Future Hadron Colliders

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ICHEP 2000, Osaka, Japan

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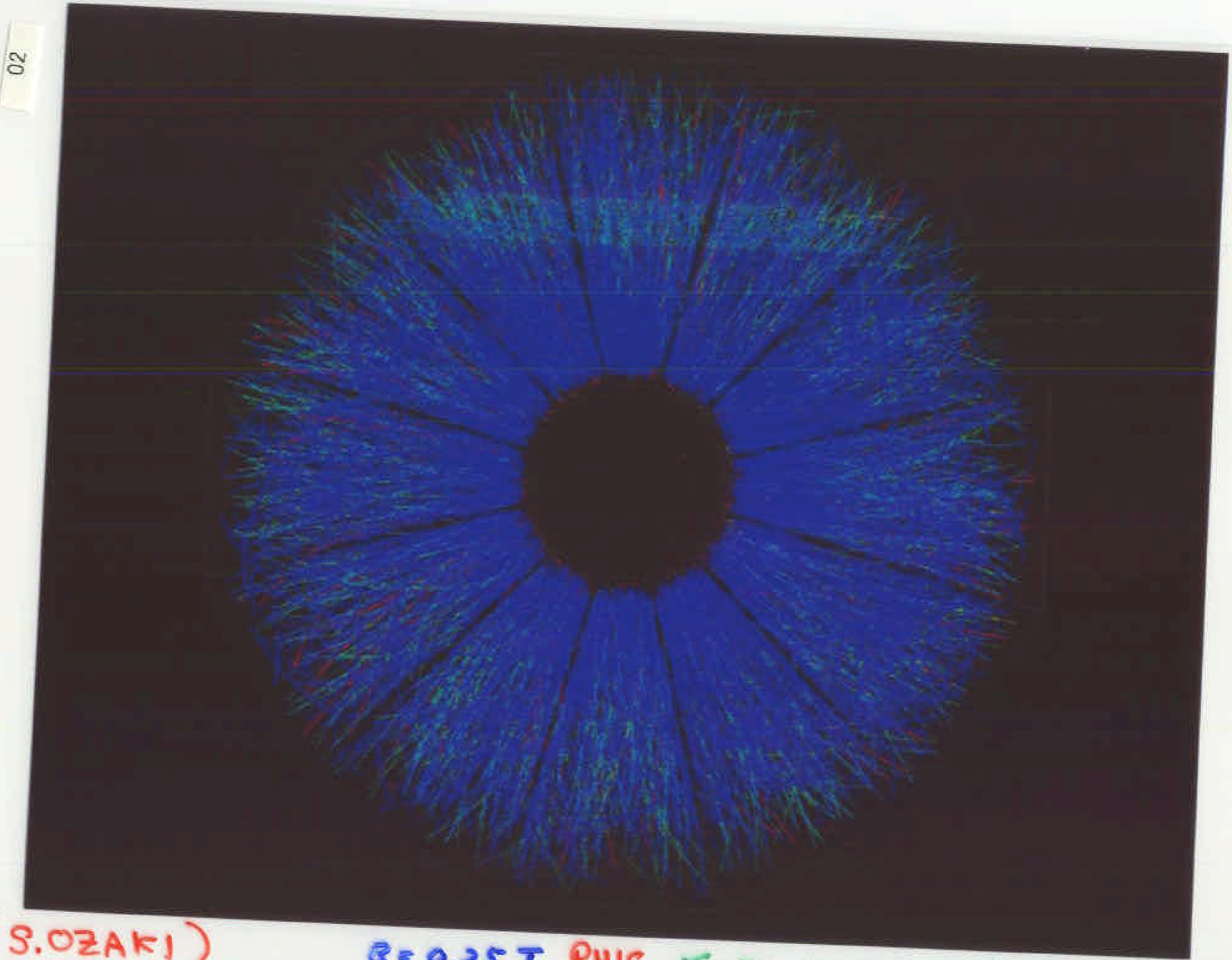


(S.OZAKI)

B=0.25T RHIC γ=70 Au-Au 26 TeV, 66 GeV/u

- Tevatron Collider upgrade
- LHC
- "VLHC"

(S. Holmes)

(W. Barletta)

Tevatron Collider upgrade

- Collider Run IB (1993-96) Performance
- Run II Goals
- Accelerator Status
- Detector Status
- Longer Term Prospects

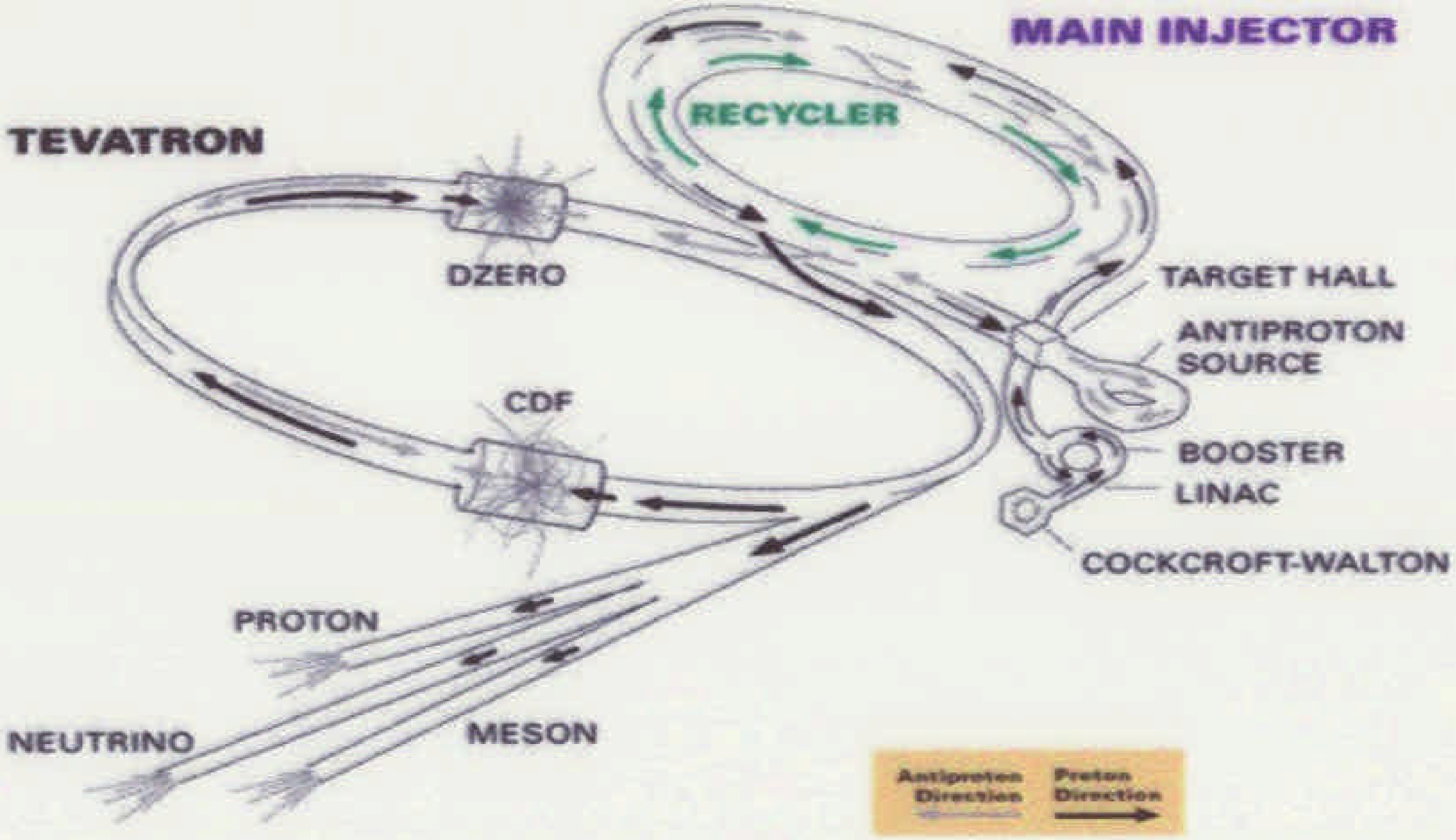
Collider Run IB (1993-96) Performance

The last Tevatron Collider Run was completed over the period 1993-96. An integrated luminosity of approximately 150 pb^{-1} was delivered to each detector at E_{cm} = 1800 GeV

- Delivered luminosity = 2 pb^{-1}/week (end of run)
- Typical initial luminosity = 1.6×10^{31} $cm^{-2}sec^{-1}$ (end of run)

Record initial luminosity = 2.5×10^{31} $cm^{-2}sec^{-1}$
Record monthly integrated luminosity = 18 pb^{-1}

Fermilab's
ACCELERATOR CHAIN



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Goals of the upgrade

- The Fermilab Tevatron is the highest energy collider operating in the world today. The aim of upgrade projects currently nearing completion is to exploit the capabilities of the Tevatron to the fullest extent possible while it retains this unique position.

- *Collider Performance Goals*
- The initial Run II goal is to deliver an integrated luminosity of >2 fb^{-1} by about the end of 2002.

- ⇒ *Run II Luminosity Goal:* >8-20x$10^{31}cm^{-2}sec^{-1}$

Requirements for Collider Run II

For Run II the Fermilab complex will be required to support:

- More protons in collision
- Many more antiprotons in collision
- A significant increase in the antiproton stacking rate
- Recovery of antiprotons at the end of stores

Run II schedule

- The Fermilab complex is being readied for the start of Collider Run II.
- Tevatron collider changeover will be initiated in the winter of 2000, with a collider commissioning run scheduled to start in spring/summer 2000.
- Significant upgrades to the collider detectors are underway to capitalize fully on improved Tevatron collider performance:
- \- *A detector commissioning run, without silicon, is scheduled for fall 2000.*
- Start-up of Run II with both completed detectors is expected in late winter/early spring 2001.

Possible Accumulation of Luminosity in the pre-LHC Era

2001	Main Injector and Recycler	0.6	fb^{-1}
2002	Initiate antiproton recycling	1.0	fb^{-1}
2003	Achieve $2x10^{32}$ $cm^{-2}sec^{-1}$	2.0	fb^{-1}
2004	6 month shutdown to install e-cool, 132 nsec, etc.	1.0	fb^{-1}
2005	Achieve $3.5x10^{32}$ $cm^{-2}sec^{-1}$	3.5	fb^{-1}
2006	Achieve $5x10^{32}$ $cm^{-2}sec^{-1}$	4.5	fb^{-1}
2007	Initiate Kaon program?	3.0	fb^{-1}
TOTAL		~15	fb^{-1}

LONGER TERM PROSPECTS

- The initial Run II goal is achievement of a luminosity of ~1×10^{32} $cm^{-2}sec^{-1}$, with 2 fb^{-1} delivered to each detector by end 2002. Further performance enhancements would be based upon:
    - Improved antiproton availability
  - *Electron cooling; liquid lithium lens; increased aperture*
    - Controlling the antiproton (long-range) beam-beam interaction.
  - *Electron beam compensation*
- R&D projects aimed at these improvements are underway
- Expect luminosity could rise to the mid 10^{32} $cm^{-2}sec^{-1}$

LHC

- Overview
- Status report
  - Planning
  - Civil engineering
  - Magnets
  - Cryogenics
- The international aspect

Project Goals

- **Provide design luminosity (10^{34} $cm^{-2}s^{-1}$) at design energy (7+7 TeV)**

- **Schedule**
- 1999 - complete R+D on models and prototypes
- 1999 - order full-size pre-series magnets
- 2001 - 2004 - produce and test magnets
- 2005 - start commissioning machine

2 to 3 years to reach design parameters

Characteristics of the LHC Project

- **Superconductivity**
  NbTi superconductor is now a commodity
  -> high field magnets at reasonable cost

- **Advanced cryogenic technology**
  -> cool with superfluid helium

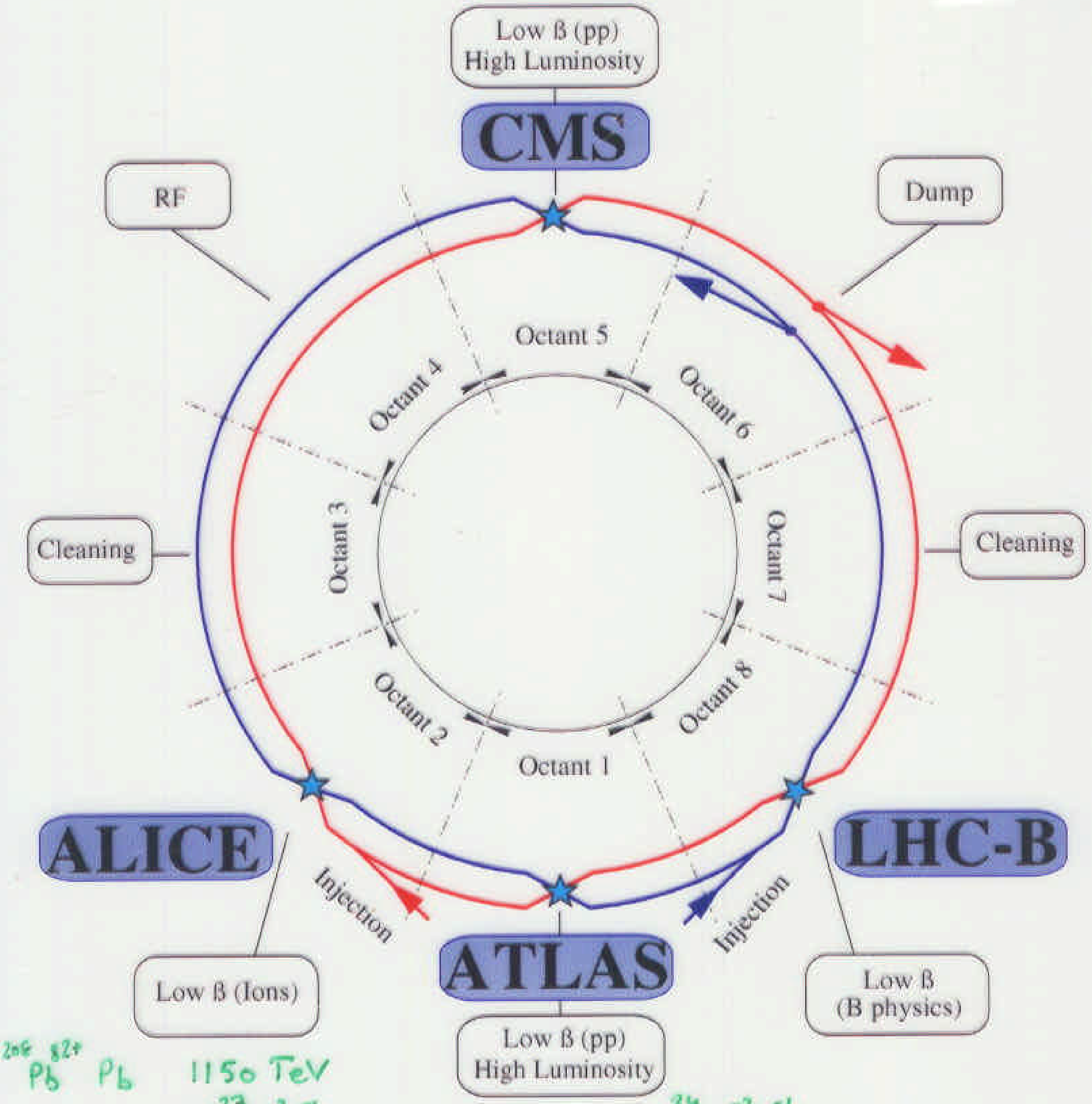
- **Use of accumulated expertise**

ISR -> SppS-> Tevatron -> LEP -> HERA -> SSC -> RHIC-> LHC

- **Re-use of existing infrastructure**
  injector complex suitable for upgrade
  tunnel and cryogenic infrastructure of LEP

Machine performance

Energy	**7 TeV**	*per beam*
Luminosity	**10^{34} cm^{-2}s^{-1}**	*points 1 & 5*
Bunch spacing	**25 ns**	*protons*
Particles/bunch	**1.1 10^{11}**	*protons*
Bunch radius	**16 μm**	*σ*
Bunch length	**75 mm**	*σ*
Crossing angle	**300 μrad**	*full angle*
Luminosity lifetime	**10 h**	*beam: 22 h*
Nearest quadrupole	**23 m**	*- other equipment*
Events per collision	**19**	*high lum. protons*



$^{206}Pb^{82+}$ Pb 1150 TeV

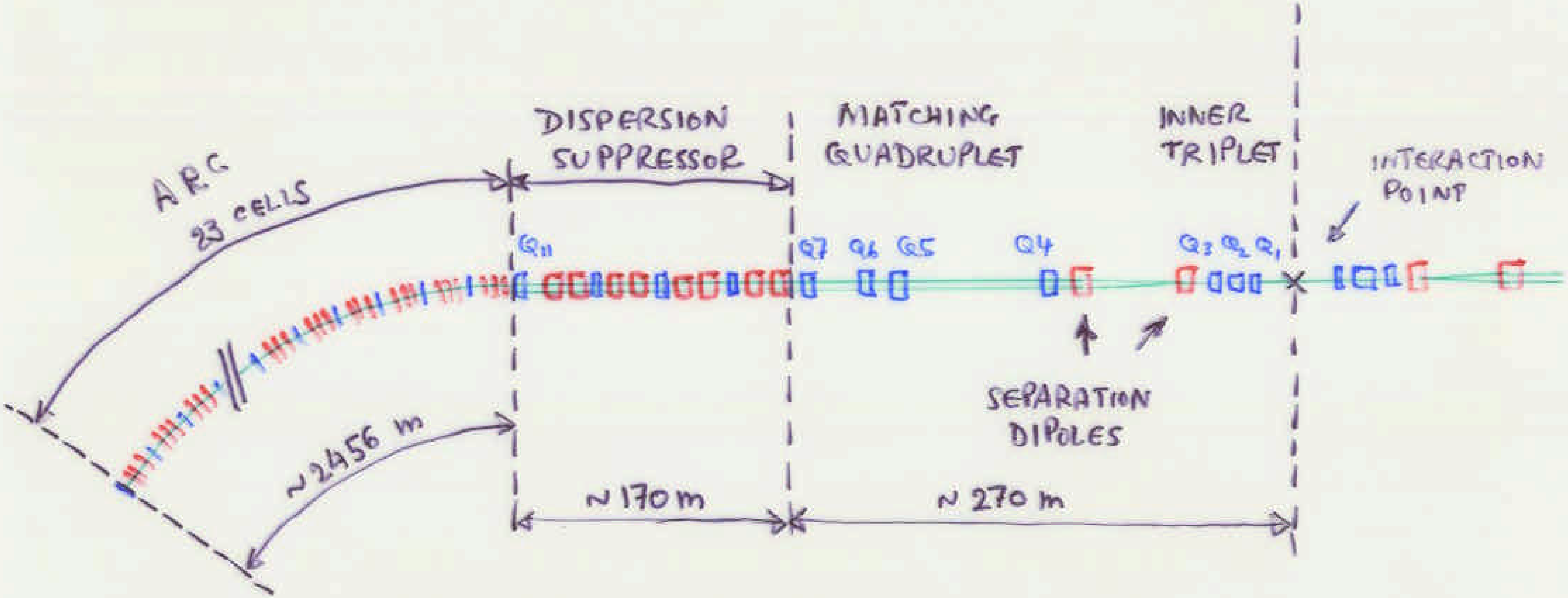
10^{27} cm^{-2} s^{-1}

pp 14 TeV 10^{34} cm^{-2} s^{-1}

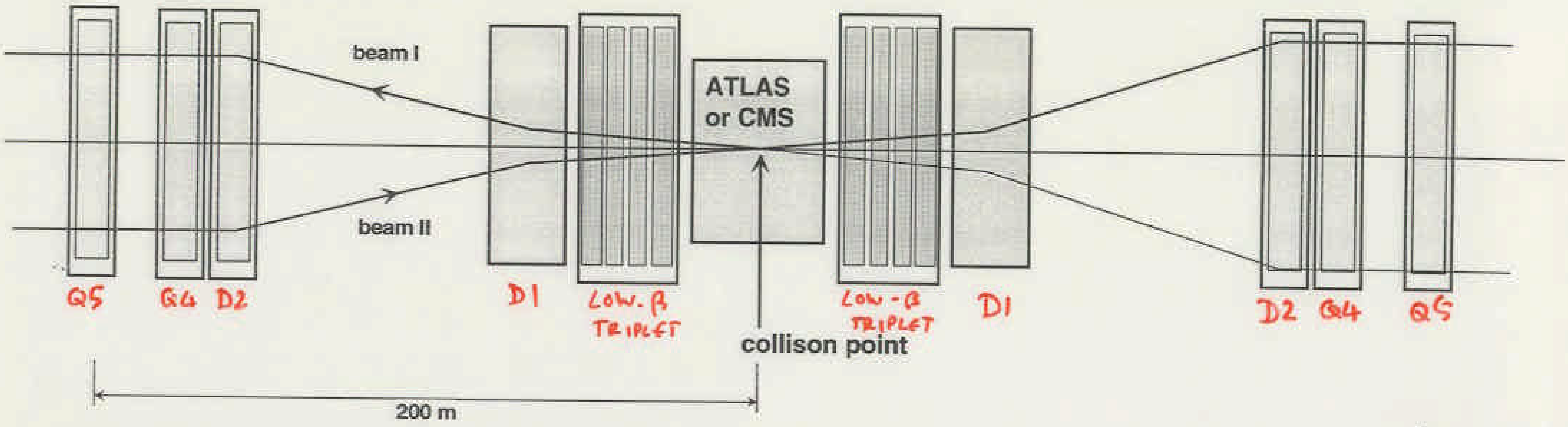
LHC layout

HF239 EXP.

LHC LAYOUT
(SCHEMATIC)



TOTAL CIRCUMFERENCE 26658.883 m



Example for an LHC staight section with one of the experiments

Machine performance - continued -

- Energy

  - **7 TeV** corresponds to 8.35 T in the main dipole.
  The actual energy will depend on the performance of the "worst" magnet of the 1232 in the ring. It is planned to train the magnets up to 9 T. The conductor cross-section is sufficient for > 9.5 T .

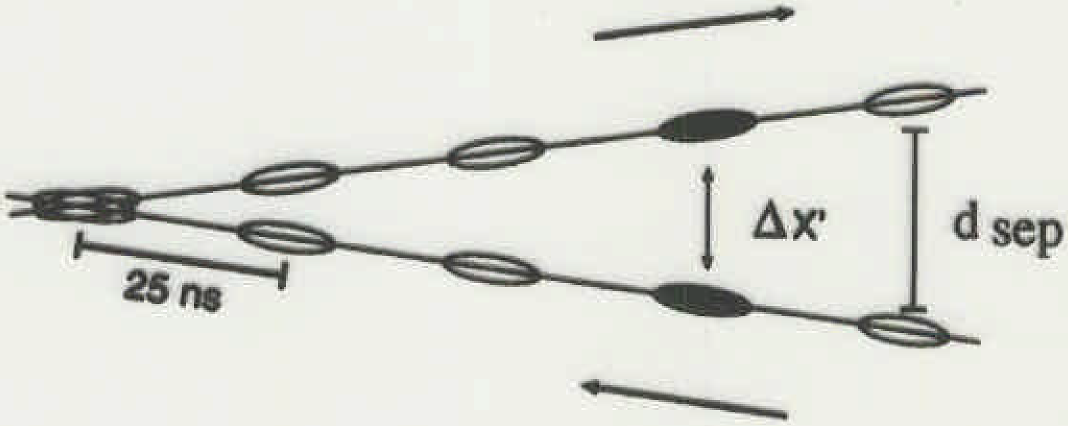
- Bunch spacing

  - **25 ns** is equivalent to about 7.5 m (crossings occur every 3.75 m).
  Luminosity is achieved by accumulating a total 2835 bunches, filling every 10th RF bucket (RF frequency 400 MHz).

- Crossing angle

  - **300 µrad** is required to minimize effect of secondary crossings.
  Long range beam-beam interactions consume the beam-beam budget.

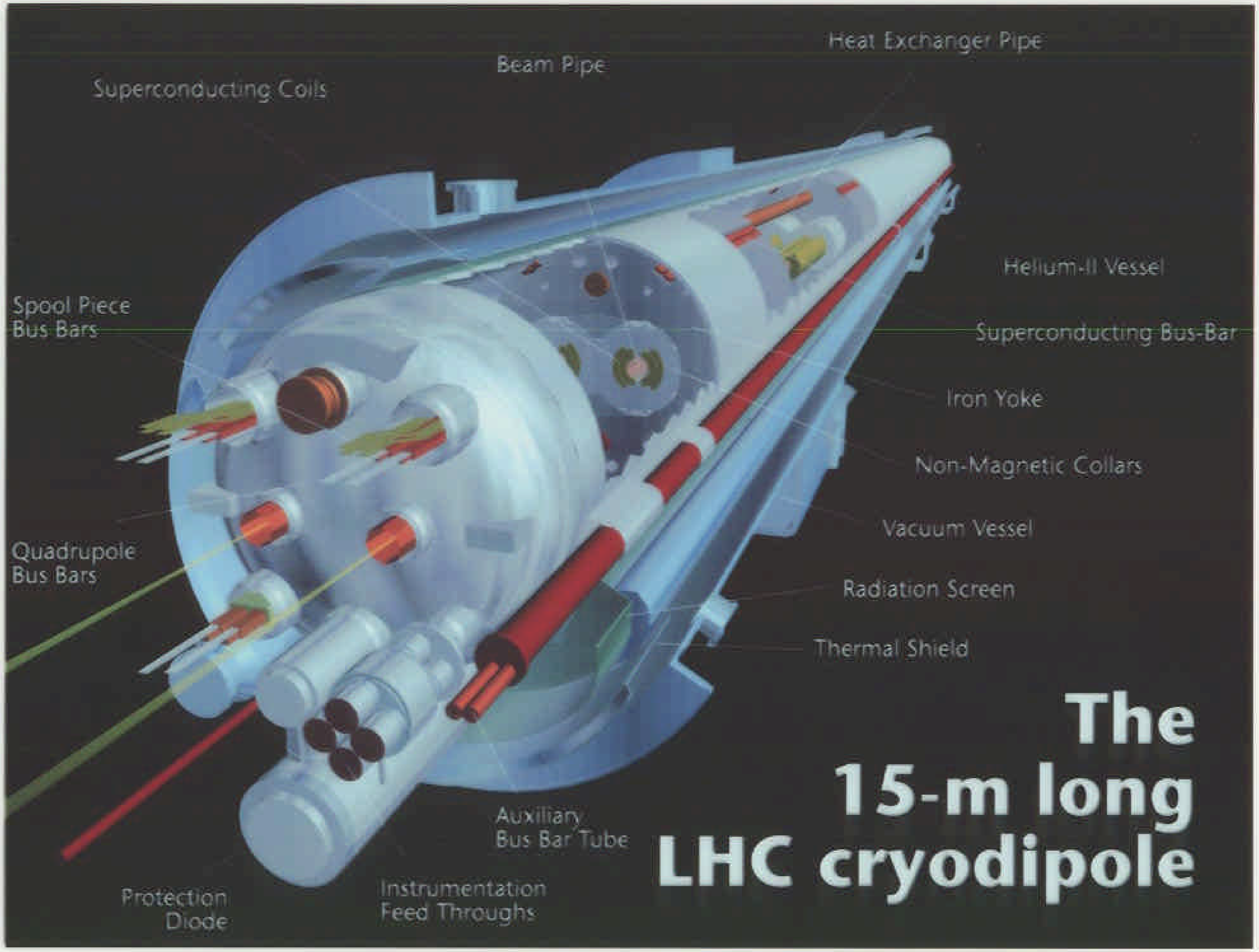
Long range interactions



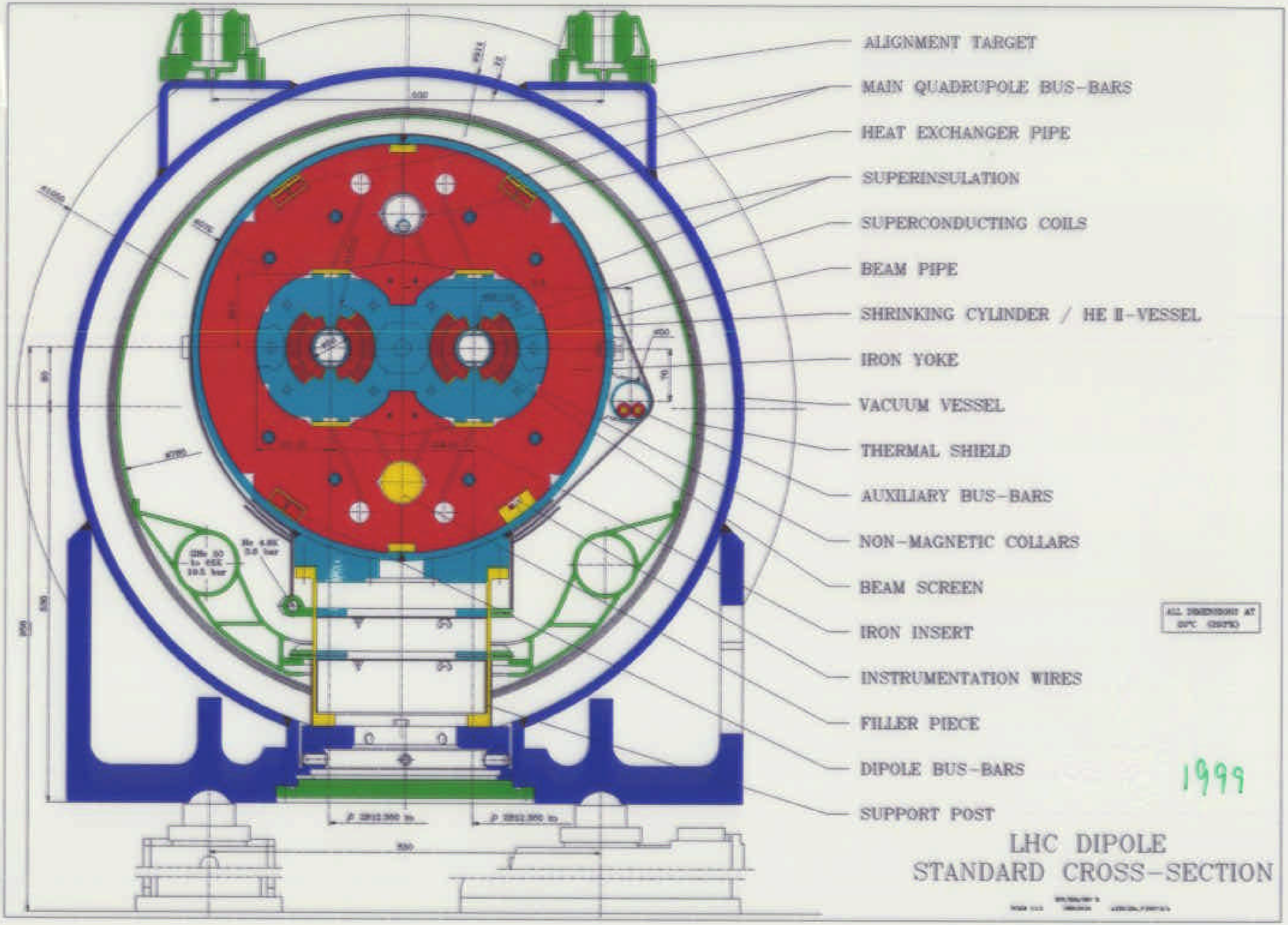
- Number of long range interactions depends on spacing and length of common part
- For standard spacing (25 ns): ≈ 15 collisions on each side
- Effects depend on separation. In driftspace:

$$d_{sep} \approx \frac{\alpha\cdot\beta^*}{\sigma^*} = \frac{\alpha\cdot\sqrt{\beta^*}\cdot\sqrt{\gamma}}{\sqrt{\epsilon^*}} = const.$$

- Most important in high luminosity IP (β^* small)



The 15-m long LHC cryodipole

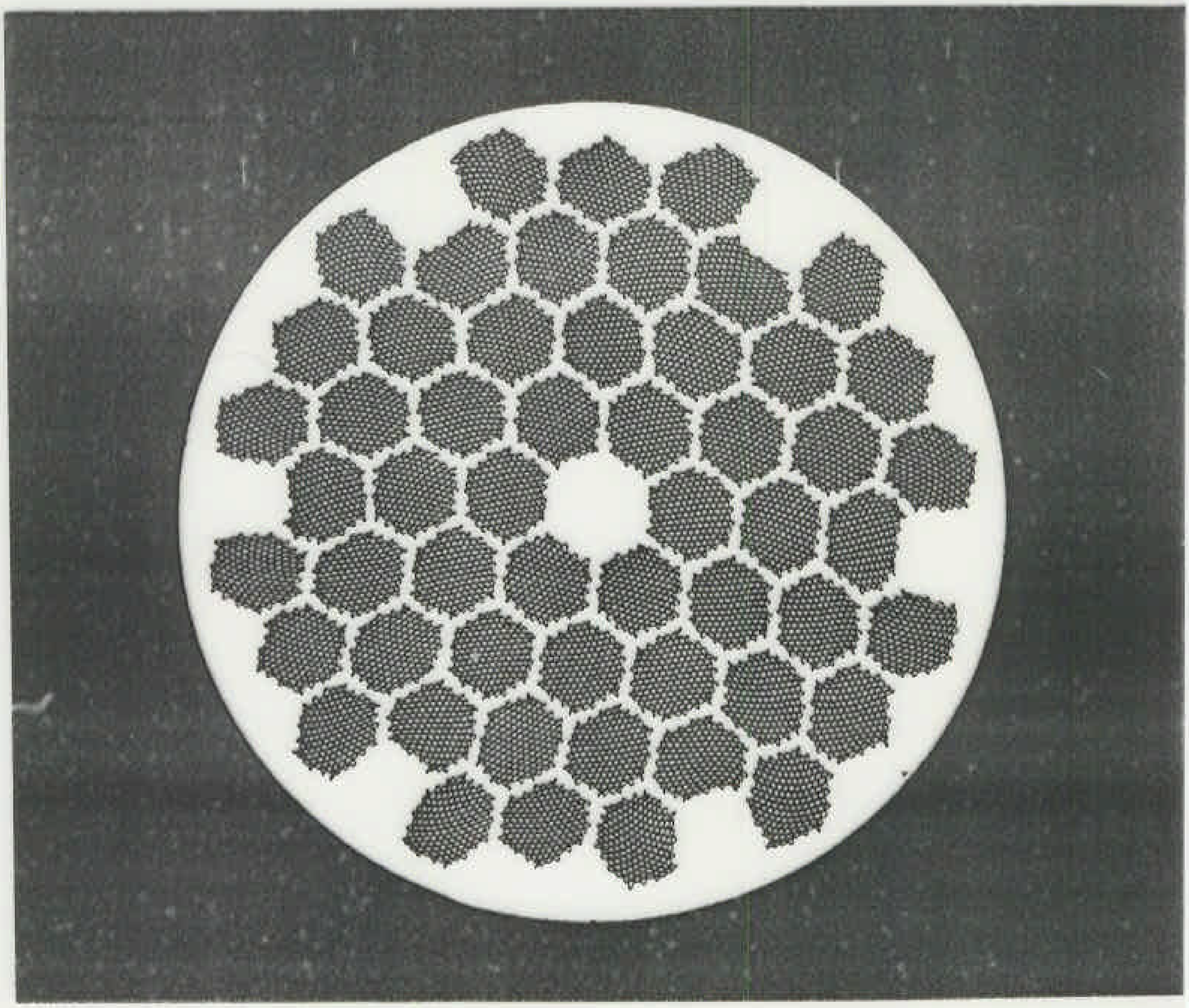


1999

LHC DIPOLE
STANDARD CROSS-SECTION

Superconductor

- The heart of the magnets is the NbTi superconductor
- NbTi is chosen because it is a commodity
    - Thanks to HEP and MRI
- The SC strands are combined in a flat "Rutherford" cable
    - invented at RAL, and first exploited at the Tevatron
    - cable is 15.1 mm wide, of trapezoidal x-section
- High homogeneity material (developed for SSC) is needed
- The dipoles use two grades of cable
    - the outer cable has a higher current density
- In total about 7,000 km of cable are required
    - deliveries have started and will spread over 6 years



Quantity and Delivery Schedule

of Superconducting Cable for LHC Project

Year	Number of Unit Length of Cable1 from European		Number of Unit Length of Cable2 from European		Number of Unit Length of Cable2 from American & Japanese		Total	
1999	52 =	1%	48 =	1%			100 =	1%
2000	576 =	11%	640 =	14%	296 =	19%	1 512 =	13%
2001	968 =	19%	1 028 =	23%	624 =	40%	2 620 =	24%
2002	1 288 =	25%	1 164 =	26%	640 =	41%	3 092 =	28%
2003	1 308 =	25%	972 =	22%			2 280 =	20%
2004	960 =	19%	648 =	14%			1 608 =	14%
Total	5 152 =	100%	4 500 =	100%	1 560 =	100%	11 212 =	100%
Total in km	2 370 km		3 320 km		1 150 km		6 840 km	

Unit Length of Cable1 = 460 m
Unit Length of Cable2 = 750 m for dipoles
= 660 m for quadrupoles

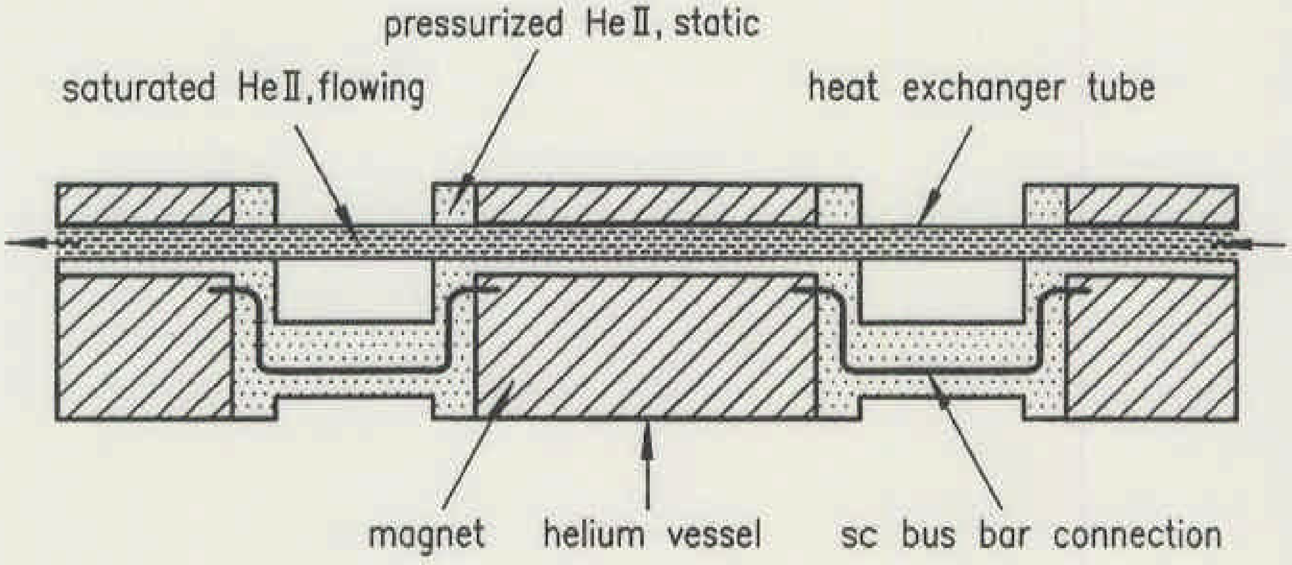
Machine performance - continued

Ions

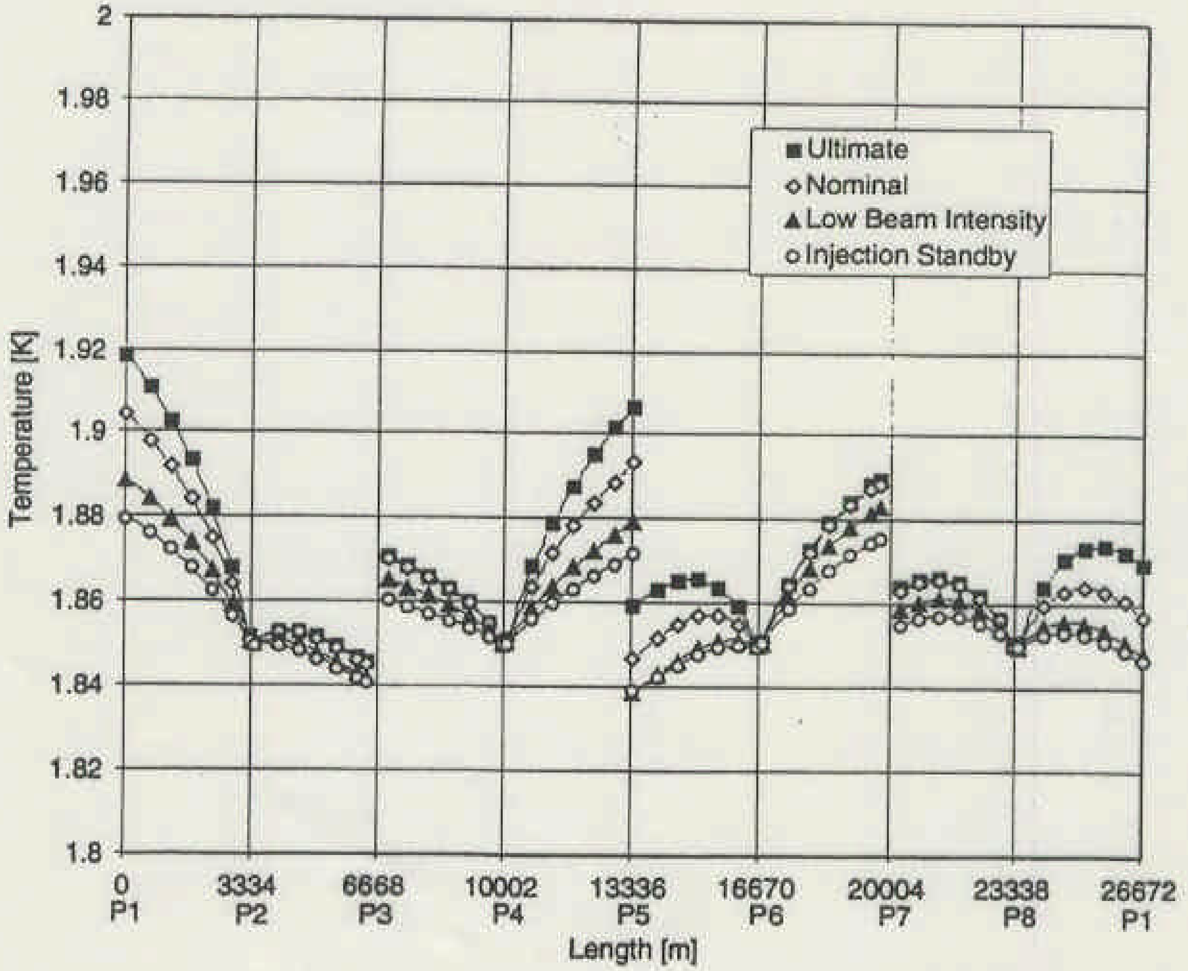
In addition to p-p operation, LHC will be able to collide heavy nuclei produced in the existing accelerator complex.

- Pb-Pb
  - centre-of-mass energy **1150 TeV** (2.76 TeV/u , 7 TeV per charge)
  - Luminosity **10^{27} $cm^{-2}s^{-1}$**
  - bunch spacing **125 ns**
- Lighter ions
  - **Zenon, Oxygen and deuterium** are good candidates. Under study

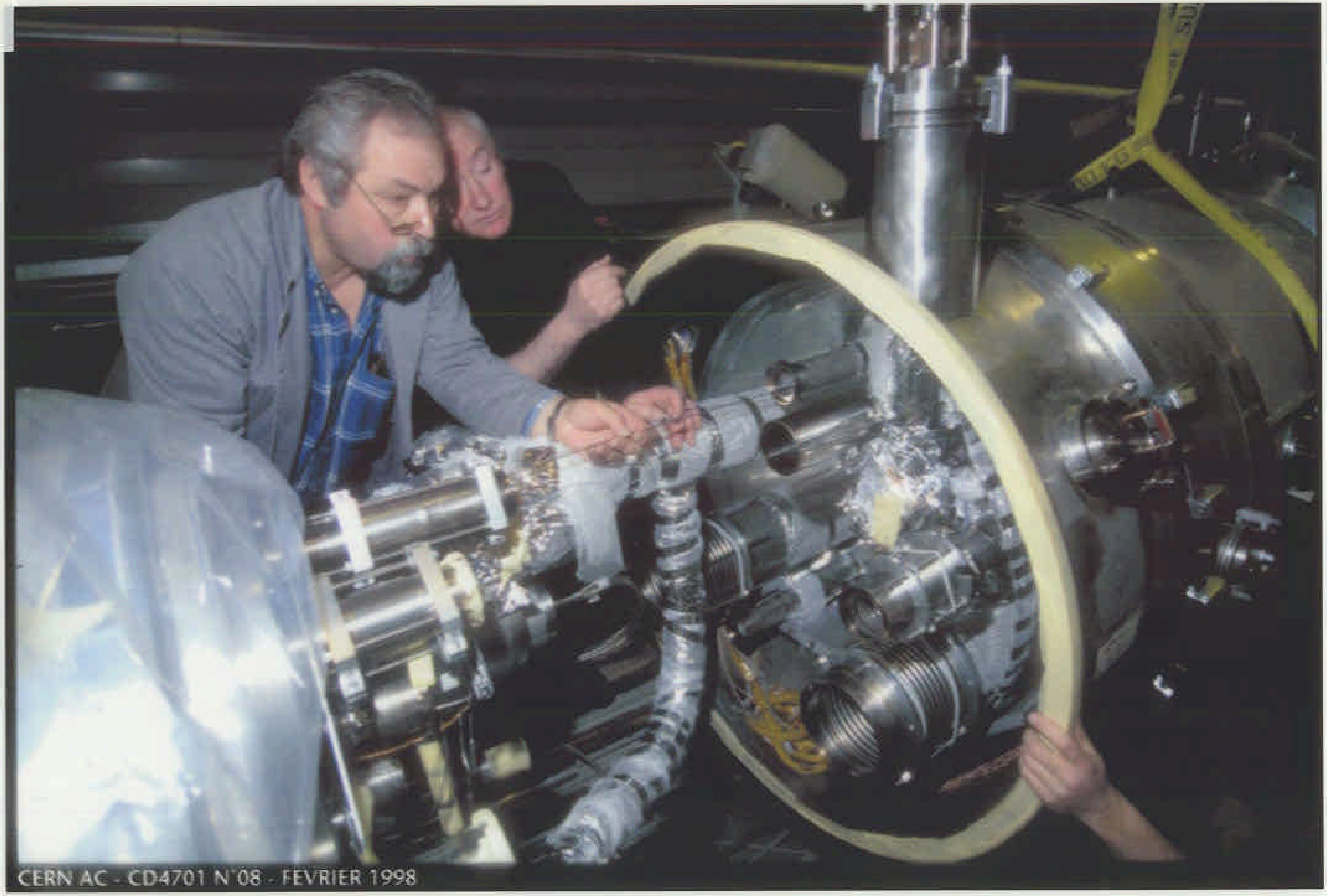
Collision of unlike species would require independent timing for the two rings (upgrade with respect to the baseline)



The LHC superfluid helium cooling scheme



Temperature profiles in pressurized helium II baths



CERN AC - CD4701 N°08 - FEVRIER 1998

LHC status

- Major components are on schedule and within estimates
  - Magnets
    - Prototype main dipoles achieve required performance;
      delivery of pre-series magnets will start this fall
  - Cryogenics
    - Overall design of the system is established
    - The big cryogenic plants are ordered
- Civil engineering
  - Tunnels and surface buildings progress well, but some months delay in excavation of ATLAS and CMS caverns
- Schedule
  - Target date to start commissioning remains July 2005

LHC status continued

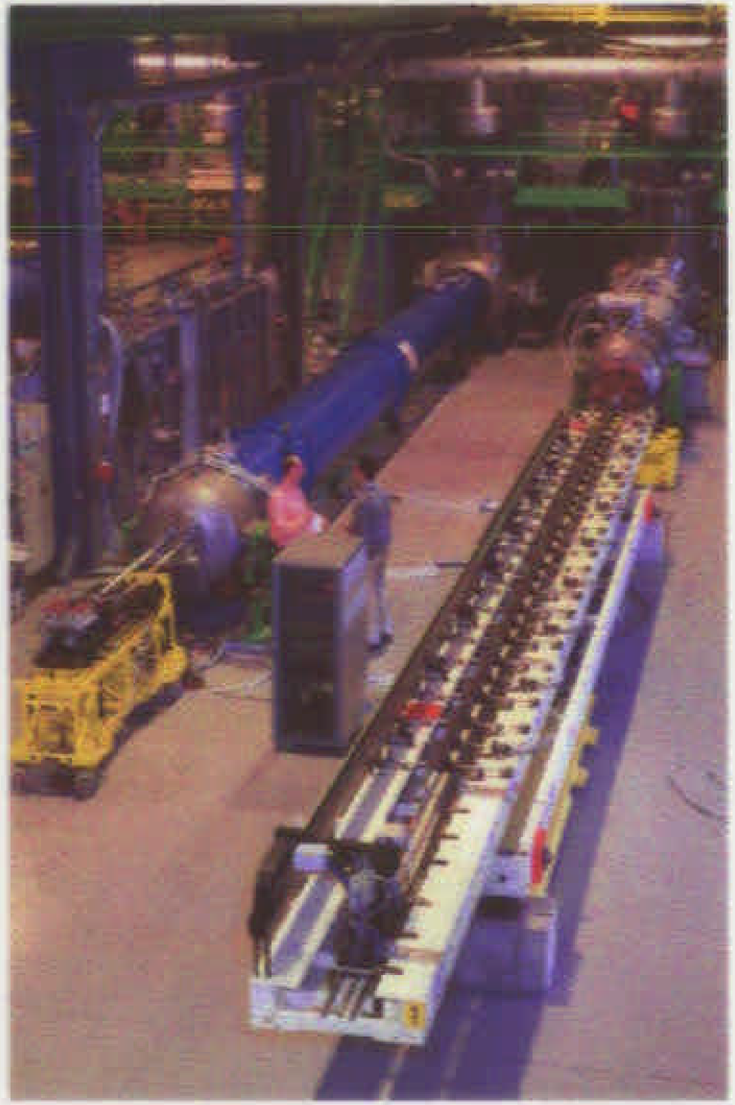
- Experiments
  - ATLAS + CMS are in the initial stages of construction
  - Work is starting on ALICE (heavy ions) and LHCb

- A major review of the LHC project is planned for fall 2000

- The LHC is a truly international collider
  - The machine is 20% financed by non-member countries
    - The expertise of participating labs is highly appreciated

the Large Hadron Collider project

Magnets



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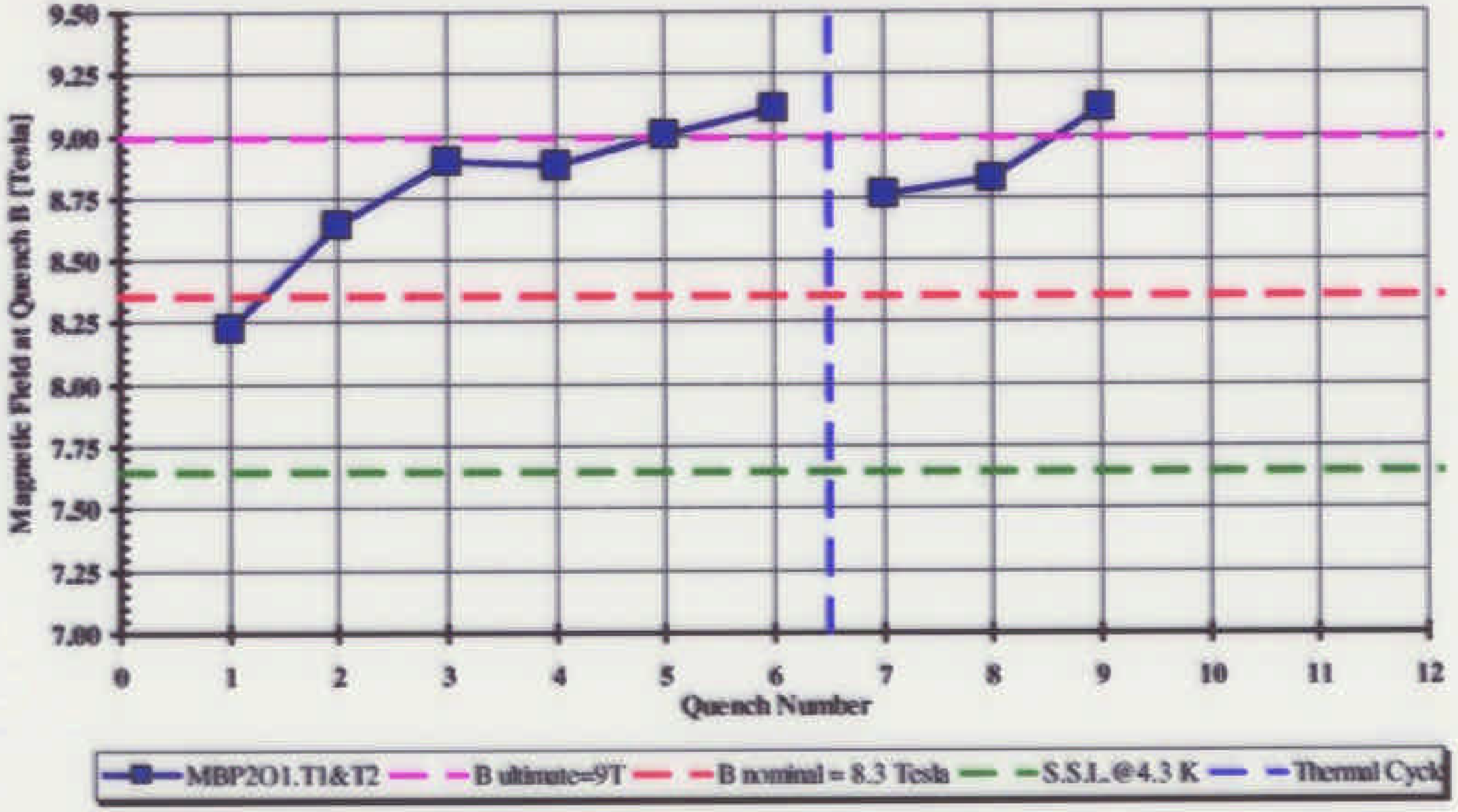
Magnets - training quench performance

Training Quenches at 1.8K



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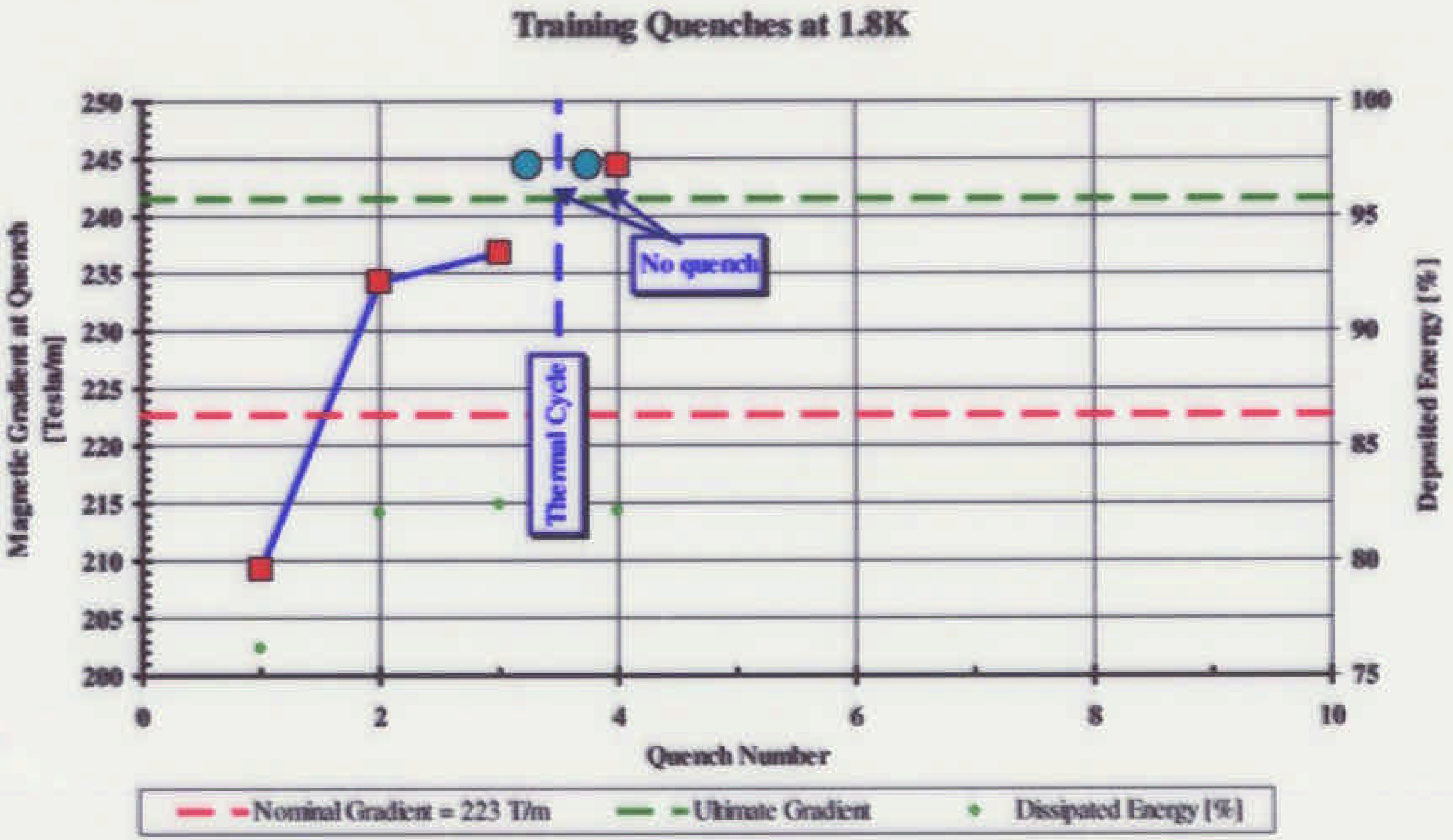
Magnets - SSS3



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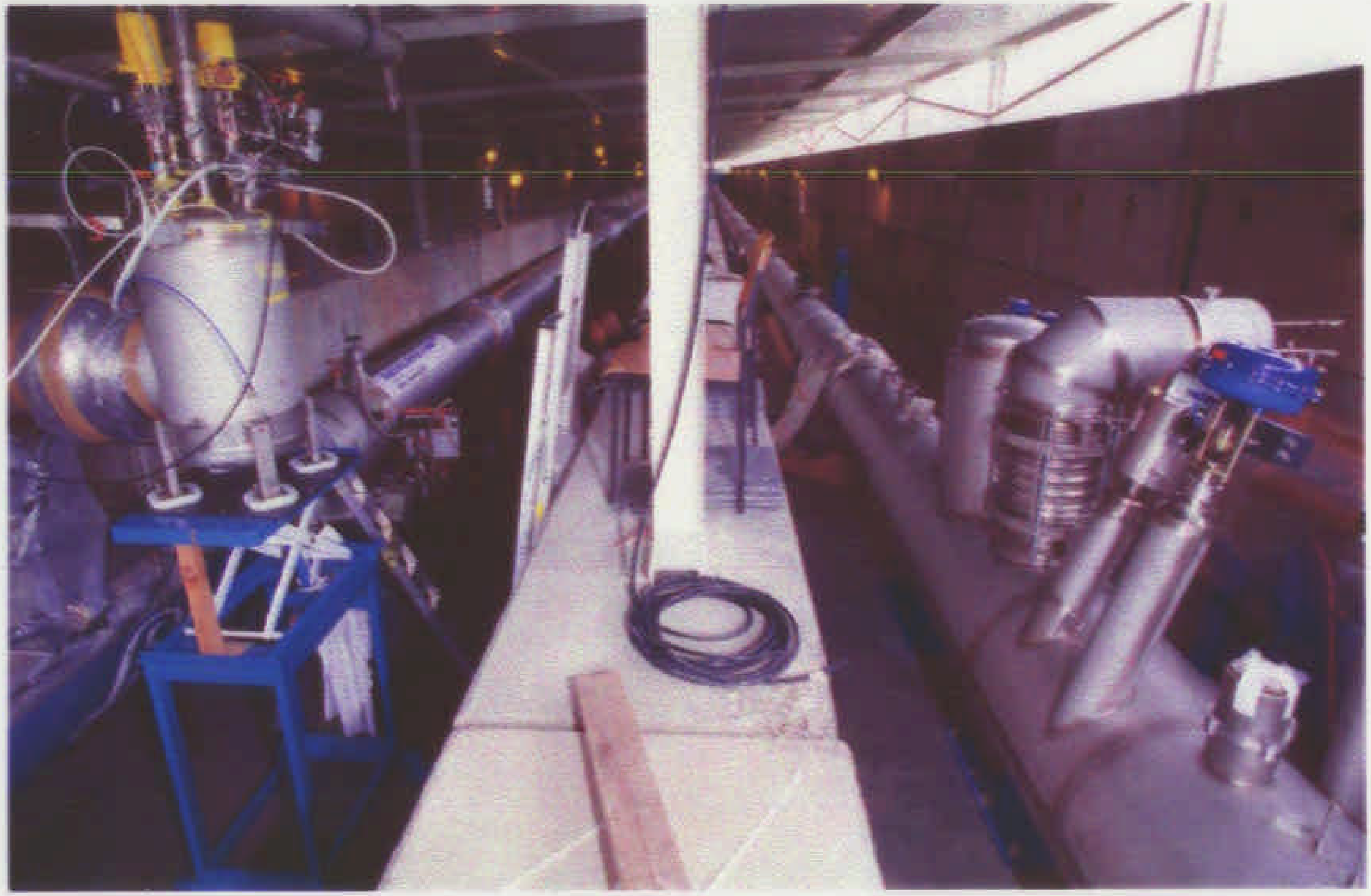
Cryogenics



the Large Hadron Collider project

TI8 tunnel (March 2000)

the Large Hadron Collider project

TI8 tunnel (March 2000)

the Large Hadron Collider project

TI2 tunnel (March 2000)

Conclusion regarding LHC

- The construction of the LHC machine is proceeding according to plan, within the allocated budget.
- Continuing studies regarding machine performance confirm early forecasts of expected energy and luminosity.
- Commissioning the hardware and the beams will be difficult, and requires careful planning and execution.
- Besides the rich experimental physics potential, the LHC will provide important experimental data for accelerator physicists concerning the working of very large machines.

The international dimension of the LHC machine project

With the LHC, CERN is acquiring a new dimension

25% of users come from outside the 20 member states. The LHC experiments are fully international collaborations which rely on contributions from institutes in both member and non-member states

The LHC machine is also a worldwide project

20% of the budget is financed by special contributions from Non-Member States, and whole subsystems are being supplied by external laboratories

Non-Member State Collaborations and Special contributions

Canada - TRIUMF
India - CAT, BARC
Japan - KEK, industry
Russia - BINR, IHEP, JINR, etc.
USA - FNAL, BNL, LBNL, industry

"VLHC"

- Variously described as

"Very Large Hadron Collider"
"Eloisatron"
"ELN"
"Grand Hadron Collider"

this is a collider which could usefully follow the LHC

VLHC-type machine

- Should be a large step beyond LHC
  - *50 to 100 TeV per beam*
- No extraordinary technical difficulties preclude VLHC at 10^{35} cm^{-2} s^{-1} with conventional technologies
  - *Radiation damage to detectors is a serious issue*
- Discovery potential of VLHC far surpasses that of lepton colliders
  - *High energy plus high luminosity*

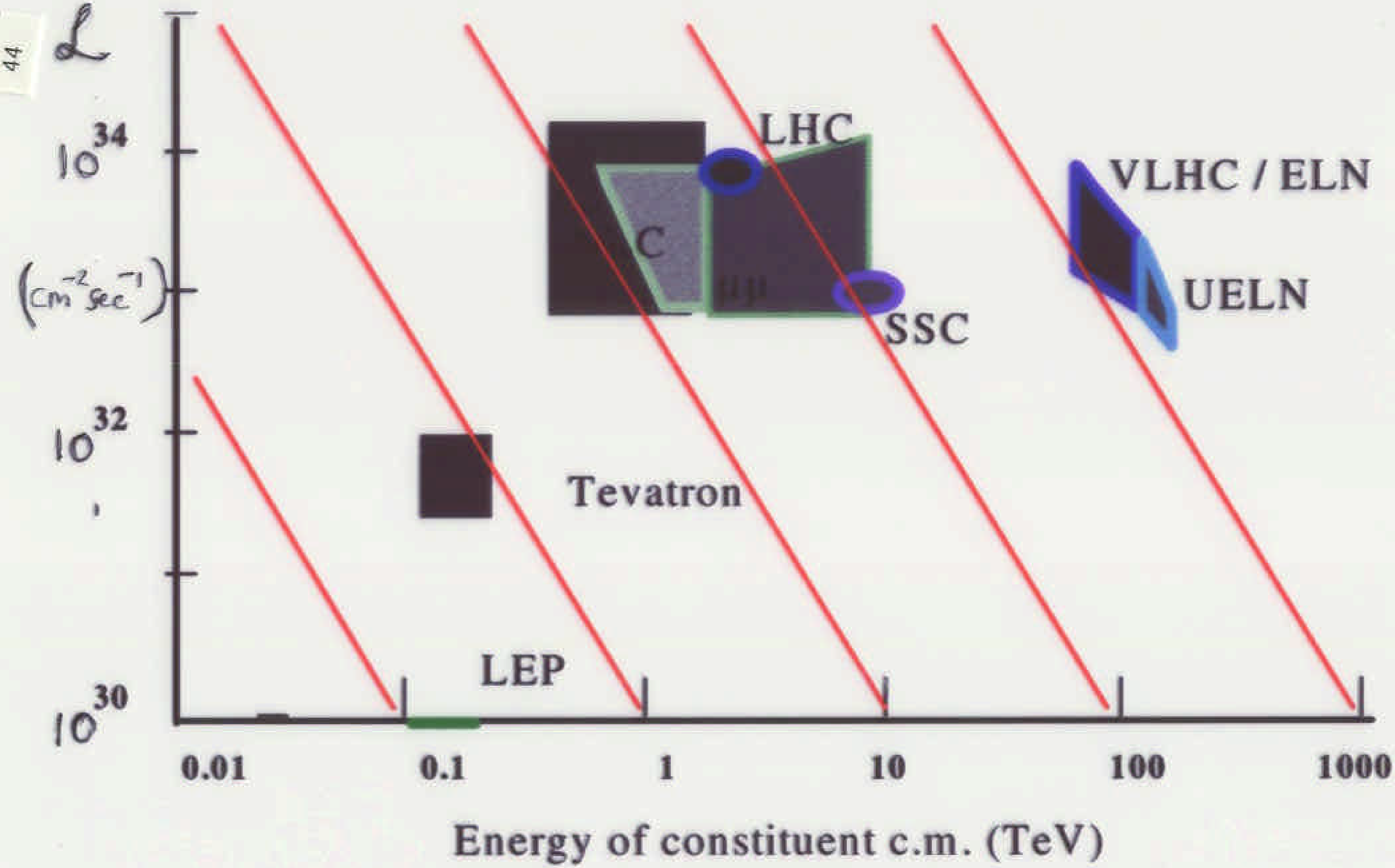
What sets the discovery potential ?

- (1) Energy
  - *determines the scale of phenomena to be studied*
- (2) Luminosity (collision rate)
  - *determines production rate of "interesting" events*

"useful" $\mathcal{L} \sim \frac{E \cdot I}{d \cdot Q}$

- Critical limiting technologies:

E - Energy - *Size, dipole field, accelerating gradient*
I - Current - *Synchrotron radiation, wake fields*
d - Focal depth - *IR quadrupole gradient*
Q - Beam quality - *Source, impedance, feedback*



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Synchrotron radiation is a dominant feature of proton supercolliders

- Advantages
  - emittance damping *(but is it fast enough ?)* being studied
  - maybe loosen tolerances

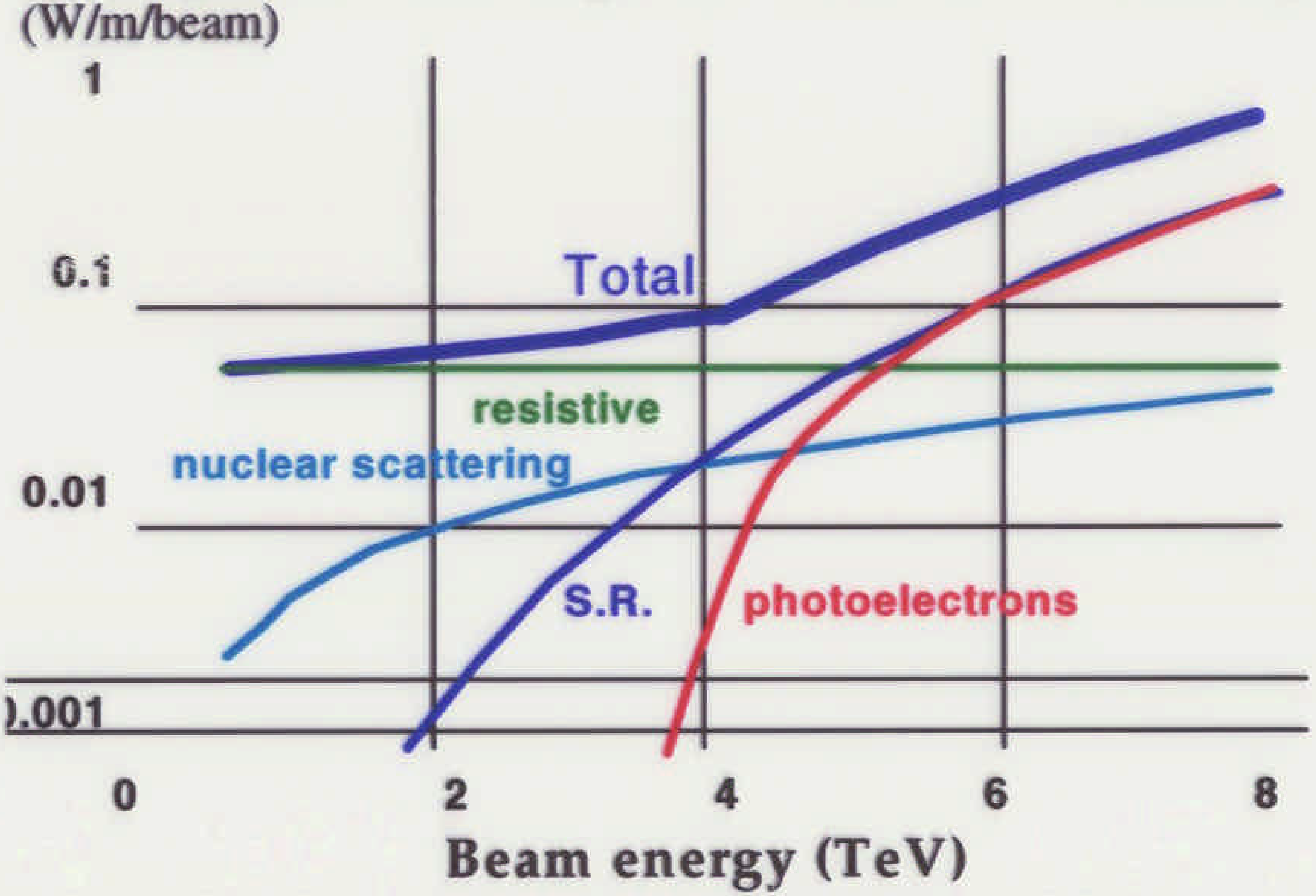
==> Saves money ???

- Disadvantages
  - direct waste heat
  - indirect waste heat (e.g., electron cloud)
  - photo-desorption of gas New NEG Coatings ?

==> Costs money

- What do we do about it ??? need new ideas !

Cryogenic cooling for the LHC beampipe



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How to reduce the dipole cost

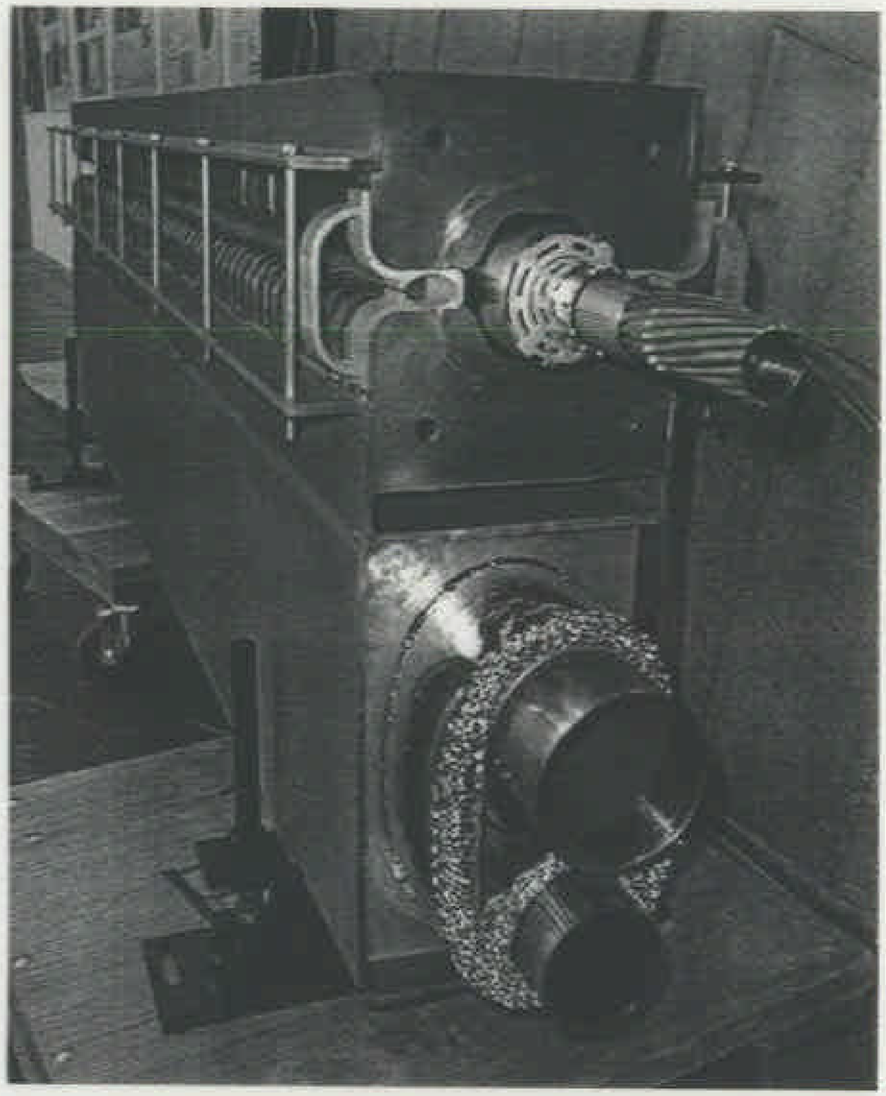
- Keep B small
- Reduce aperture
- Different coil geometry -
  - *cosine v. block (racetrack)*
  - *High stress v. segmented stress management*
- Different conductors - *Nb_3Sn (aps), Nb_3Al, HTS, etc.*
- Different insulators
- Different processing - *wind & react v. react & wind*
- Different conductor geometry - *cable v. tape*
- Simpler coil winding / splicing

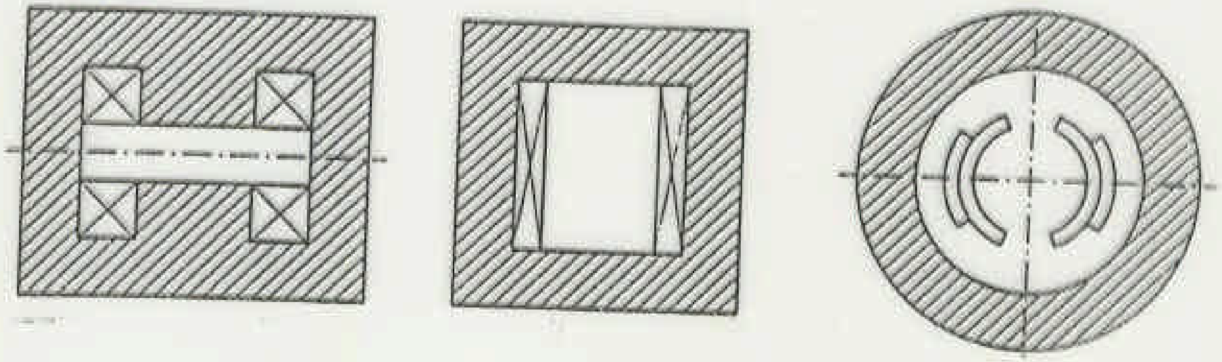
Three approaches under study

- Low field, superferric magnets
  - *Large tunnel, very large stored beam energy*
- Medium field design
  - *Uses ductile superconductor at 8 - 9 T (LHC-like)*
- High field magnets with brittle conductor
  - *Maximizes effect of synchrotron radiation*

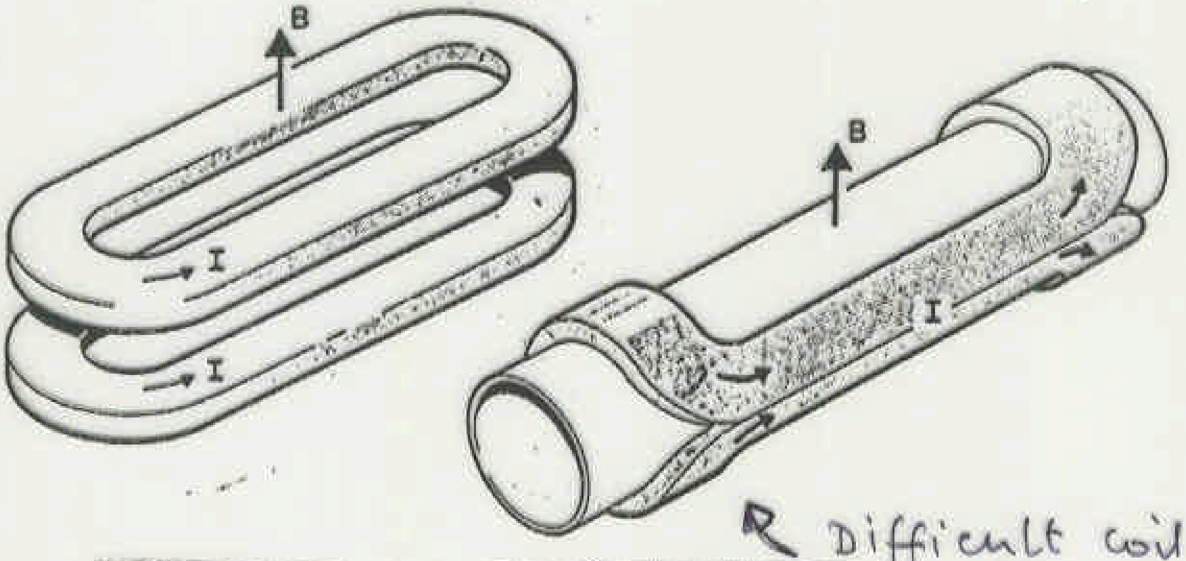
2-in-1 transmission line magnet

- * 2-in-1 Warm-Iron "Double-C" Magnet has small cold mass.
- * 75 kA SC transmission line excites magnet; low heat-leak.
- * B @ conductor ~ 1 T; NbTi has high Jc ==> reduced quantity.
- Extruded Al warm-bore beam pipes with side chambers.
- Simple cryogenic system.
- Current return is in He line.



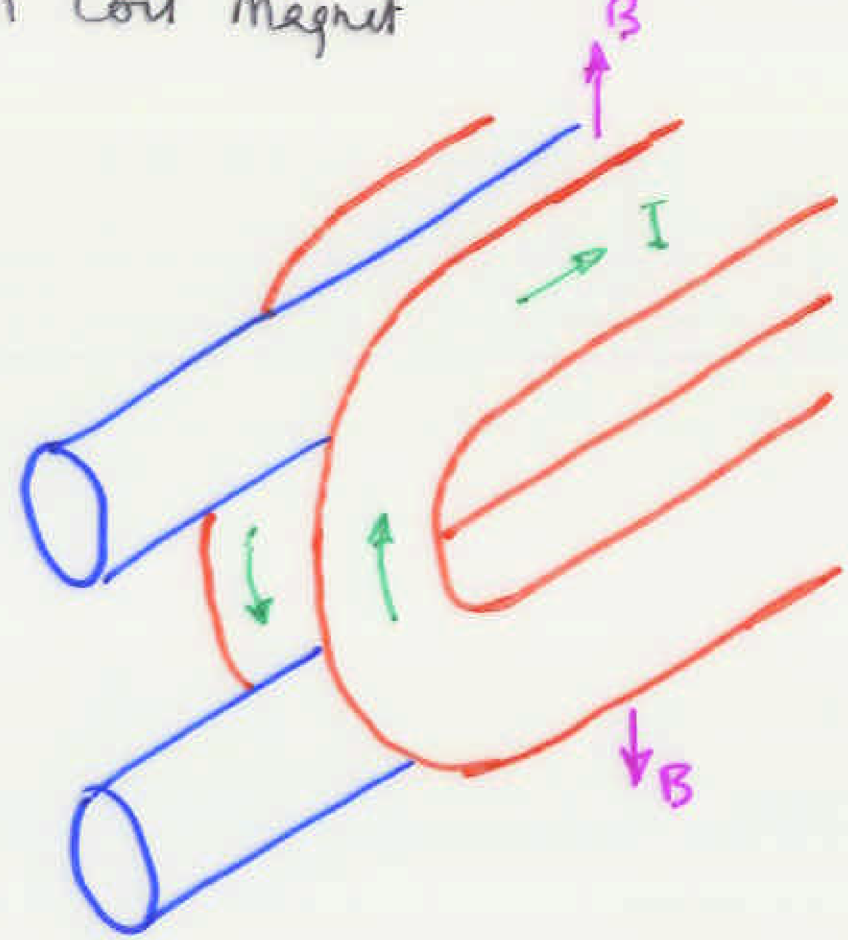


"$\cos\Theta$" design



↖ Difficult coil ends

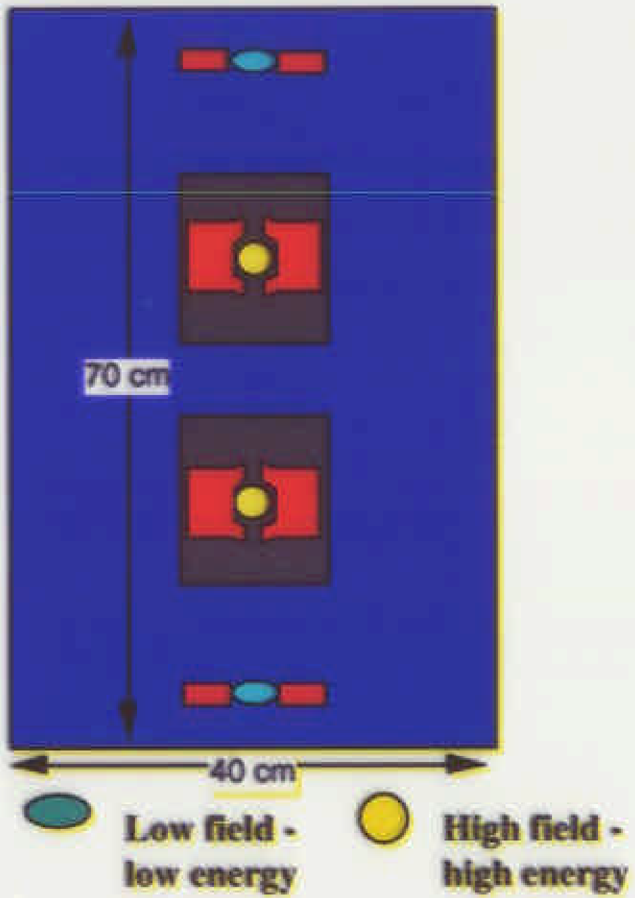
"Common Coil magnet"



Flat pancakes

- Less complicated
- permit "react + wind" (?)

Common coil magnet



- Compact 4-in-1 magnet
- Inject at low field
  - iron-dominated aperture
  - *good at low field (0.1-1.5 T)*
- Transfer at medium field
  - conductor dominated
  - *good at high field (1.5-15 T)*

(Gupta)

Pragmatic conclusion on the "VLHC"

- Experience tells us the next machine should be
  - located at an established laboratory
  - internationally supported
  - have upgrade potential
- A major ingredient is a long circular tunnel ...
- It can be built if only we can get the support - *but support has to be of a long-term nature*

Conclusion

- Hadron colliders provide experimental physics with great discovery potential.
- We may expect results
    - from 2001 - from the upgraded Tevatron
        - from 2005 - from the LHC

- Now is the time to prepare for a machine to follow the LHC