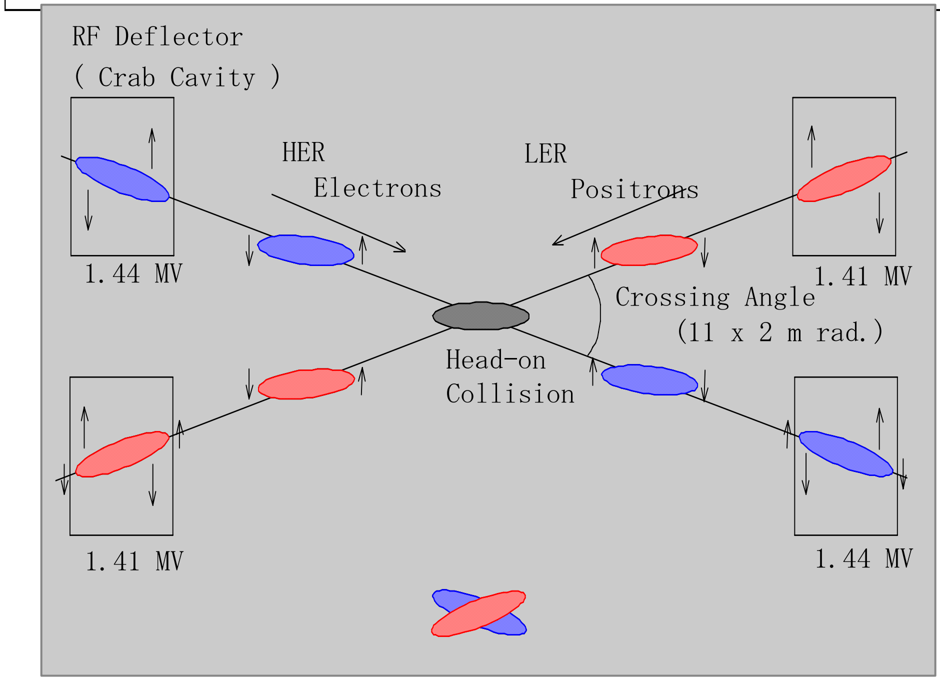
LR beam-beam compensation: remarks and open issues

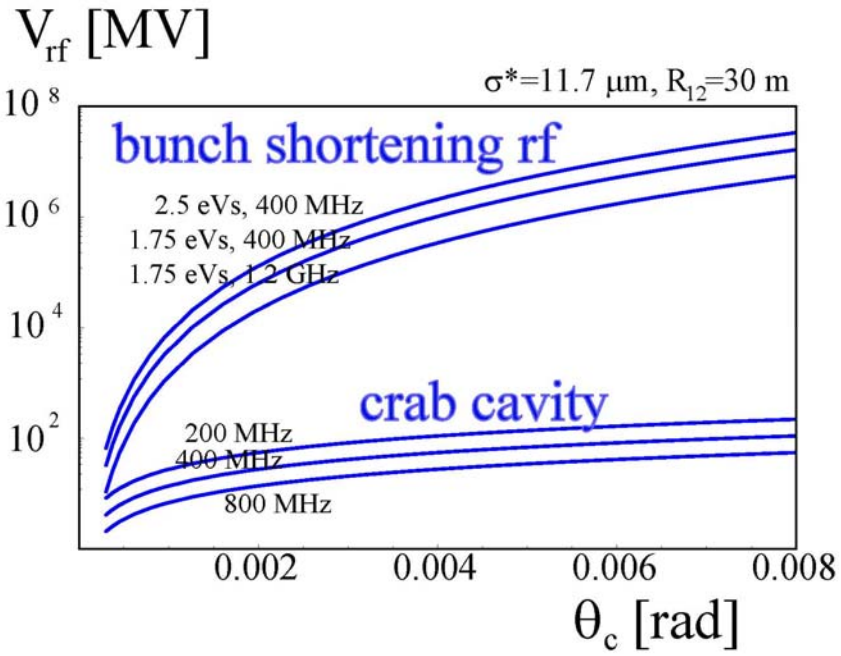
- Simulations of LR compensation with 2 wires indicate that lifetime is recovered over a wide tune range but not for all tunes.
- The measured SPS lifetime is 5 ms x $(d/\sigma)^5$. Extrapolation to LHC beam-beam distance (9.5 σ) would predict 6 minutes beam lifetime! Tevatron observations with electron lens show cubic dependence. Further SPS tests at different energy are needed.
- Lifetimes predicted by simulation codes are much larger than those observed, even though sensitivity to parameters seems correct. **Needs further understanding and beam tests, e.g. at RHIC.**
- For extreme PACMAN bunches there is overcompensation which causes the footprint to flip over or to increase instead of shrinking. **To avoid degraded lifetime for PACMAN bunches, the wire should be pulsed train by train.** It is rather challenging to make a pulsed wire for BB compensation: the required average pulse rate is 439 kHz and the turn-by-turn amplitude stability 10^{-4}.
- Experiments at RHIC (Fischer) **with a single LR encounter show that the BB effect is visible starting from a 5σ separation**, consistent with Tevatron and Daphne observations, but contrary to LHC simulations and possibly earlier observations at the SPS collider.

LRBB successfully tested in Dafne in Dec,2006



Crab cavities vs bunch shortening





Crab cavities combine advantages of head-on collisions and large crossing angles

require lower voltages compared to bunch shortening RF systems

but tight tolerance on phase jitter to avoid emittance growth

Comparison of timing tolerances

	KEKB	Super-KEKB	ILC	Super-LHC
σ_x^*	100 μm	70 μm	0.24 μm	11 μm
θ_c	+/- 11 mrad	+/-15 mrad	+/-5 mrad	+/- 0.5 mrad
Δt	6 ps	3 ps	0.03 ps	**0.08 ps**

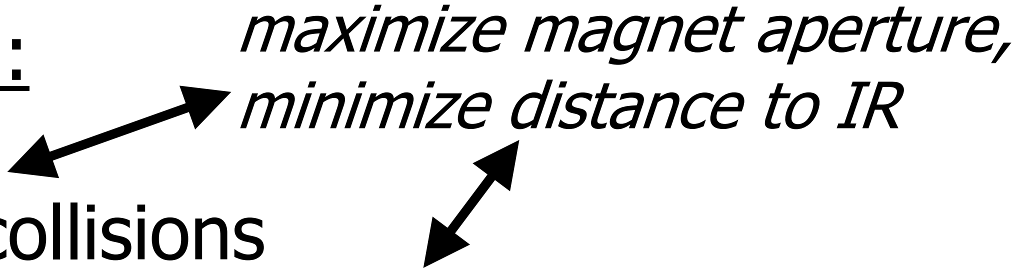
Tentative milestones for future machine studies

- **2006**: installation and test of a beam-beam long range compensation system at RHIC to be validated with colliding beams
- **2006/2007**: new SPS experiment for crystal collimation, complementary to recent positive results at the Tevatron reported by V. Shiltsev
- **2006**: installation and test of Crab cavities at KEKB to validate higher beam-beam limit and luminosity with large crossing angles
- **2007**: if KEKB test successful, test of Crab cavities in a hadron machine (RHIC?) to validate low RF noise and emittance preservation

Interaction Region upgrade

goal: reduce *β^** by at least a factor 2

options: NbTi 'cheap' upgrade, NbTi(Ta), Nb_3Sn
new quadrupoles
new separation dipoles

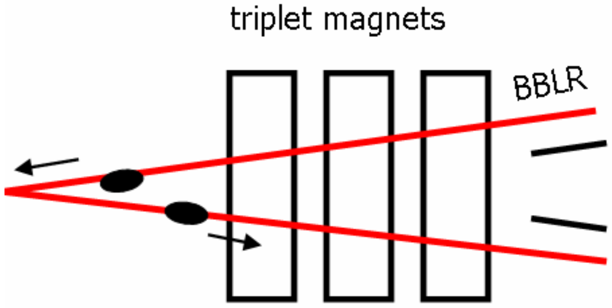


maximize magnet aperture,
minimize distance to IR

factors driving IR design:

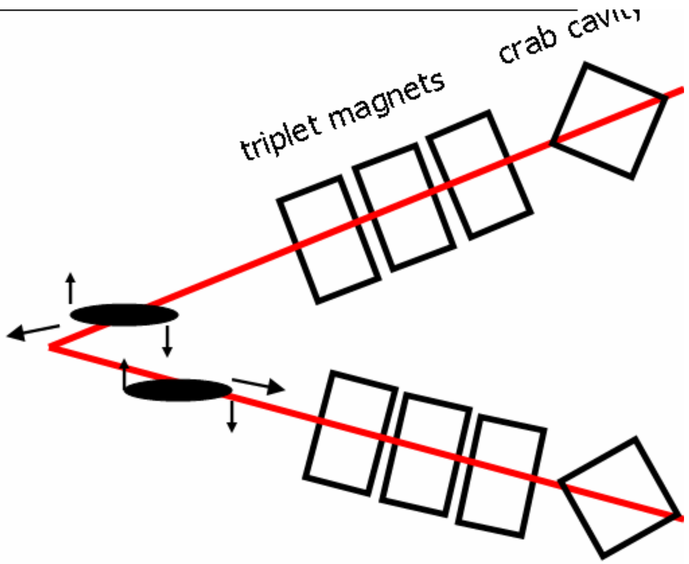
- minimize β^*
- minimize effect of LR collisions
- large radiation power directed towards the IRs
- accommodate crab cavities and/or beam-beam compensators. Local Q' compensation scheme?
- compatibility with upgrade path

IR ‘baseline’ schemes

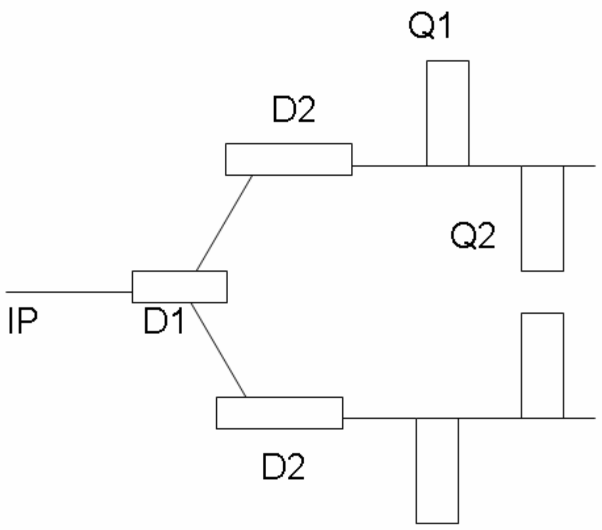


short bunches &
minimum crossing angle &
BBLR

- Requires beams to be in separate focusing channels
- Fewer magnets
- Beams are not round at the IP
- Polarity of Q1 determined by crossing plane – larger beam size in the crossing plane to increase overlap
- Opposite polarity focusing at other IR to equalize beam-beam tune shifts
- Significant changes to outer triplet magnets in matching section.



crab cavities &
large crossing angle
(what is minimum crossing
angle for separate channels?)



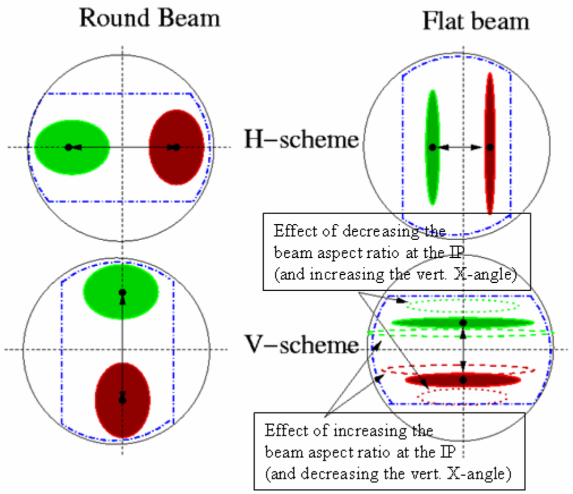
Focusing symmetric about IP

Dipoles first and doublet focusing

Flat beams

- Interesting approach, flat beams could increase luminosity by ~20-30% with reduced crossing angle
- Symmetric doublets studied by J. Johnstone (FNAL) require separate magnetic channels, i.e. dipole-first, Crab cavities or special quads
- Tune footprints are broader than for round beams, since there is only partial compensation of parasitic beam-beam encounters by the H/V crossing scheme. More work needed to evaluate nonlinear resonance excitation.
- Probably requires BBLR compensation
- Recently S. Fartoukh has found a more interesting flat beam solution with anti-symmetric LHC baseline triplets

- Beam screen orientation for H/V scheme



→ In both cases, H-separation of about 9.5*max($\sigma_{x,b1}$,$\sigma_{x,b2}$)

→ In both cases, V-separation of about 9.5*max($\sigma_{y,b1}$,$\sigma_{y,b2}$)

Effect of decreasing the beam aspect ratio at the IP (and increasing the vert. X-angle)

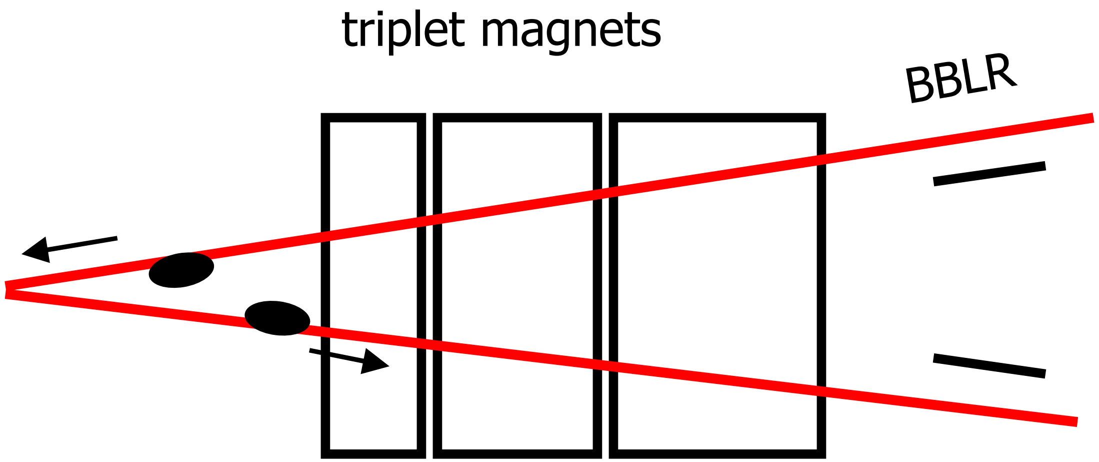
Effect of increasing the beam aspect ratio at the IP (and decreasing the vert. X-angle)

→Find the optimum matching between beam-screen and beam aspect ratio

S. Fartoukh, ABP-RLC meeting, 28-10-2005

‘cheap’ IR upgrade

in case we need to double LHC luminosity earlier than foreseen



short bunches &
minimum crossing angle &
BBLR

each quadrupole individually optimized (length & aperture)
reduced IP-quad distance from 23 to 22 m
conventional NbTi technology: β^*=0.25 m seems possible

LHC-LUMI-05 workshop: some conclusions on the IR Upgrade

Three IR layout options were identified that should be studied in more detail:

1) dipole-first based on Nb3Sn technology with ℓ* = 19 m
2) quad-first layout based on Nb3Sn technology ℓ * = 19 m
3) low gradient quad-first layout based on NbTi technology

- we still need to fix ℓ* and required length for the TAS upgrade. E. Tsesmelis will clarify the ℓ* options with the LHC integration team (agreement to assume ℓ* = 19 m
as a reasonable estimate)
- CARE-HHH web repository with optics solutions is very desirable → we should all use the same input (MADX)
- the goal is to have an update of the 3 proposals by the **end of 2005**

Energy Deposition Issues in LHC IR Upgrades, N. Mokhov (FNAL)

- All three aspects, i.e. *i)* quench limit, *ii)* radiation damage (magnet lifetime), and *iii)* dynamic heat load on the cryo system should be simultaneously addressed in the IR magnet design. *i)* and *ii)* are linked
- The peak power deposition at the non-IP end of IR magnets is approximately proportional to $\int B d\ell$
- Estimated dipole field with TAS in quad-first option to reduce peak energy deposition "well below" quench limits ⇒ **15-20 Tm for magnetic TAS**

  Estimated thickness of internal absorbers?

  ⇒ **a 5 mm thick SS absorber reduces peak power by a factor ~2**

  Choose ℓ^*=19 m ⇒ **no results available yet**
- Scaling laws for energy deposition. What are the limits of validity and how can they be improved? Variation with ℓ^*?

  ⇒ **more work needed**
- Impact of orbit corrector D0 inside the experiment on energy deposition in downstream magnets, including detector solenoid field

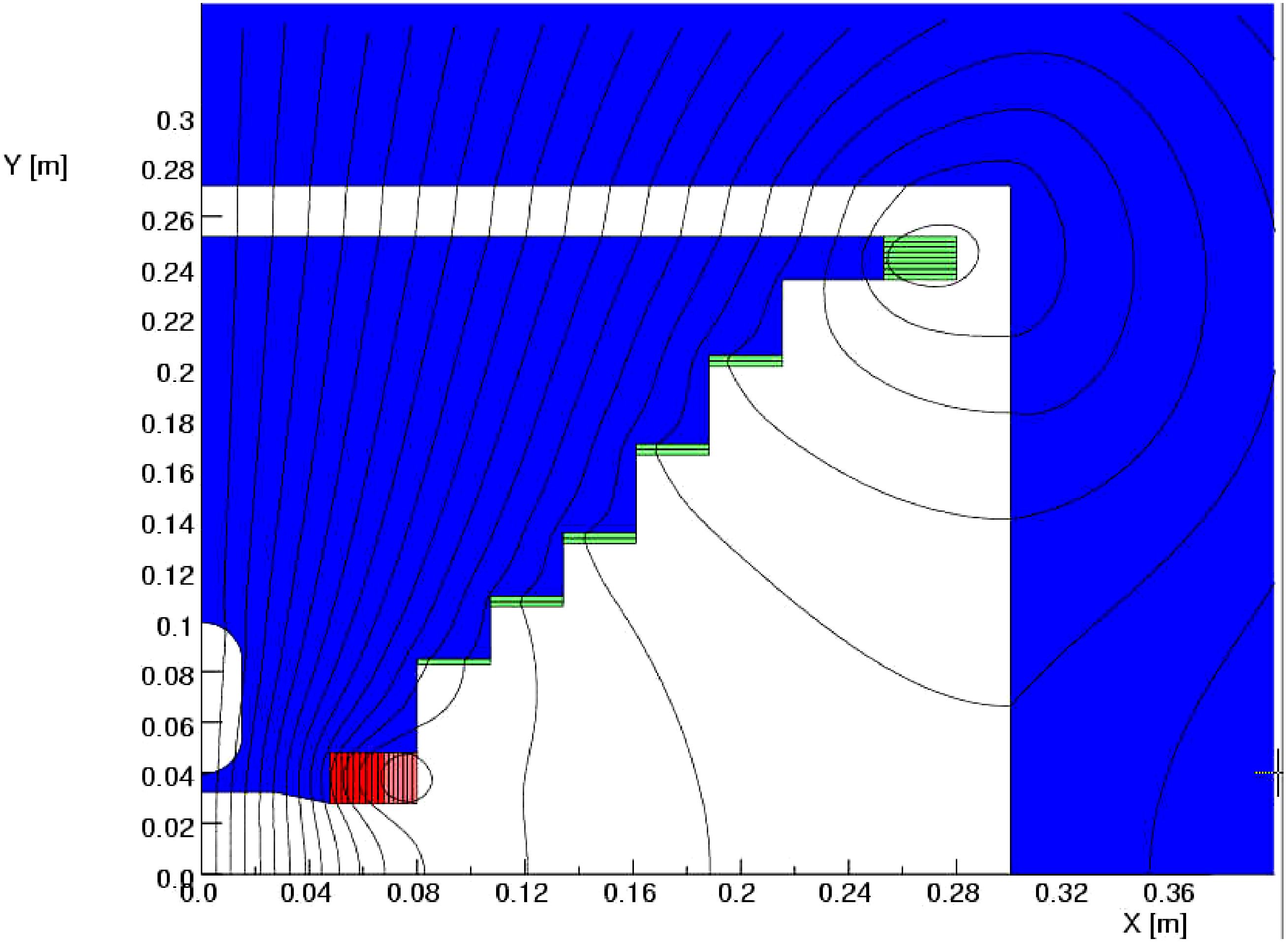
  ⇒ **more work needed, modest impact of solenoid field on energy deposition (more from fringe fields)**

Potential impact of novel magnet technology for IR elements,

Peter McIntyre

- Designs have been suggested for novel magnet technology to mitigate limitations from heat deposition and radiation damage from deposition of secondary particles in the quadrupole triplet and separation dipole. One example is an ironless quadrupole using structured-cable Nb3Sn conductor, which could provide 390 T/m gradient at a location as close as 12 m from the IP, and compatibility with supercritical helium flowing throughout the coils. A second example is a 9 T levitated-pole dipole for D1, which would open the transverse geometry so that secondaries are swept into a room-temperature flux return.
- In order to evaluate the potential benefit of these concepts it is necessary to model the heat deposition and radiation damage in the more compact geometries, and to examine potential interference with the performance of the detectors.
- Of particular importance is to undertake a consistent examination of the impact of reducing ℓ^* on the ensemble of issues that impact achievable β^* the interface of the IR with the machine lattice (chromaticity and dispersion, multipole errors, orbit errors, etc.), and the strategy for accommodating long-range beam-beam effects.
- Also of interest is to evaluate the pros and cons of the alternatives for operating temperature (superfluid, two-phase, or supercritical cooling) for the IR elements that must operate with substantial heat loads.

Latest design: 9 Tesla @ 4.5 K



All windings are racetracks.

Only pole tip winding is Nb_3Sn.

All others are NbTi.

Support each pole piece using tension struts (low heat load).

56 mm clear aperture

Action Items from the IR-2005 mini-workshop

- CERN beam physicists will circulate a draft proposal for aperture and field quality requirements
- CERN beam physicists will circulate a draft proposal to assess and compare the performance of any IR solution, including quantitative considerations for luminosity or lifetime (possibly based on tune footprints for off-momentum particles)

Tentative conclusions for the LHC IR Upgrade

- We do need a back-up or intermediate IR upgrade option based on NbTi magnet technology. What is the maximum luminosity?
- A vigorous R&D programme on Nb_3Sn magnets should start at CERN asap, in parallel to the US-LARP programme, to be ready for 10^{35} luminosity in ~2015
- Alternative IR layouts (quadrupole-first, dipole-first, D0, flat beams, Crab cavities) should be rated in terms of technological and operational risks/advantages

Reference LHC Luminosity Upgrade: workpackages and tentative milestones

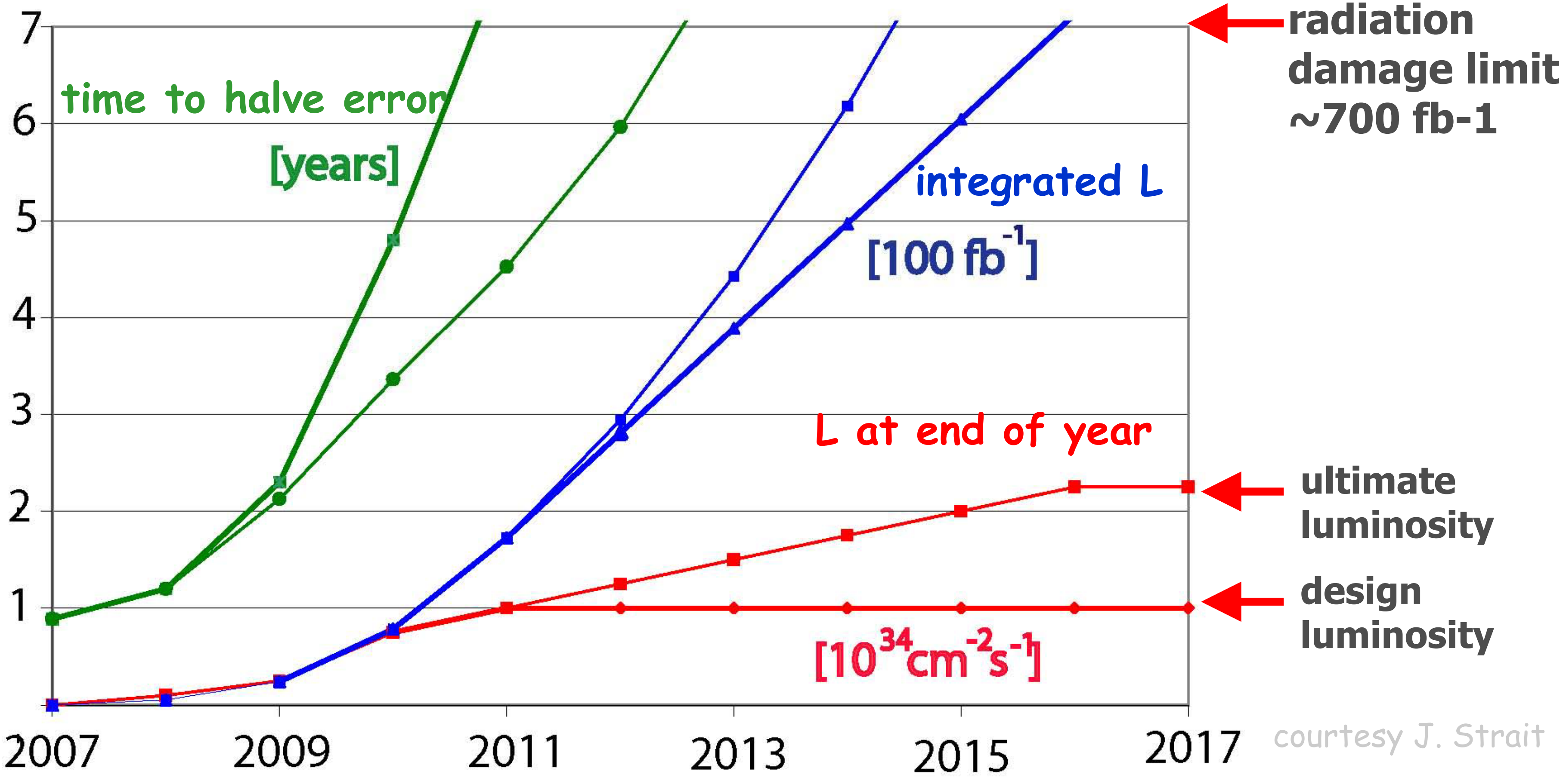
accelerator	WorkPackage	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	after 2015
LHC Main Ring	Accelerator Physics	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩		
	High Field Superconductors	🟥	🟥	🟨	🟨	🟨	🟩	🟩	🟩			
	High Field Magnets		🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟦	
	Magnetic Measurements			🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟦	
	Cryostats					🟥	🟨	🟨	🟩	🟩	🟦	
	Cryogenics: IR magnets & RF		🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟦	
	RF and feedback	🟥	🟨	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟦	
	Collimation&Machine Protection	🟥	🟨	🟨	🟩	🟦	🟥	🟥	🟥	🟥		
	Beam Instrumentation	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟦	
	Power converters					🟥	🟨	🟨	🟩	🟩	🟦	
SPS	SPS kickers			🟥	🟥	🟥	🟨	🟨	🟩	🟦		
	Tentative Milestones	Beam-beam compensation test at RHIC	SPS crystal collimation test	LHC collimation tests	LHC collimation tests	Install phase 2 collimation	LHC tests: collimation & beam-beam			Install new SPS kickers	new IR magnets and RF system	
	Other Tentative Milestones	Crab cavity test at KEKB	Low-noise crab cavity test at RHIC	**LHC Upgrade Conceptual Design Report**		LHC Upgrade Technical Design Report	Nominal LHC luminosity 10^34			Ultimate LHC luminosity 2.3x10^34	beam-beam compensation	Double ultimate LHC luminosity 4.6x10^34

LHC Upgrade Reference Design Report

R&D - scenarios & models	🟥
specifications & prototypes	🟨
construction & testing	🟩
installation & commissioning	🟦

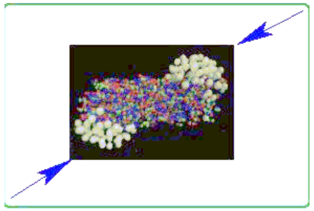
Reference LHC Upgrade scenario: peak luminosity 4.6x10^34/(cm^2 sec)
Integrated luminosity 3 x nominal ~ 200/(fb*year) assuming 10 h turnaround time
new superconducting IR magnets for beta*=0.25 m
phase 2 collimation and new SPS kickers needed to attain ultimate LHC beam intensity of 0.86 A
beam-beam compensation may be necessary to attain or exceed ultimate performance
new superconducting RF system: for bunch shortening or Crab cavities
hardware for nominal LHC performance (cryogenics, dilution kickers, etc) not considered as LHC upgrade
R&D for further luminosity upgrade (intensity beyond ultimate) is recommended: see Injectors Upgrade

Time scale of LHC upgrade



- the **life expectancy of LHC IR quadrupole magnets** is estimated to be **<10 years** owing to high radiation doses
- the **statistical error halving time** will exceed 5 years by 2011-2012
- therefore, it is reasonable to plan a **machine luminosity upgrade based on new low-ß IR magnets before ~2015**

The CARE-HHH Network



Mandate

Coordinate and integrate the activities of the accelerator and particle physics communities, in a worldwide context, towards achieving superior High-Energy High-Intensity Hadron-Beam facilities for Europe

- Roadmap for the upgrade of the European accelerator infrastructure (LHC and GSI accelerator complex)
    - luminosity and energy upgrade for the LHC
    - pulsed SC high intensity synchrotrons for the GSI and LHC complex
    - R&D and experimental studies at existing hadron accelerators
    - select and develop technologies providing viable design options
- Coordinate activities and foster future collaborations
- Disseminate information

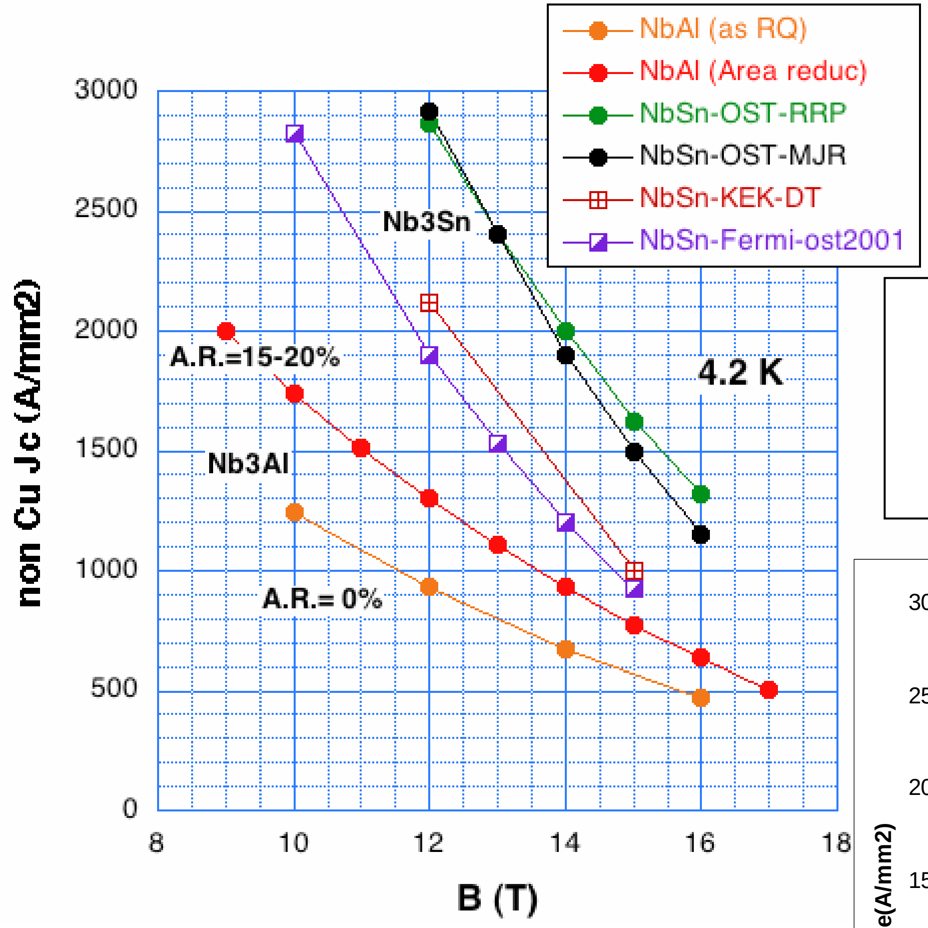
- **HHH coordination: F. Ruggiero (CERN) & W. Scandale (CERN)**

1. Advancement in Acc. Magnet Technology (AMT): L. Rossi (CERN) & L. Bottura (CERN)
2. Novel Meth. for Acc. Beam Instrumentation (ABI): H. Schmickler (CERN) & K. Wittenburg (DESY)
3. Accelerator Physics and Synchrotron Design (APD): F. Ruggiero (CERN) & F. Zimmermann (CERN)

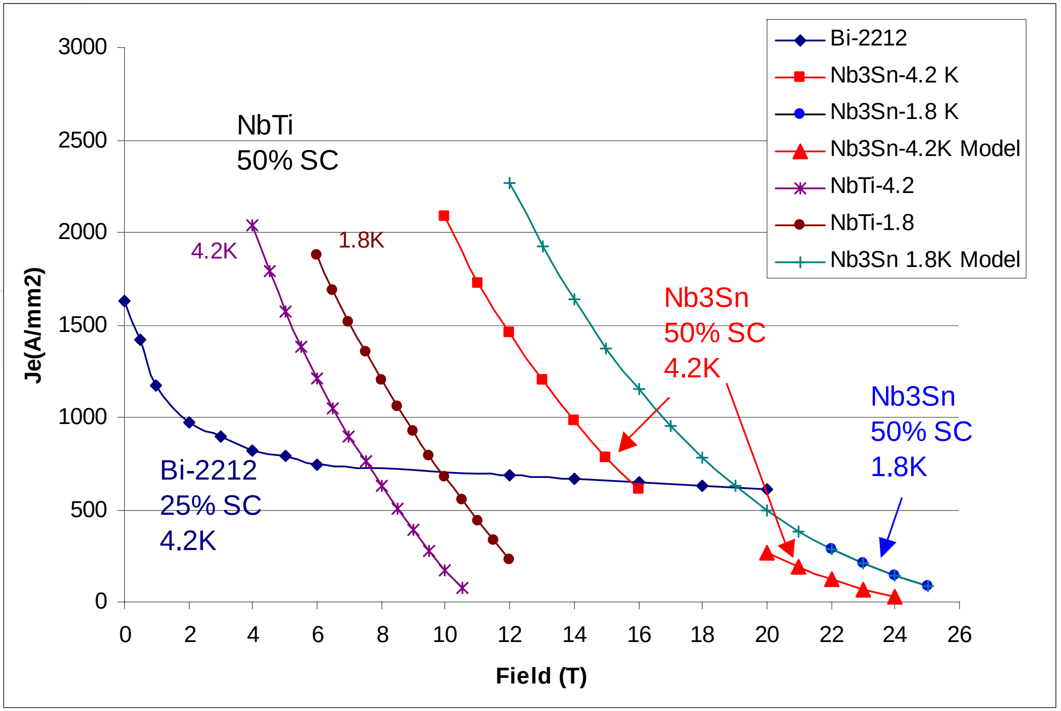
LHC Energy Upgrade from 7 TeV to 14TeV: Conductor Options

- NbTi
    - B_{c2} (0K) ~ 14 T
    - T_c (0K) ~ 9.5 K
        - Max practical field at 4.2 K is 7 T (9 T @ 1.8 K)
        - Excellent mechanical properties
- Nb_3Sn
    - B_{c2} (4.2 K) ~ 23 – 24 T
    - T_c (0T) ~ 18 K
        - Max practical field 17 – 18 T?
        - Brittle and strain sensitive
- Nb_3Al
    - Higher magnetic field capability
        - So far, difficulty in reaching performance level of Nb_3Sn
    - Rapid-quench process requires later addition of stabilizer
    - Actively pursued in Japan with small effort in US
        - National Research Institute for Metals (NRIM)

Nb_3Sn/Nb_3Al Comparison



Conductor Performance Comparison

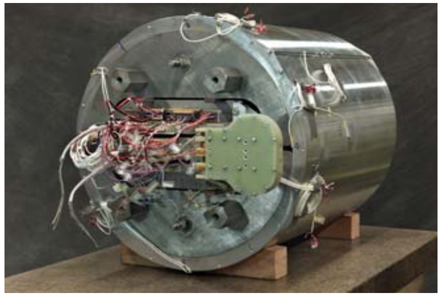


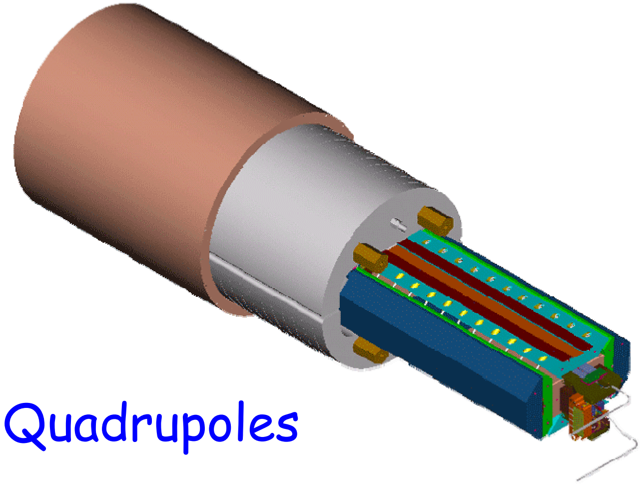
Conductor Development Programs

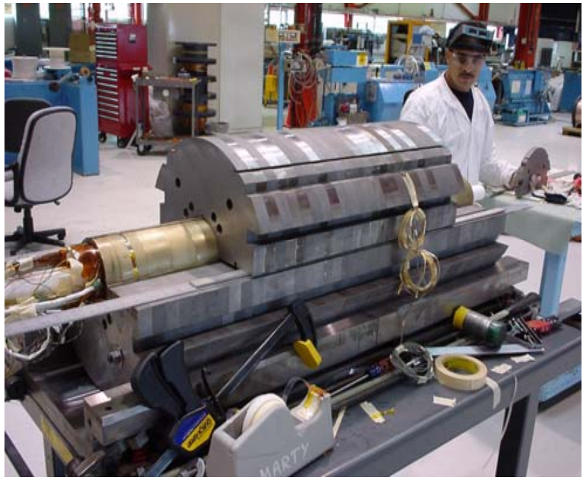
- US/DOE HEP
  - Since 1999 has increase J_c of Nb_3Sn by 50%
    - Over 3,000 A/mm² at 12 T and 4.2 K
    - Working on filament diameter and cost issues
    - SBIR – Nb_3Sn, MgB_2 and past work on Nb_3Al

- EU/CARE NED
  - Parallels US program for Nb_3Sn, aiming at 1500 A/mm² at 15 T and 4.2 K with 50 micron filaments
- Japan
  - Distributed Tin method has produced Nb_3Sn with J_c greater than 2,000 A/mm² at 12 T and 4.2 K with 60 micron filaments (High RRR)
  - Rapid-Heating Quenching Transformation (RHQT) to produce Nb_3Al
    - Collaboration between KEK and NIMS

High Field Magnets







- Interaction Region (IR) Quadrupoles
  - LHC Luminosity Upgrade
    - LHC Accelerator Research Program (LARP)
    - Next Eurpoean Dipole (NED)
  - Linear Collider IR's

Next European Dipole

- Promote high-field Nb_3Sn accelerator magnet R&D in Europe
- It aims at developing a large aperture (88 mm), high field (15 T conductor peak field) dipole magnet, serving two purposes
  - Getting ready for LHC IR upgrade
  - Upgrade of CERN/FRESCA cable test facility
- At present, only Phase I of the program (conductor development and limited studies on insulation and magnet design) has been funded

LHC Energy Upgrade

- New arc dipoles and quadrupoles
  - Expensive
  - Unprecedented dipole fields (> 17 T)
  - Quadrupoles with G ~ 450 T/m in 50 mm bore
  - 15 – 20 year program

Muons, Inc.

The path to Muon Colliders:
- Muon cooling
- Neutrino Factory

Muons, Inc. Grants and Proposals

Rolland Johnson, Muons, Inc.

In the last four years, several new techniques to cool muon beams have been invented and are under development supported by DOE Small Business Innovation Research grants. Muons, Inc. now has 4 Phase II grants and two Phase I grants. On December 1, Muons, Inc. submitted 5 new Phase I proposals. A short summary of the grants and proposals follows.

In February we will have the first annual low-emittance muon collider workshop at Fermilab. The goal is an end-to-end simulation of a believable muon collider. We need a keynote speaker!

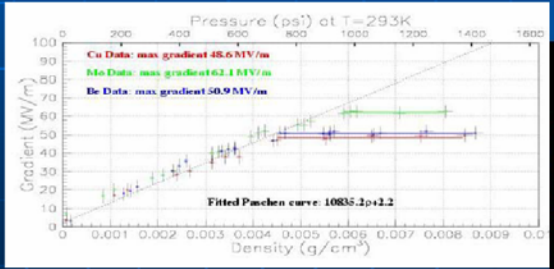
Papers on all that follows at http://www.muonsinc.com
workshop link is at http://www.muonsinc.com/mcwfeb06/

Muon Beam Cooling Innovations

- Many new inventions and reestablishment of the principle that a neutrino factory should be on the direct path to a muon collider
- Muon Colliders need small transverse emittance and low muon flux for many reasons (see workshop main page)
- A Neutrino Factory using a very cool muon beam which is accelerated in a superconducting proton driver Linac may be very cost-effective
- Several new ideas have arisen in the last 4 years which are being developed under SBIR grants and have the potential to form muon beams with transverse emittances of a few mm-mrad

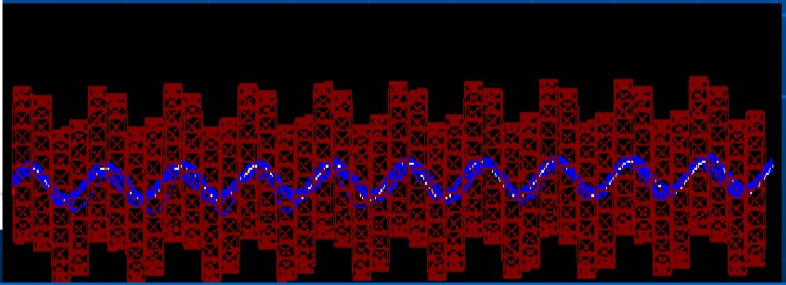
1) **Pressurized High Gradient RF Cavities**
(IIT, Dan Kaplan)

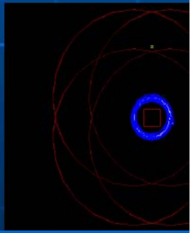
- 800 MHz test cell with GH2 to 1600 psi and 77 K in Lab G, MTA
- Paschen curve verified
- Maximum gradient limited by breakdown of metal
  - fast conditioning seen
- Cu and Be have same breakdown limits (~50 MV/m), Mo ~20% better



2) **Six-Dimensional Cooling in a Continuous Absorber** (JLab, Slava Derbenev)

- Helical cooling channel (HCC)
  - Continuous absorber for emittance exchange
  - Solenoidal, transverse helical dipole and quadrupole fields
  - Helical dipoles known from Siberian Snakes
  - z-independent Hamiltonian
  - Derbenev & Johnson, Theory of HCC, April/05 PRST-AB





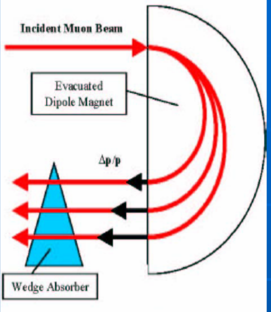


Figure 1. Use of a Wedge Absorber for Emittance Exchange

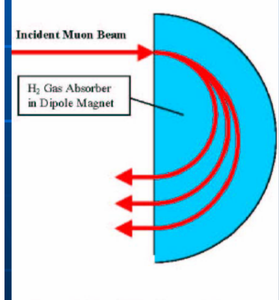
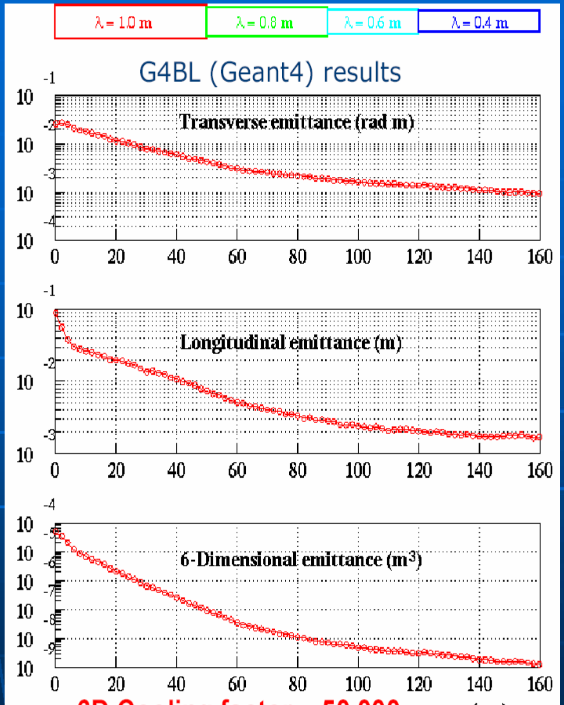


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange



6D Cooling factor ~ 50,000

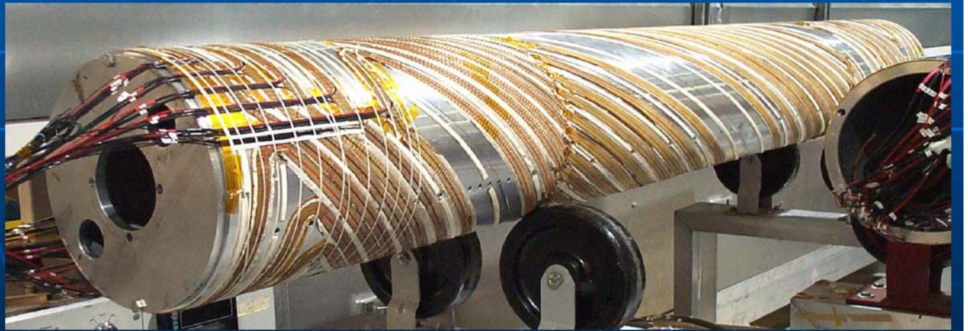
3) **Hydrogen Cryostat for Muon Beam Cooling**
(Fermilab, Victor Yarba)

Technology for HCC components:

HTS (nice BSSCO data from TD Ph I), Helical magnet design,

low T Be or Cu coated RF cavities, windows, heat transport, refrigerant

Cryostat for the 6DMANX cooling demonstration experiment (proposal 7)



BNL Helical Dipole magnet for AGS spin control

2. Report on work carried out in financial year 2004/05

2.1 MICE-UK work package 1: MICE Muon Beam and infrastructure

Over the past year, design work on the various systems required for the MICE Muon Beam and the infrastructure for the MICE experiment has continued. In particular, the cost of MICE, both the UK and the international contributions, has been carefully analysed within the MICE collaboration. A significant contribution to cost saving resulted from a complete revision of the cryogenic system. Each of the magnets in MICE as well as the liquid-hydrogen absorbers and the VLPC cryostats will now be cooled using closed-cycle cryo-coolers [8]. This distributed cooling scheme, obviates the need for a large central refrigerator, a significant saving to the UK infrastructure budget. The fact that each magnet is a self-contained system also has advantages for the magnet suppliers, but at the penalty of a slight increase in the cost of the magnets.

The primary objective of the work on the beam line in 2004/05 was to insure that future work in the MICE Hall could be carried out in parallel to ISIS operation by separating the installation of the beam-line components housed in the synchrotron vault from those housed in the MICE Hall. This was achieved by rearranging the shielding in the MICE Hall and boring the hole that will take the nose of the beam-line solenoid in the wall separating the MICE Hall and the synchrotron vault. The hole was plugged with a concrete-filled steel tube and the shielding was replaced. The MICE Hall is now isolated from the synchrotron vault, allowing work in the MICE Hall to continue during ISIS operation. The elements of the beam line that will be sited in the synchrotron vault and the MICE Hall can now be prepared separately, thus minimising the time required for MICE-related work in the synchrotron vault. The layout of the MICE Muon Beam and the MICE Hall is shown in figure 1.

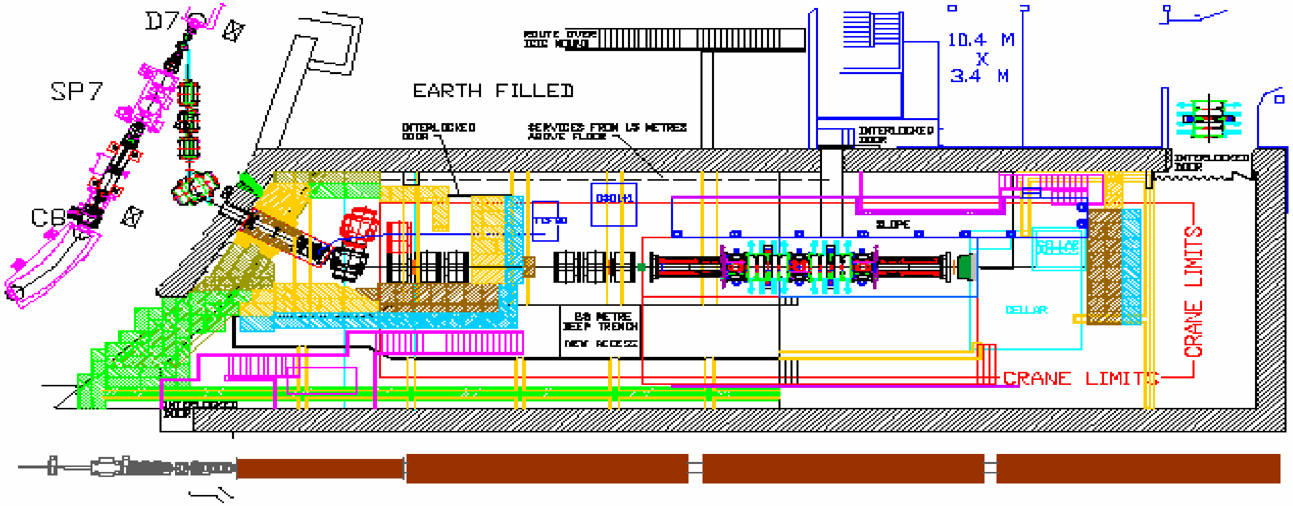


Figure 1: The layout for the MICE Muon Beam and the MICE experiment in the MICE Hall.

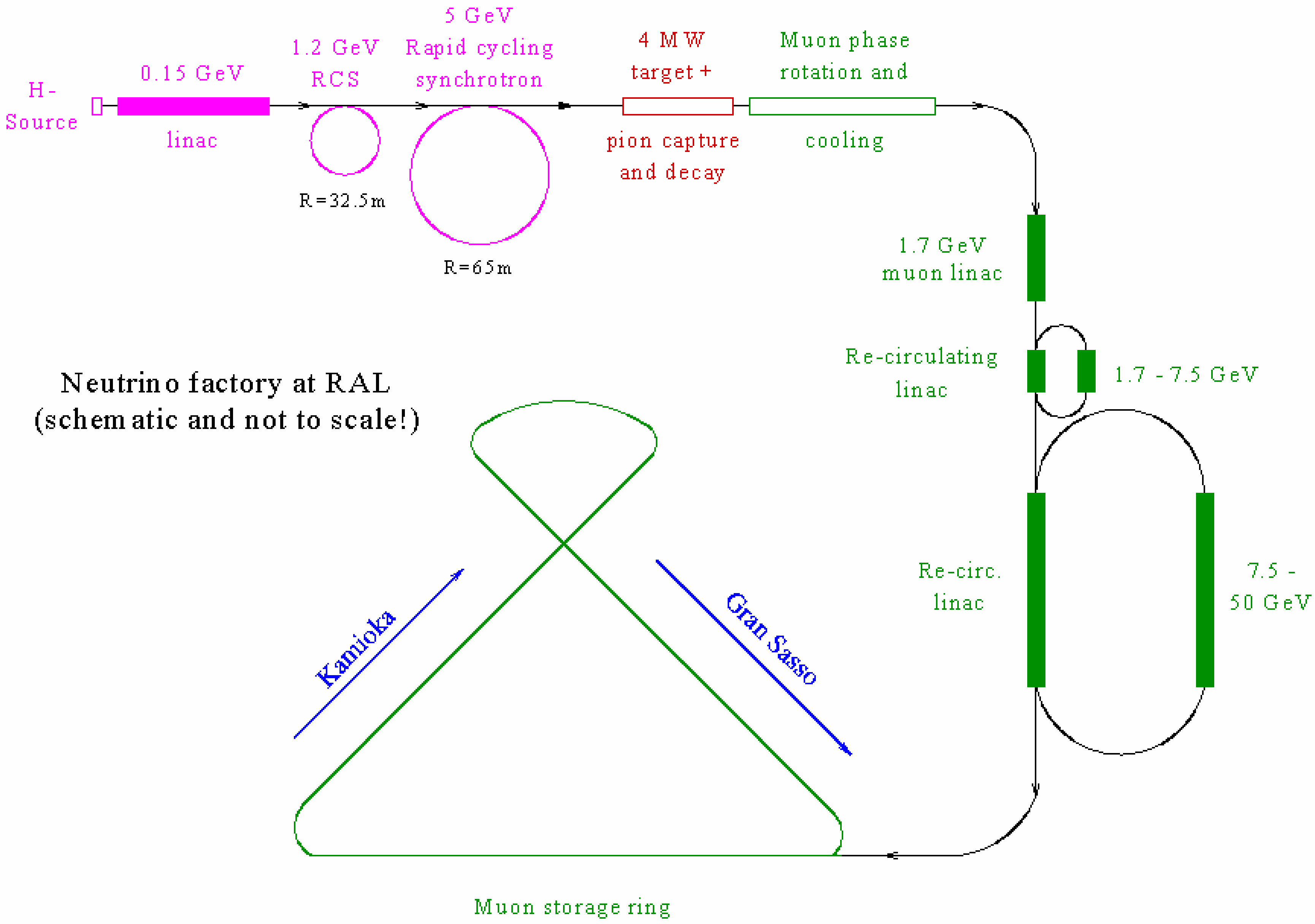
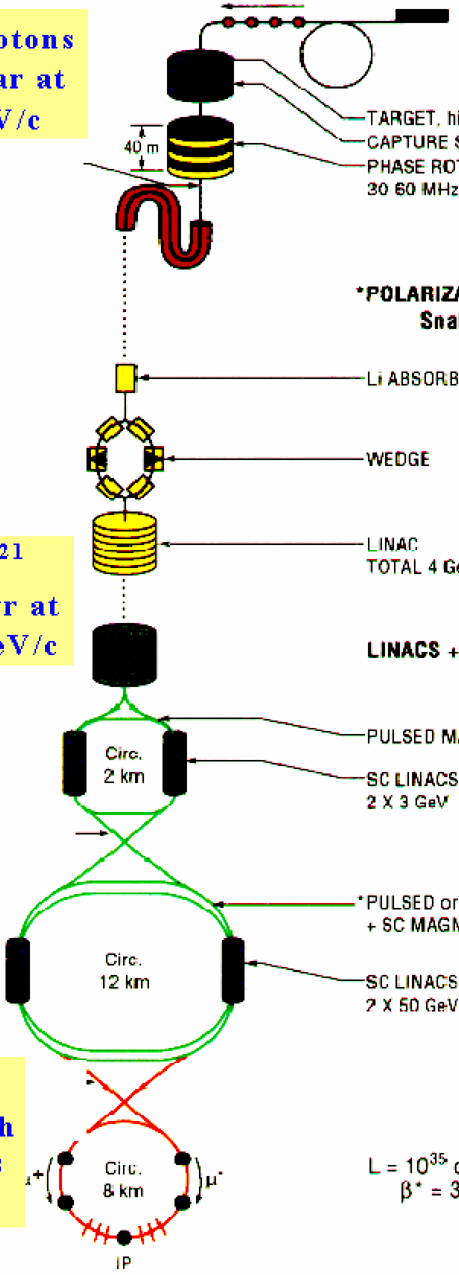


Figure 2: Outline design for a RAL neutrino factory

2 x 2 TeV Muon Collider Schematic

10^{22} protons per year at 8 GeV/c



PROTON SOURCE

TARGET, high Z liquid
CAPTURE SOLENOID, 20T
PHASE ROTATION,
30 60 MHz, 5T

40 m

μ PRODUCTION

***POLARIZATION & P SELECTION**
Snake + Collimator

Li ABSORBER

WEDGE

IONIZATION COOLING
20 Stages

LINAC
TOTAL 4 GeV, 900 m

2 x 10^{21} muons/yr at ~100 MeV/c

LINACS + RECIRCULATION

PULSED MAGNETS

Circ.
2 km

SC LINACS
2 X 3 GeV

*PULSED or ROTATING
+ SC MAGNETS

Circ.
12 km

SC LINACS
2 X 50 GeV

FAST ACCELERATION

~2 x 10^{12} muons/bunch x 4 bunches x 15 Hz

μ^+

Circ.
8 km

μ^-

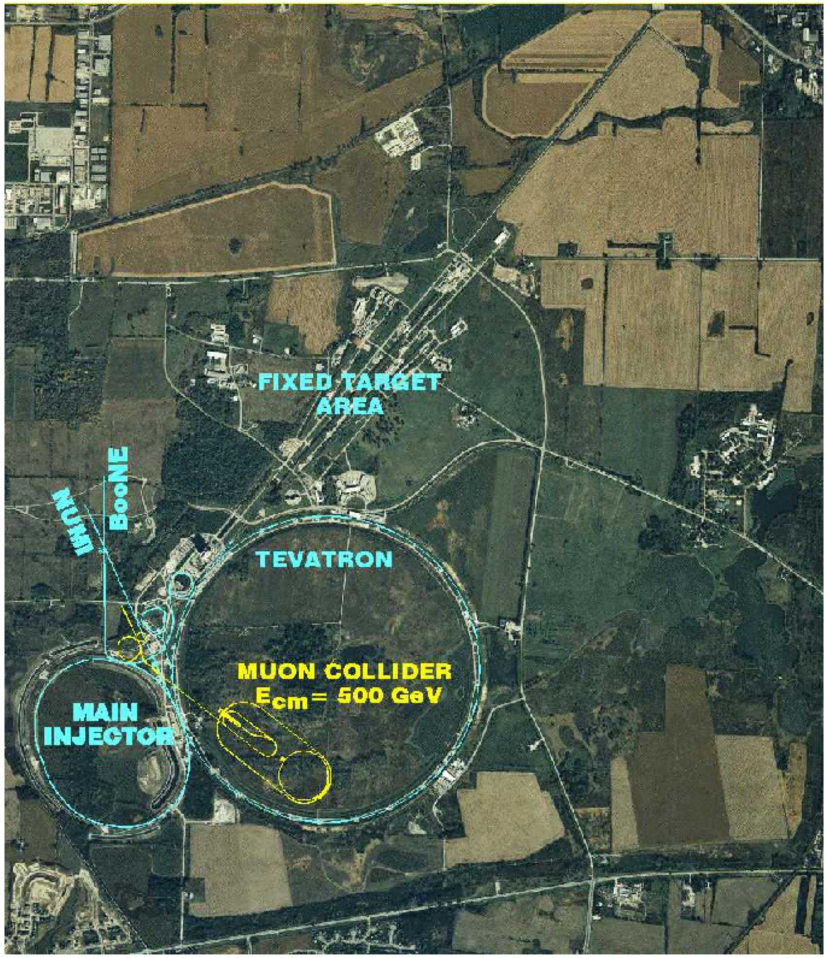
IP

$L = 10^{35}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
$\beta^* = 3$ mm

COLLIDER RING

CANDIDATE MUON COLLIDER (E_{cm} = 500 GeV)

July 1998
FERMILAB



Intermediate Energy Luminosity Frontier

- To complement the Physics reach of the High Energy Machines several very high luminosity Factories are being considered

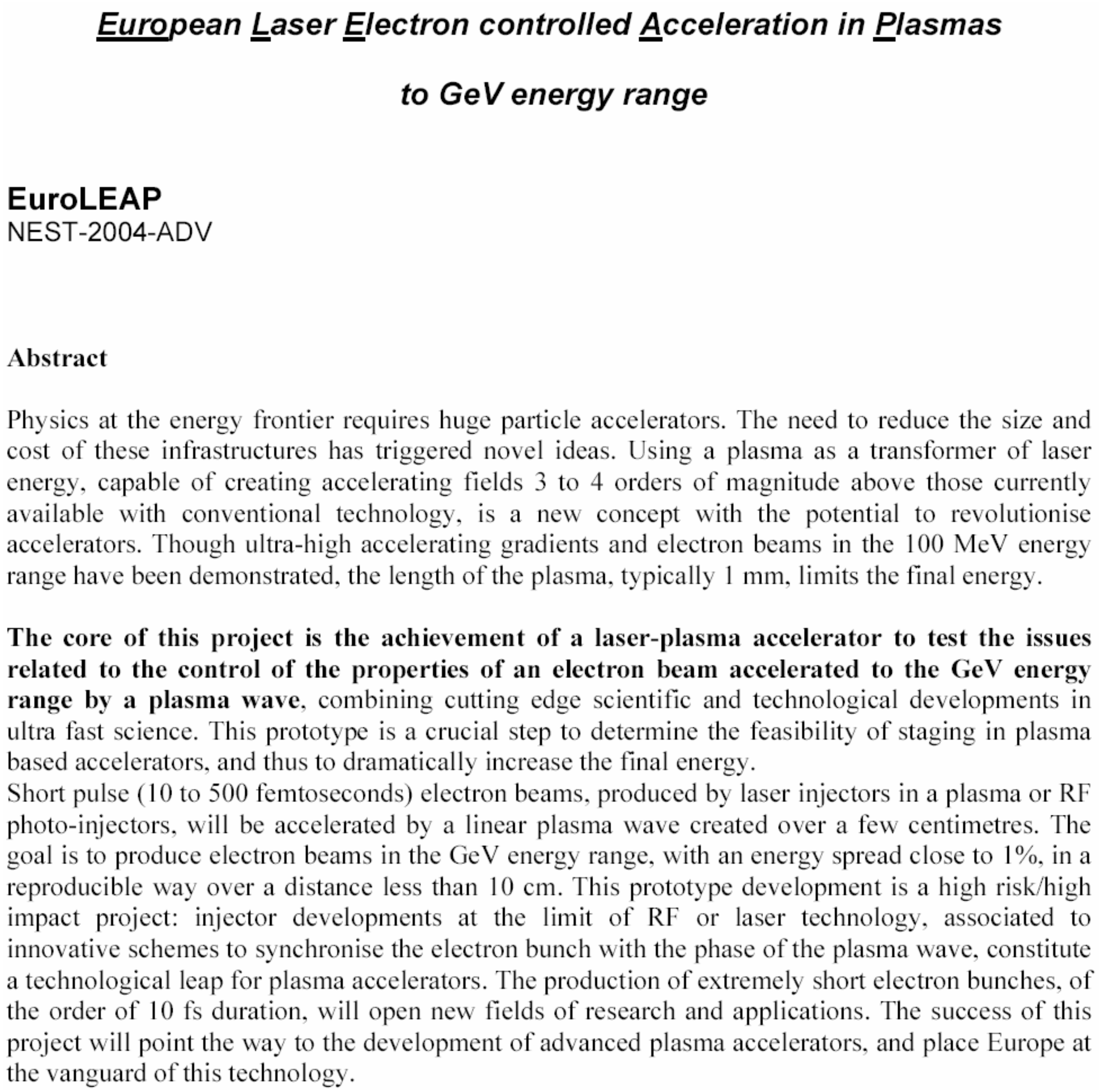
- KEK-B upgrade to exceed $2*10^{35}$, to be approved and build around 2010

- Dafne-Phi to exceed 10^{33} to be approved and build around 2010

- SuperB aimed to exceed 10^{36}, under very preliminary conceptual study, at least around 2015

Ultra High Energy Luminosity Frontier

- Several techniques are being investigate to push the energy frontier.
- Plasma acceleration R&D is very vigorous around the world



European Laser Electron controlled Acceleration in Plasmas

to GeV energy range

EuroLEAP
NEST-2004-ADV

Abstract

Physics at the energy frontier requires huge particle accelerators. The need to reduce the size and cost of these infrastructures has triggered novel ideas. Using a plasma as a transformer of laser energy, capable of creating accelerating fields 3 to 4 orders of magnitude above those currently available with conventional technology, is a new concept with the potential to revolutionise accelerators. Though ultra-high accelerating gradients and electron beams in the 100 MeV energy range have been demonstrated, the length of the plasma, typically 1 mm, limits the final energy.

The core of this project is the achievement of a laser-plasma accelerator to test the issues related to the control of the properties of an electron beam accelerated to the GeV energy range by a plasma wave, combining cutting edge scientific and technological developments in ultra fast science. This prototype is a crucial step to determine the feasibility of staging in plasma based accelerators, and thus to dramatically increase the final energy.

Short pulse (10 to 500 femtoseconds) electron beams, produced by laser injectors in a plasma or RF photo-injectors, will be accelerated by a linear plasma wave created over a few centimetres. The goal is to produce electron beams in the GeV energy range, with an energy spread close to 1%, in a reproducible way over a distance less than 10 cm. This prototype development is a high risk/high impact project: injector developments at the limit of RF or laser technology, associated to innovative schemes to synchronise the electron bunch with the phase of the plasma wave, constitute a technological leap for plasma accelerators. The production of extremely short electron bunches, of the order of 10 fs duration, will open new fields of research and applications. The success of this project will point the way to the development of advanced plasma accelerators, and place Europe at the vanguard of this technology.