LEP Status and Performance in 2000

R. Assmann, SL/OP
for the SL Division

Outline:

- *Operational strategy*
- *Overview on luminosity and energy performance*
- *Energy reach*
- *Luminosity performance*
- *Other issues*
- *Further improvements/options*
- *Conclusion*

Operational strategy:

Traditional:
1) Select a working point for beam energy
2) Optimize luminosity production
3) Collect all required luminosity
4) Select a new beam energy …

LEP before 2000:
Not more than ~3 energies per year
Unscheduled change of beam energy discouraged
(e.g. not possible for energy to follow available RF voltage)

LEP in 2000:
Optimize for ultimate discovery reach
- Unconstrained number of beam energies
- Simultaneous luminosity production at different beam energies up to limit

Change discussed and promoted by P. Janot et al…

LEP operation and performance in this mode

Understanding the choice of beam energy E:

Energy loss U_0 per turn:

$$U_0 \propto \frac{E^4}{\rho}$$

For example:

At 104 GeV **~ 3%** of beam energy lost per turn

Limitation: ***RF voltage to compensate synchrotron radiation losses…***

Minimal accelerating RF voltage U_{min} required:

RF system with N klystrons (simplified):

$$U_{min} > U_0$$

$$U_{RF} = N \cdot U_k$$

Some probability for klystron unavailability (klystron trip rate):

- *Klystron trips occur mainly on statistical basis (LEP every ~ 14 minutes)*
- *Typical recovery time of 2-3 minutes*

Available RF voltage regularly reduced with 1 or 2 klystrons off…

Assuming fill at constant energy (traditional strategy):

Energy such that…	U_{min} = **(N-2)** · U_k	U_{min} = **(N-1)** · U_k	U_{min} = **N** · U_k
Fill length	set by dump	~ 1.5 h	~ 14 min

Fill at **highest energy** would be short and efficiency would be very low.

Fill length ~ 20 min

Overhead per fill ~ 69 min

Good efficiency requires: **Fill length >> Overhead**

For high energy LEP in 2000: ***Ramp beam energy during physics fill with colliding beams***

Typical fill in 2000:

22 GeV — *Injection*

↓

102 GeV — *Set-up, colliding beams, golden orbit, BFS, …*

↓

102.7 GeV — *Luminosity production* (2 klystron overhead)

↓

103.4 GeV — *Luminosity production* (1 klystron overhead)

↓

104.1 GeV — *Luminosity production, ended by RF trip*

↓ **Mini-ramps:**

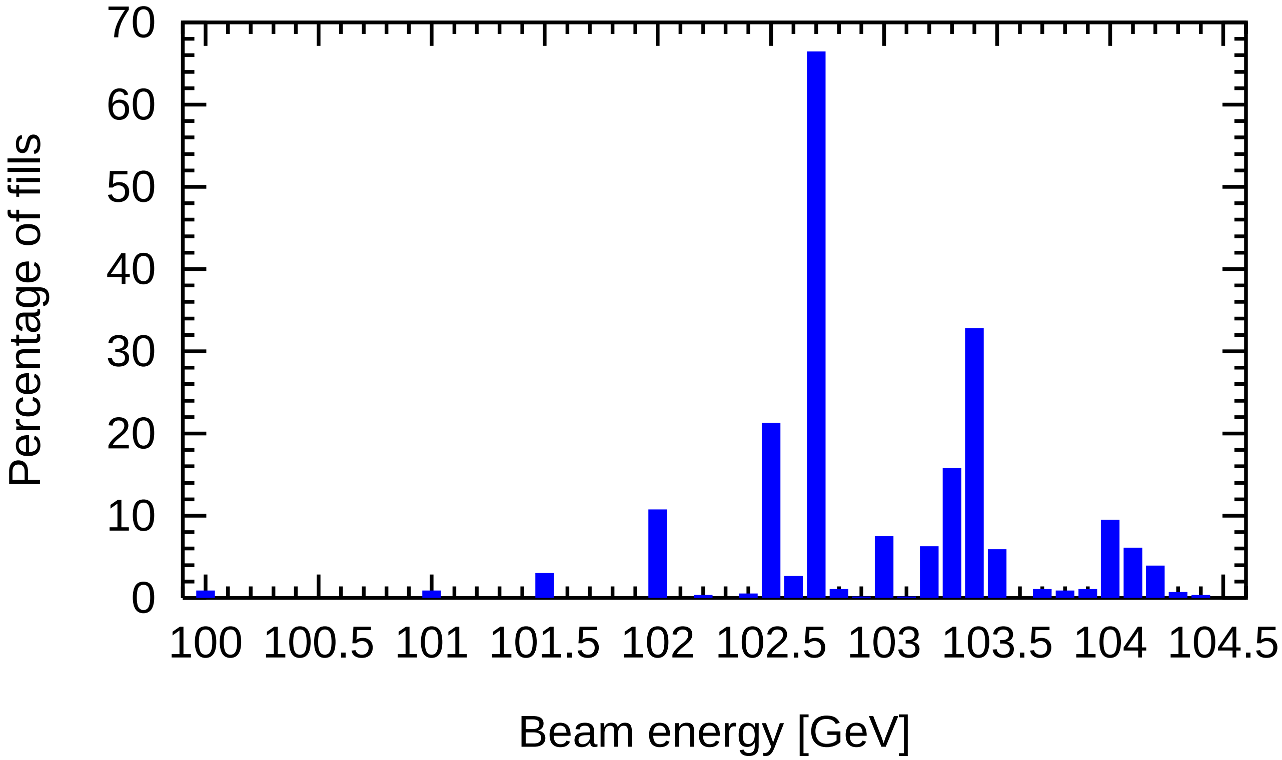
Used for polarization up to 1994
Revived for high energy
Beams ramped in collision with collimators closed
Possible due to strong radiation damping

Overview of 2000 performance:

(14-Jul-2000)

So far: **558 physics fills** (in ~3 months)

Compare: 436 physics fills 1998
653 physics fills 1999



Energy:

< 102.5 GeV — Start-up, Fall-back

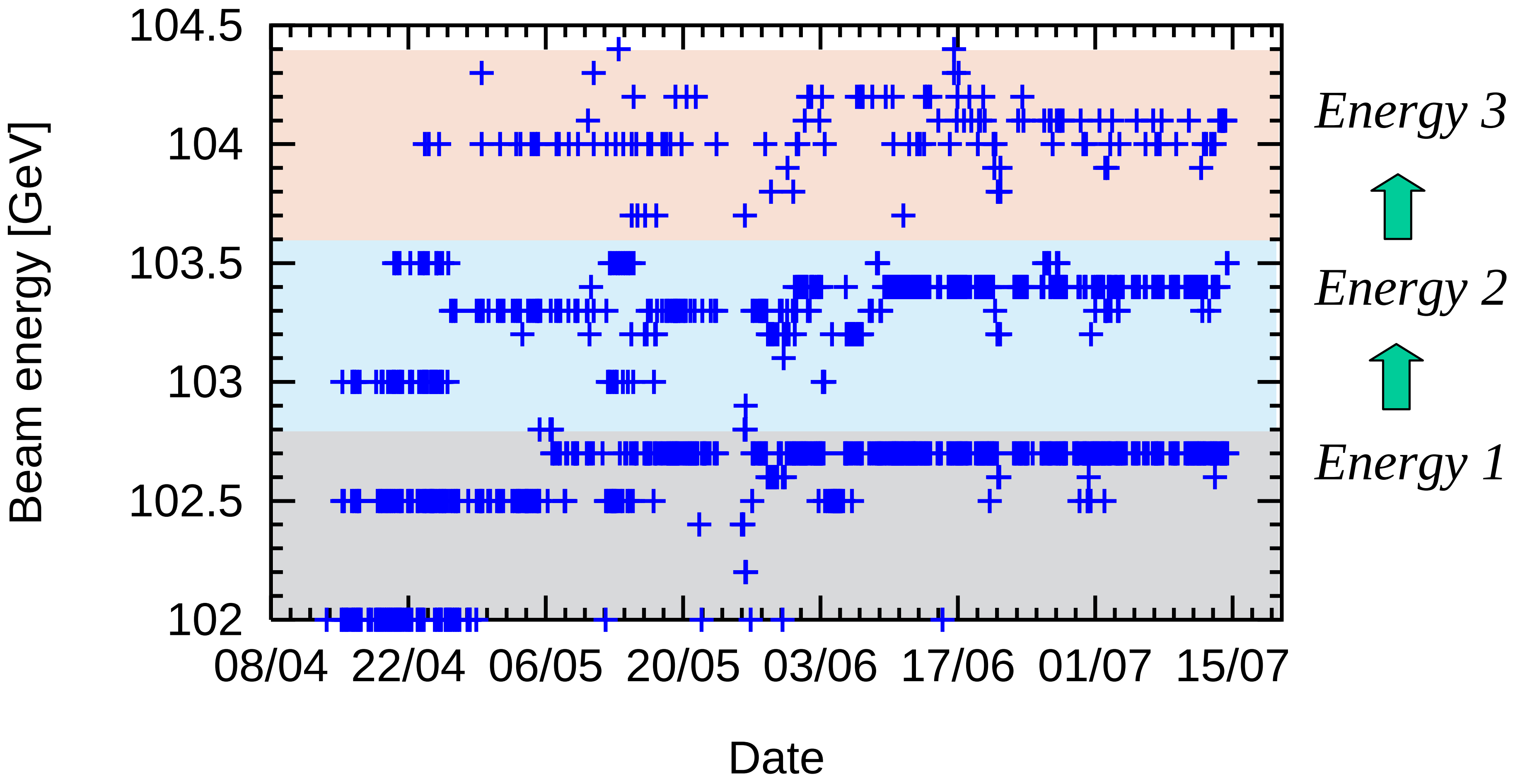
Mainly: **102.5 - 104.4 GeV**

More than 100%:

Several energies per physics fill

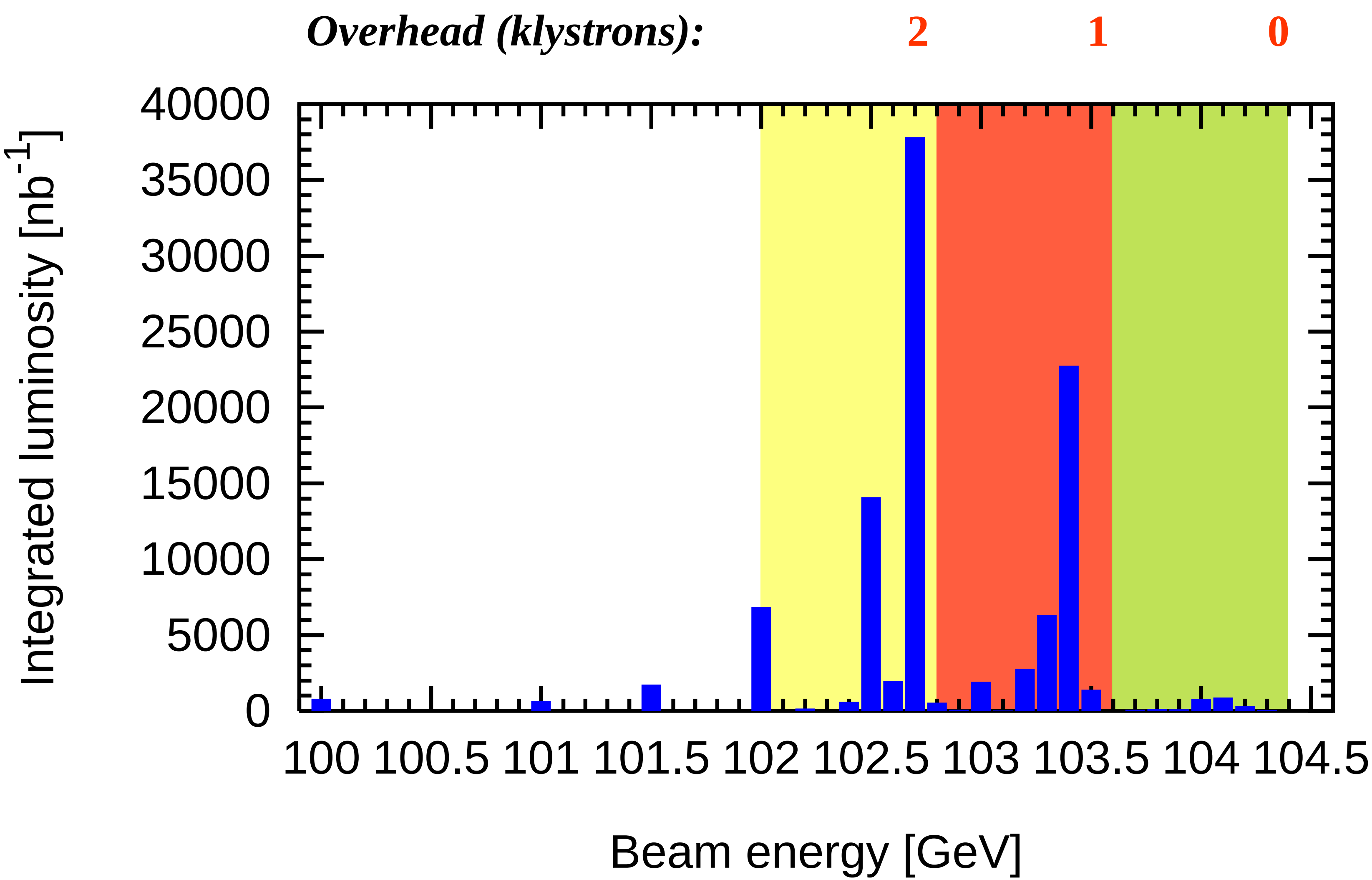
Physics energy as function of RF voltage. Many different values…

Beam energy versus time:

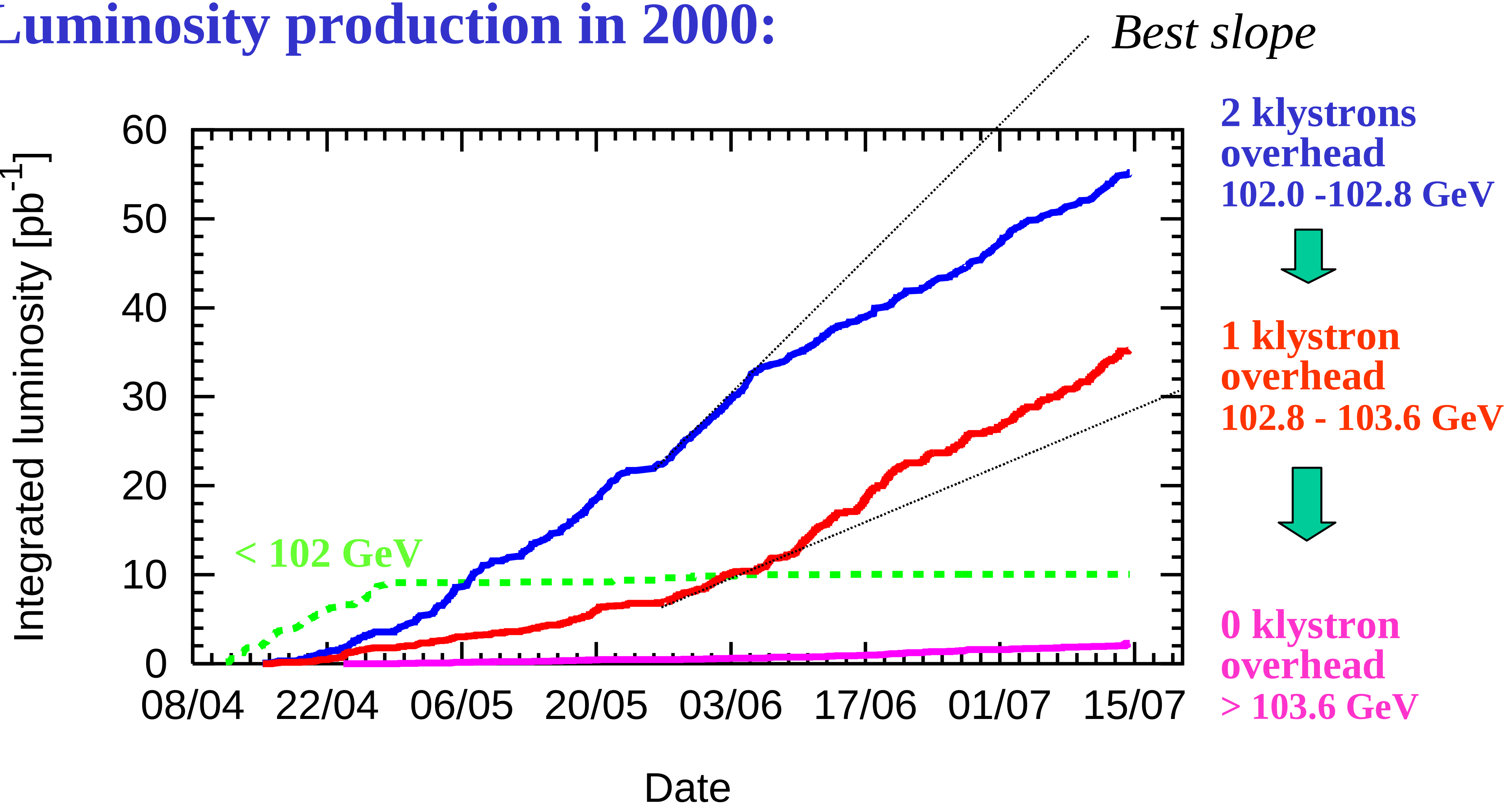


Many physics energies. Usually three energies per fill… (“mini-ramp”)

Delivered luminosity versus beam energy:

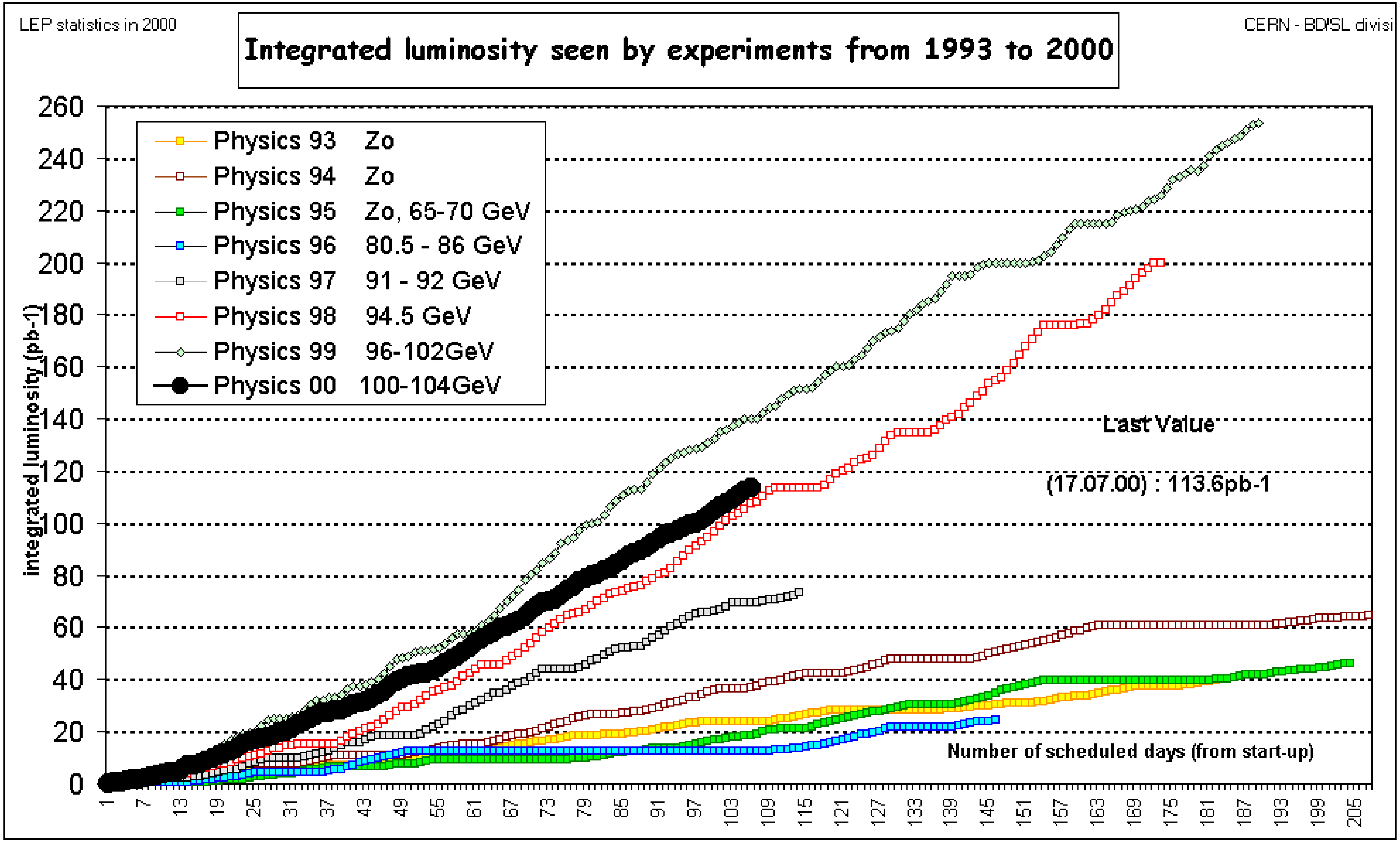


Luminosity production in 2000:



Raise of beam energy on cost of luminosity production…

Nevertheless, luminosity production in 2000 better than in 1998:



RA R. Assmann, LEPC, 20/7/2000

Energy increase of LEP from 1999 to 2000:

LEP 2000 preparation: **105 GeV** (optics, power supplies, etc checked)

Gain from 1999 physics to 2000: **101 GeV** ⇨ **104.4 GeV**

+ 3.4 GeV

Improvements:

8 additional Cu RF units	+ 0.14 GeV	RF system
Higher RF gradient	+ 0.96 GeV	RF system
Less RF margin	+ 1.50 GeV	Operational procedures
Reduced RF frequency	+ 0.70 GeV	Operational procedures
Bending length	+ 0.20 GeV	Operational procedures
Total	**+ 3.50 GeV**	

→ Reduced luminosity production, potentially higher backgrounds

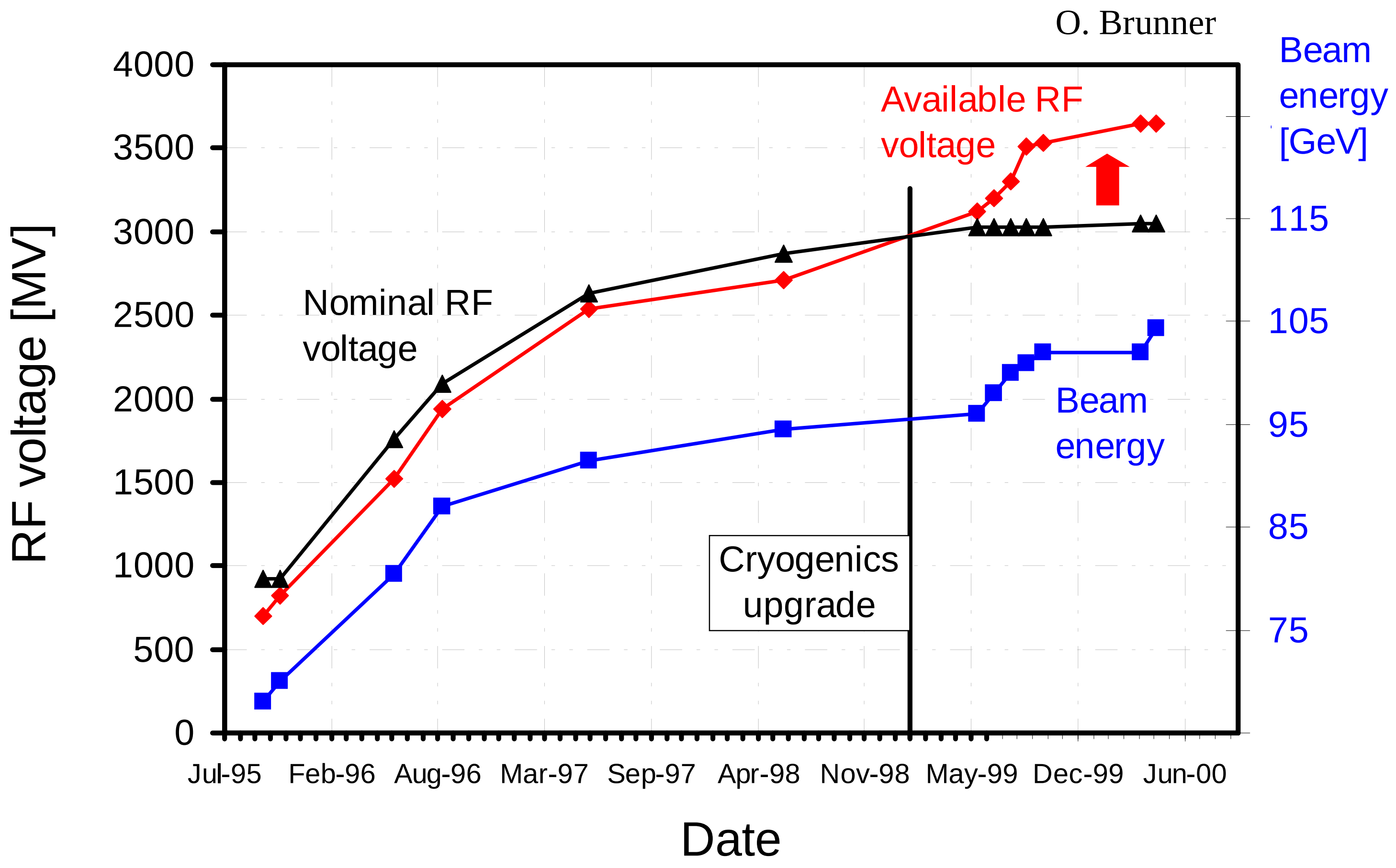
LEP RF system:

Lot of activity to optimize performance:

- Eight **additional Cu units** installed
- Clean-up on **reliability** (tuner power supplies changed)
- Condition to **higher fields** (hardware limit w/o beam)
- **Active damping** of field oscillations
- Fast **diagnostics** of RF trips
- **Automatic adjustment** of “trippy” RF units for mini-ramps
- Optimization of **RF voltage ramp** for cryogenics stability

Look at a few important points for LEP operation…

RF voltage (design and actual):



Beam energy follows available RF voltage…

Improvements:

- **Install additional RF cavities**

  (8 new CU units in 2000)

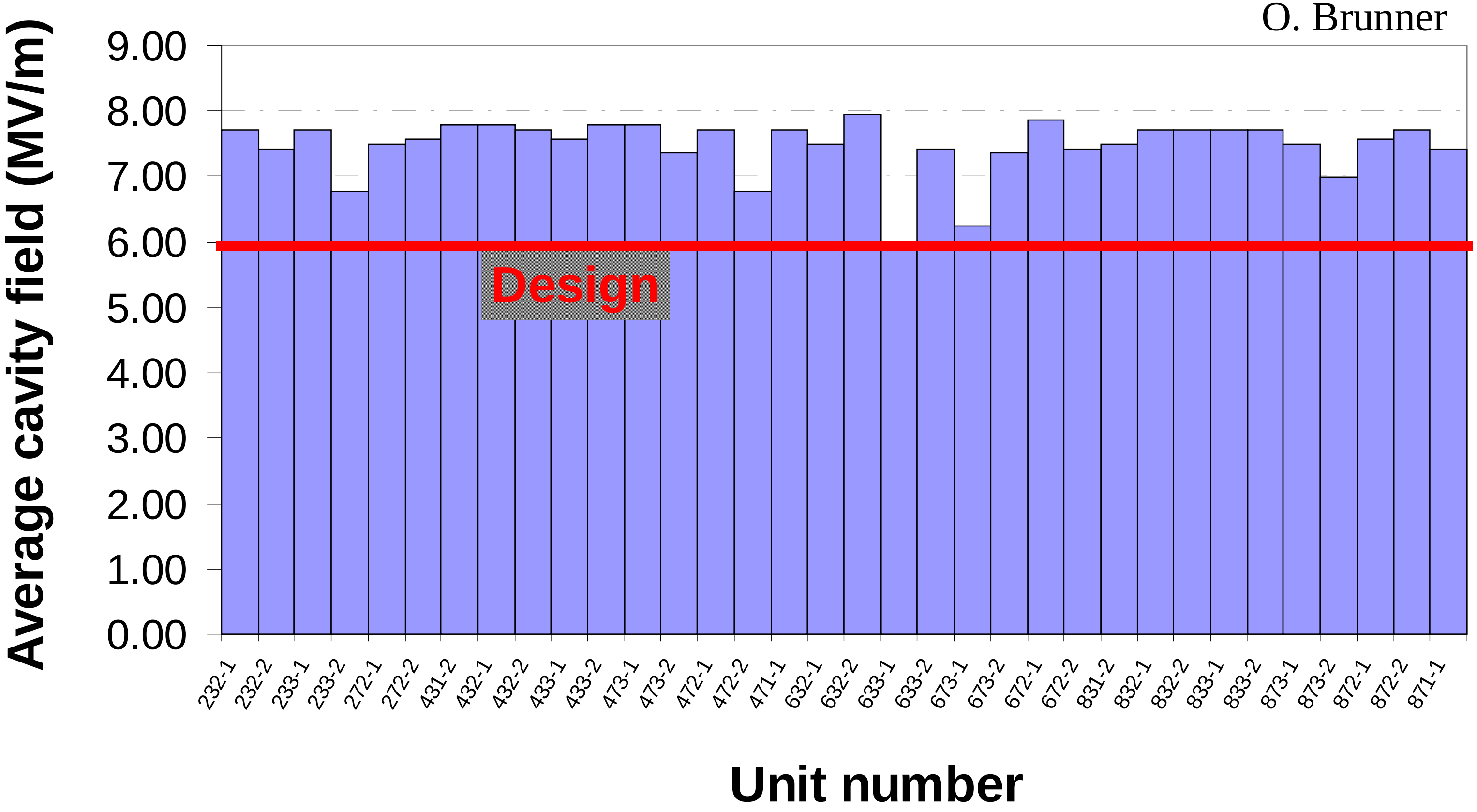
- **Increase accele-rating gradient**

Progress with RF conditioning:

Condition to higher fields (to hardware limit without beam).

Maximum gradients after 2000 conditioning
(Nb/Cu SC units)

O. Brunner



Average: **7.4 MV/m**

RF stability:

- 36/8 klystrons (SC/Cu)
- 288/56 cavities (SC/Cu)
- 53 kW cooling power (He 4.5K)
- ~ **10000** interlocks

RF trips reduce the available RF voltage:

- *Equipment failures (a few % of trips)*
- *Running at performance limit (acceptable trip rate)*
  - Mainly field emission (He pressure rise/level)
  - Arcing in RF distribution system

(Statistical processes, fast recovery ~ min)

Trip event	Voltage reduction	Rate
1 klystron loss	100 MV	~ 20 min
2 klystrons loss	200 MV	~ 1-2 hours
Beam dump		

plus transient effects

100 MV ⇔ ~ 0.8 GeV

RF voltage — Beam energy

Energy determined by RF voltage and trip rate

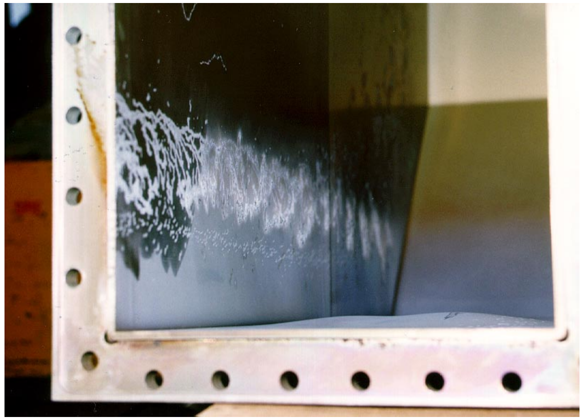
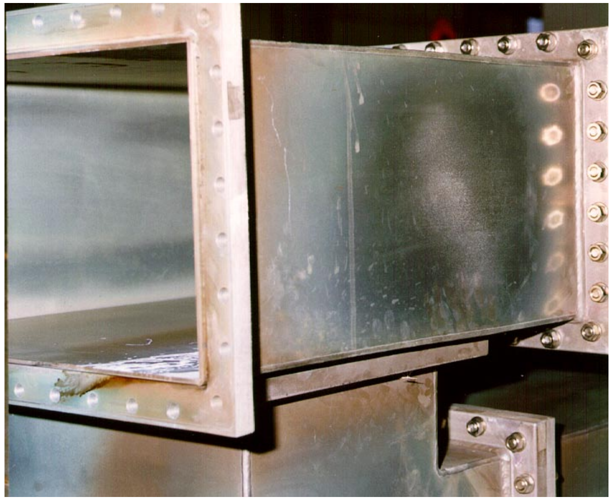
Hardware damage in RF system:

Empirical limit for total beam current: ~ 5 mA

1) Damage in waveguides

(Transport of RF accelerating fields from klystrons to cavities)

Origin: *Beam-induced electro-magnetic fields (HOM)*
Damage: *Heating, deformation, holes*


High energy operation of LEP leaves its marks…

2) Corrosion of cables in solid Niobium units

Beam induced electro-magnetic fields (HOM) are guided out with cables to avoid excessive heating/damage

Solid Niobium RF units:

1) Cable feed-through cooled too much

2) Condensation of water

3) Corrosion

4) Feed-through is destroyed (Hole between insulating vacuum and atmosphere)

Fix: Remove cable, plug connector. **HOM power stays in…**

1-3: All solid Niobium

4: One cavity of solid Niobium unit 273.

Repair: Requires opening cryostat (can be done in situ?)…

3) Loss of single cavities

3 cavities lost in 2000

Choice of RF frequency:

Damping partition number J_x used to reduce horizontal beam size σ_x:

$$\sigma_x = \sqrt{\beta_x \varepsilon_x} \propto \sqrt{\beta_x / J_x} \cdot D_x^{rms} \cdot E$$

Increase with beam energy.

Good for luminosity and backgrounds in experiments…

J_x controlled with RF frequency f_{RF}.

Δf_{RF} = 0 Hz	J_x = 1.00	
Δf_{RF} = 100 Hz	J_x = 1.55	**ΔE_{max} = - 0.7 GeV**

Pay with **reduction of maximum beam energy**.

In 2000: Keep RF frequency shift small (~ 0-20 Hz).

Increase average bending radius ρ: (BFS)

Energy loss U_0 per turn: $$U_0 \propto \frac{E^4}{\rho}$$

With larger ρ a higher beam energy E gives the same energy loss.

How to increase bending radius?

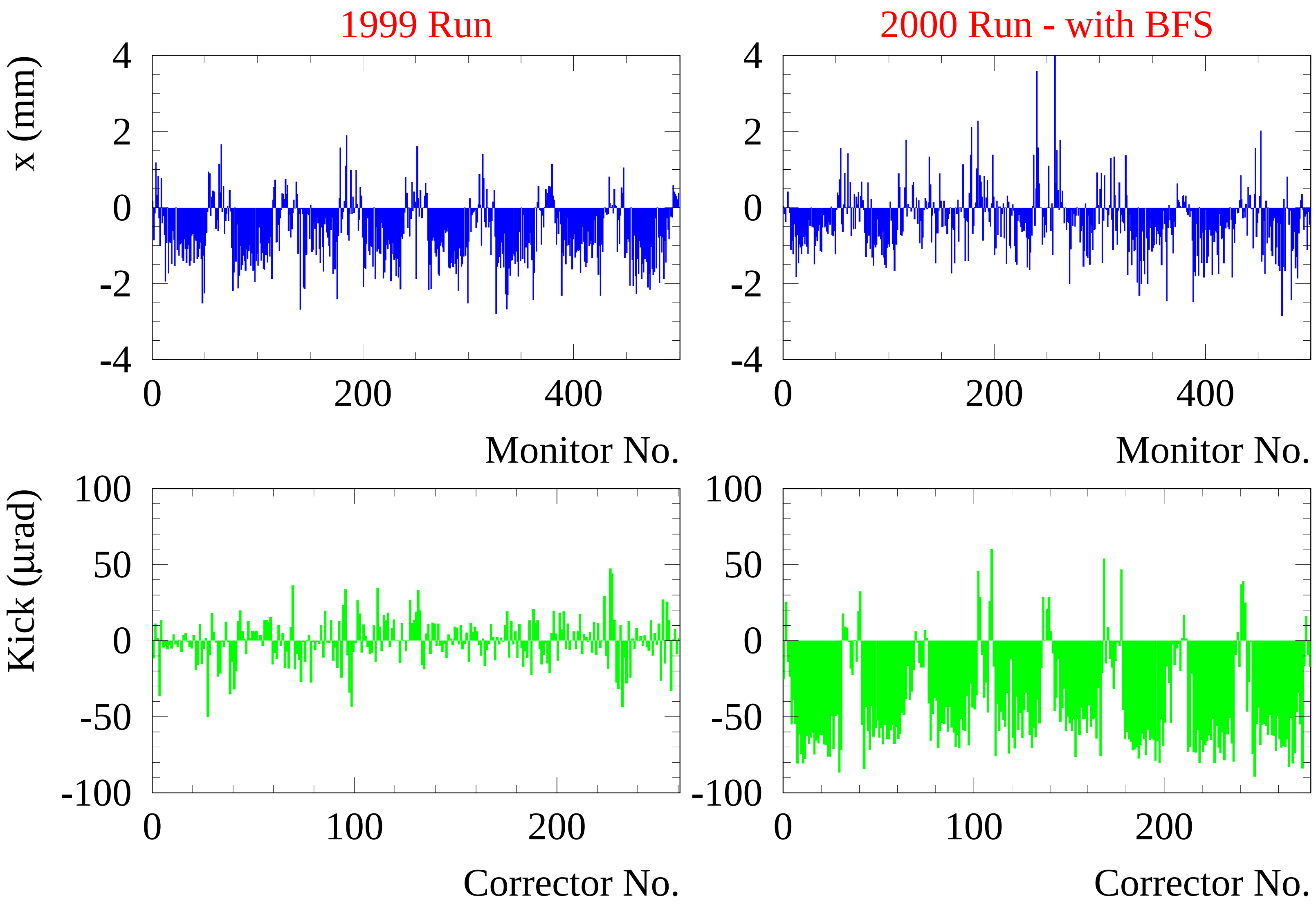
Bending installed for 2π total bending.

Add additional bending:
- Increase of beam energy to get 2π
- Less bending in original bends
- Larger bending radius in original bends

For LEP: Use horizontal correctors and quadrupoles as additional bends

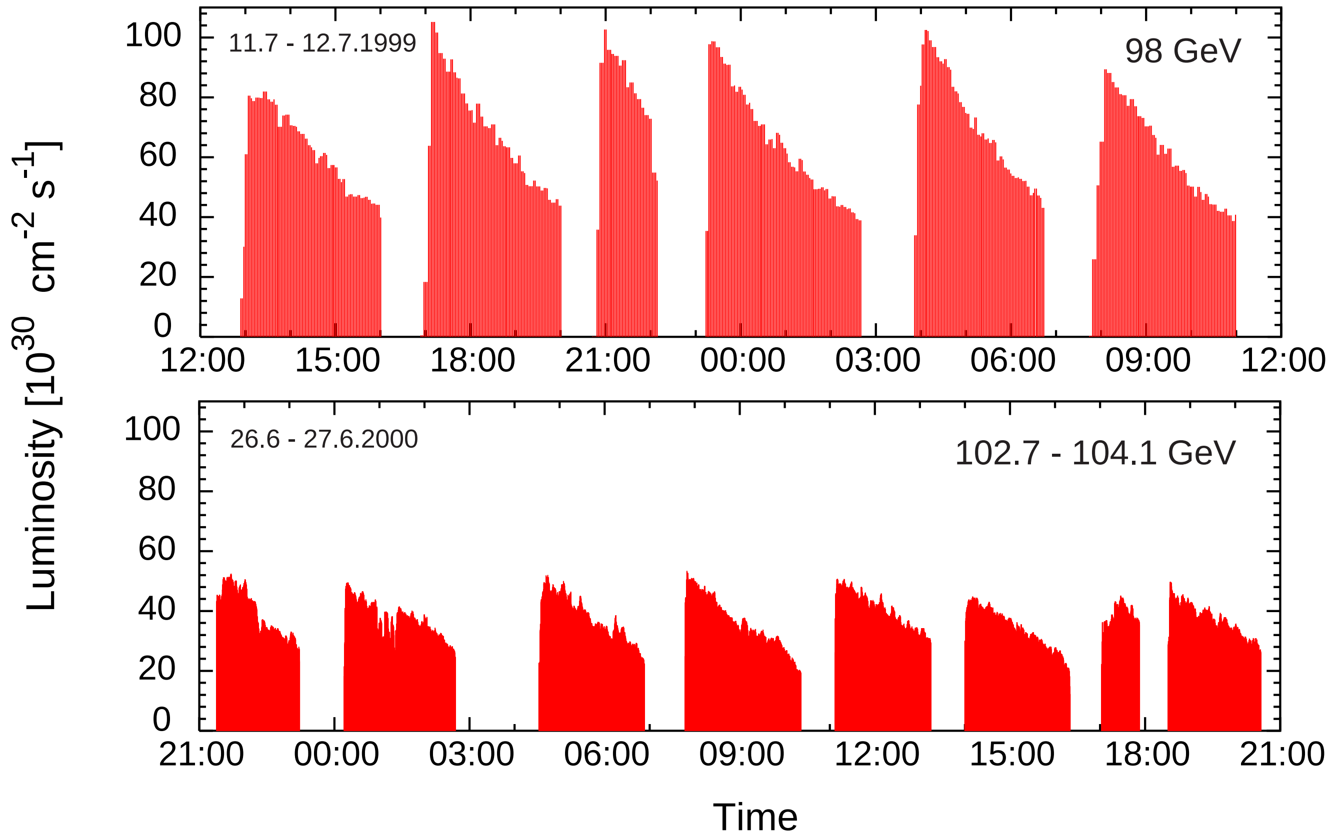
Average bending radius increased by 0.7%
0.4% of total bending from correctors (2/3) and quadrupoles (1/3)
Net gain in energy: 0.19 GeV

Dipole correctors and quadrupoles as "bending magnets":



J. Wenninger

Luminosity performance:



Year	Av. rate [pb^{-1}/day]
1994	0.31
1995	0.23
1996	0.17
1997	0.66
1998	1.16
1999	1.35
2000	1.07

Raise of beam energy on cost of luminosity production…

Production rate below 1999 value, but better than 1998 (same period)

Reduced luminosity rate due to trade-off:

Luminosity		**Energy!**
Factor 4 luminosity	~	1 GeV increase of beam energy

Standard model Higgs search optimization

Important trade-offs:

Increase J_x for small hor. beam size	Decrease J_x for highest energy reach
Increase beam current	Decrease beam current (better RF stability)
Run with RF voltage reserve	Run without any reserve in RF voltage
Stable energy for tuning, experiments	Energy follows available RF voltage
No fills lost with RF trips	All fills lost with RF trips

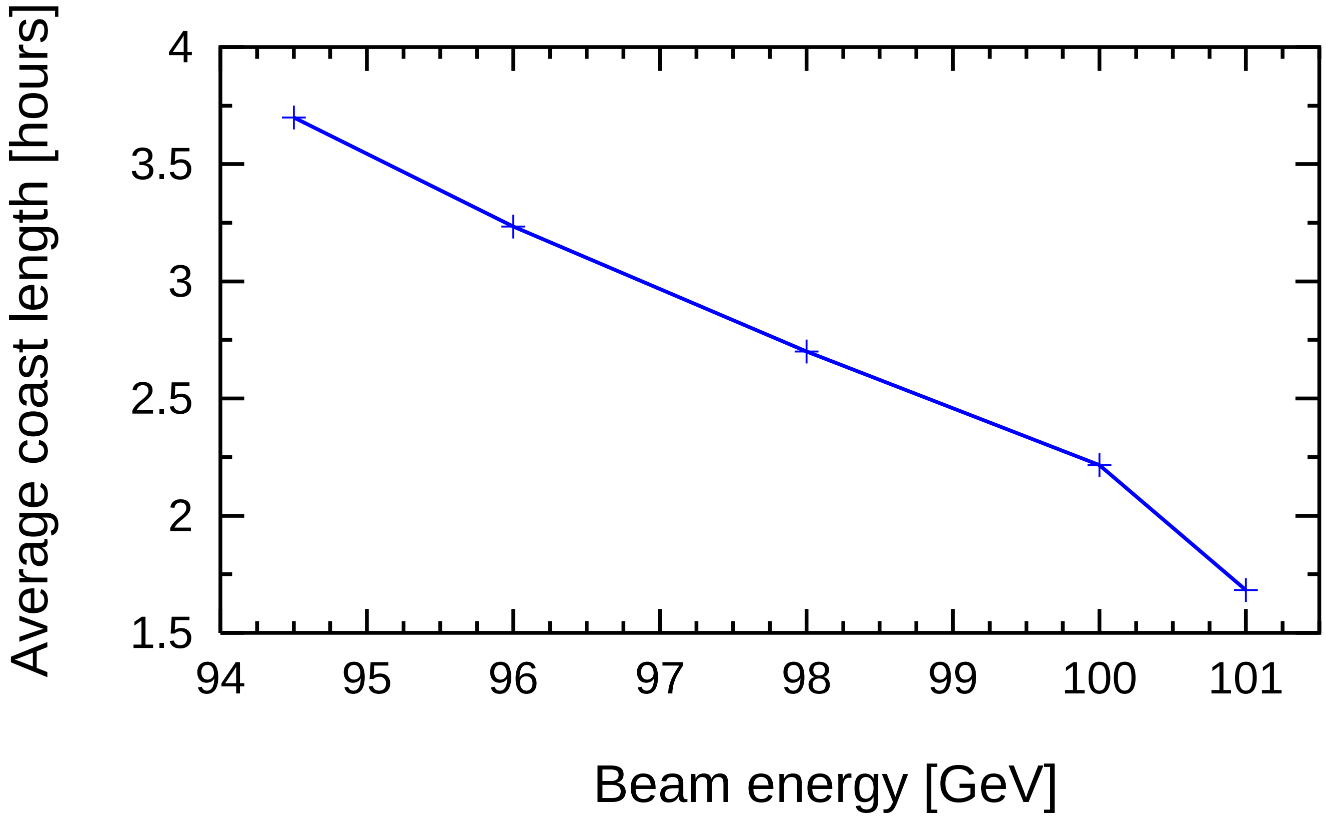
1998 → **1999** → **2000**

Trying to counteract luminosity reduction, but there are limits…

Trade-off reflects in key parameters:

Average length
of physics fills

2000: 1.82 h
(16-Jun-2000)



Overhead per fill (re-cycling, injection, ramping) very important:
1998: 110 min 1999: 93 min 2000: **69 min**

Optimization of turn-around time:

Data: 10/4-16/6

Year	Recover [min]	Filling [min]	Ramp / Squeeze [min]	Adjust [min]	Total [min]	# fills
1998	23.9	45.0	22.3	19.1	**110.3**	436
1999	22.2	30.9	23.9	15.5	**92.5**	653
2000	13.1	25.4	13.8	16.6	**68.9**	344
Diffe-rence	**-9.1**	**-5.5**	**-10.1**	**+1.1**	**-23.6**	
	Faster degauss, optimize procedure	Less current	Twice the ramp speed	BFS		

Average turn-around time improved by **~ 24 minutes**!

Typical 2000 turn-around: ~ 45 minutes

We profit from beam behavior at high energy:

Strong transverse damping

($\tau \sim 1/E^3$)

45.6 GeV 721 turns
103 GeV 63 turns

Reminder:	Particles perturbed at time t_0 (e.g. mini-ramp)
	E.g. orbit oscillation around closed orbit.
	Oscillation amplitude reduced by e after the damping time τ.

Consequences for LEP:

- Second beam-beam limit (tails, resonances) is overcome
- Higher beam-beam tune shifts with higher beam-beam limit
- 1/3 resonance can be jumped
- Beams can be ramped in collision

Vert. beam-beam parameter:

$$\xi_y = \frac{r_e \cdot m_e \cdot \beta_y^* \cdot i_b}{2\pi e \cdot f_{rev} \cdot E \cdot \sigma_x \cdot \sigma_y} \propto \frac{L}{i_b}$$

Observed in LEP (1994-2000):

Energy [GeV]	ξ_y (max) per IP	Damping [turns]	
45.6	**0.045**	**721**	*Beam-beam limited*
65.0	0.050	249	
91.5	0.055	89	*Beam-beam limit not reached*
94.5	0.075	81	
98.0	**0.083**	**73**	
101	0.073	66	
103	0.055	63	

$\xi_y \propto 1/E^3$ naively

Strong damping

↓

Beam-beam limit pushed upwards

$\sigma_x\sigma_y$ from 45.6 GeV to > 98 GeV:

Reduced by factor ~ 1.6 (factor ~2 reduction in vertical beam size)

Background in the experiments:

Higher beam energy

RF frequency shift reduced for optimization of energy reach

Larger horizontal beam size

Potentially larger backgrounds

↔ New optics in P4 and P8 to help reducing background

Steady state conditions: Good. Require continuous follow-up on collimators, orbit, tunes, …

Occasional spikes: RF trips with negative RF frequency shift
Related current loss

Hardware performance

- *Vacuum system*
- Magnets
- Power supplies
- Instrumentation etc

… excellent without major worries.

Effects from LHC civil engineering

- **No appreciable effect** on LEP operation so far

Cryogenics

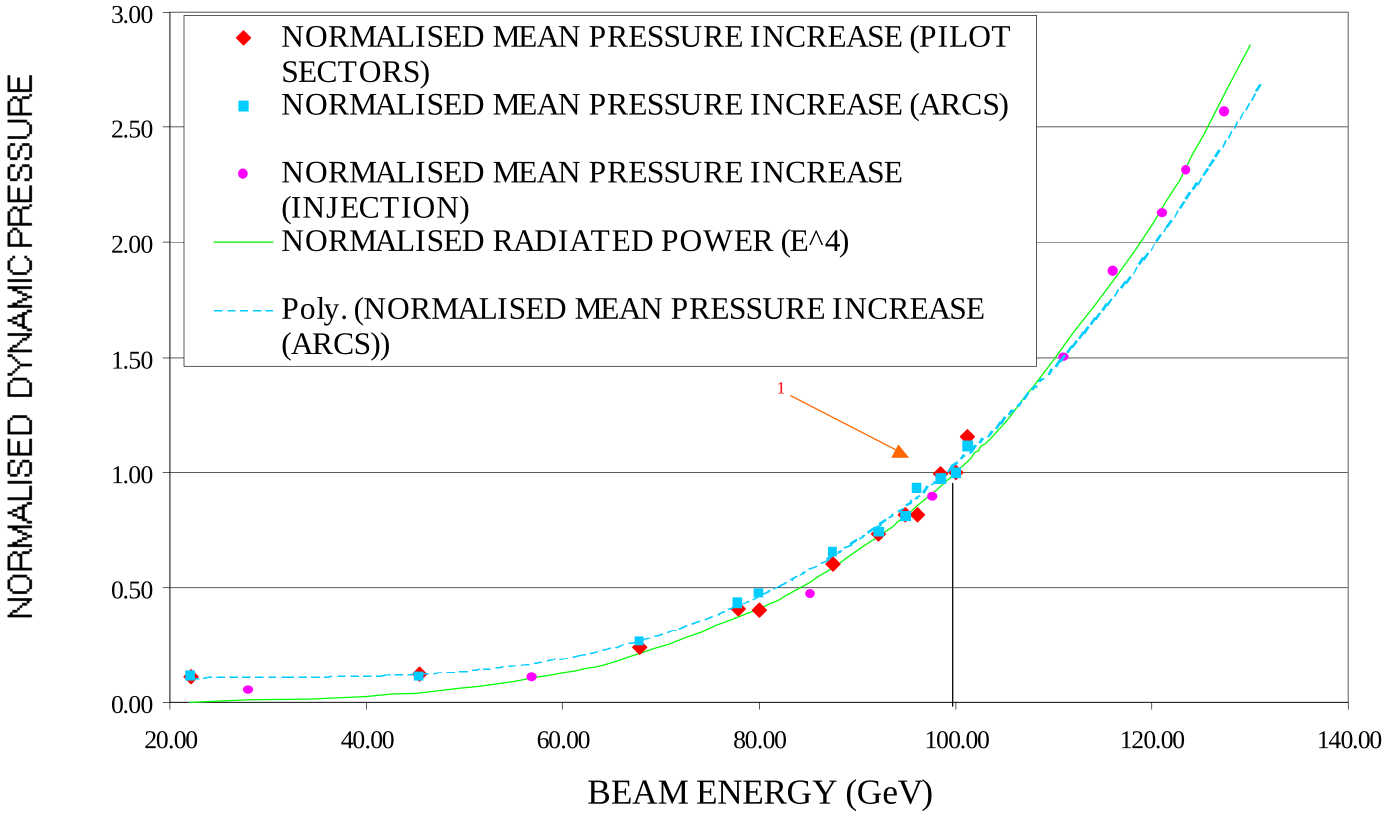
For July conditions:
7.4 MV/m, 5 mA

	RF load	Margin	Clogging
P. 2	7236 W	**2400 W**	-
P. 4	11192 W	**1400 W**	1000 W
P. 6	8960 W	**3000 W**	1000 W
P. 8	12096 W	**1300 W**	500 W

- **More margin, better stability** than in 1999.
- Clogging effects requires regular "**de-icings**"

Large radiated power at high energy:

N. Hilleret

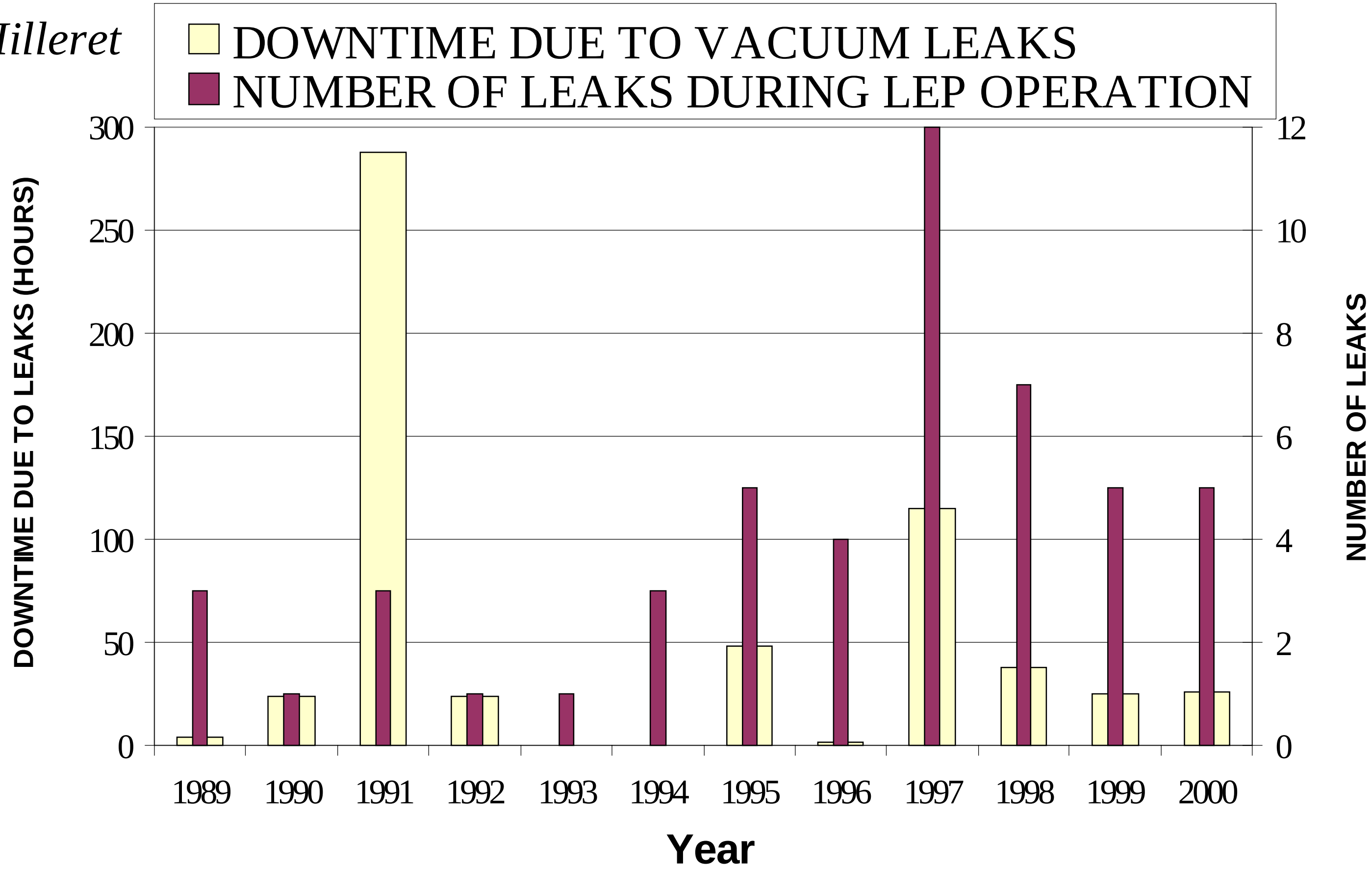


Consequences: *1) Higher vacuum pressure (no problem)*

2) ***Possible damage to vacuum system (leaks)***

Vacuum leaks and related downtime:

N. Hilleret



Data 2000
up to 15/6

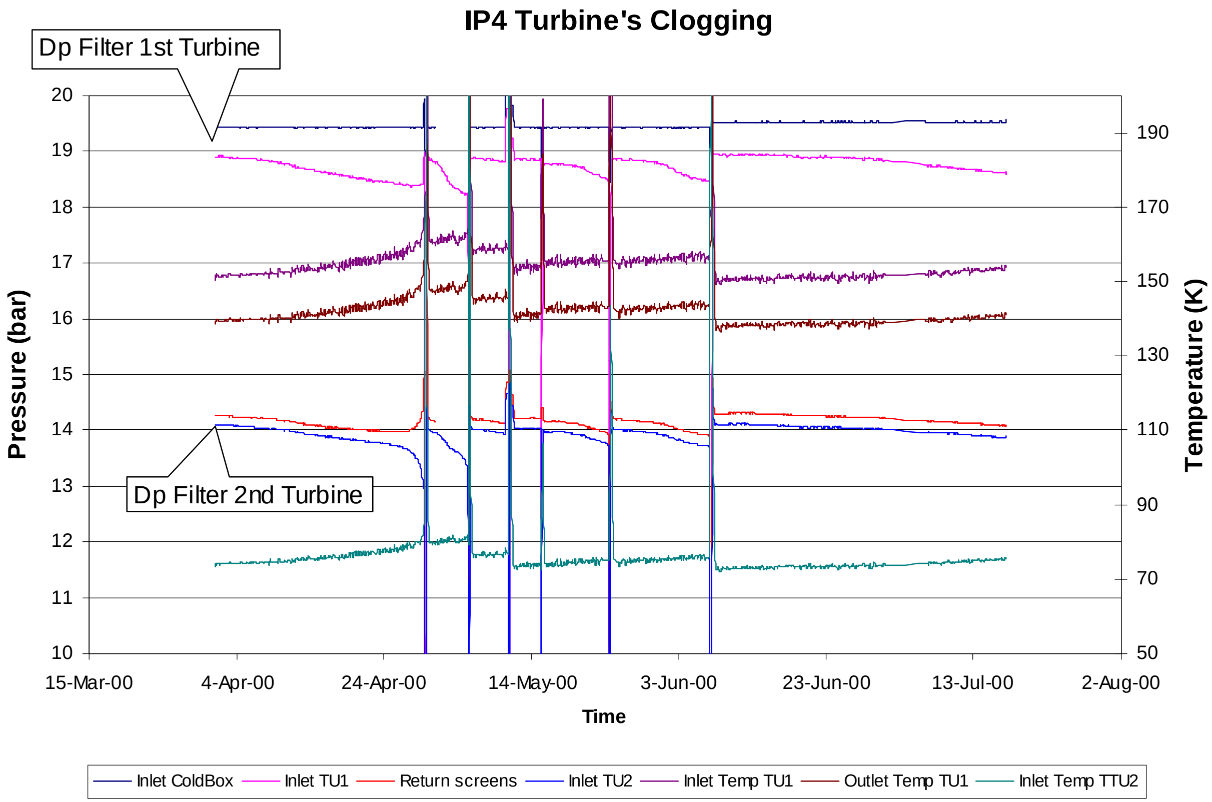
Vacuum system performs very well at highest LEP energies
Same true for magnets, power converters, instrumentation, etc…

"De-icing" of LEP cryogenics:

1) He flow rate above design
2) Unavoidable He impurities absorbed in filters
3) Ice in first (H_2O) and second (CO_2) turbine. He flow reduced.
4) De-icing to reduce clogging (~ 8 h in parallel to MD, access, …)

Example:

Pressure in IP4 turbines (M. Sanmarti)



Further improvements/options:

RF system	- **RF voltage at limit** of system capability - Slower mini-ramp for better beam stability? - **RF stability** with lower beam current (2-on-2)?
Optics	- 108/90 and 132/90 optics? Does not look hopeful.
RF frequency	- Run with **negative RF frequency** (larger beam size)? (lower luminosity, higher backgrounds)
80.5 GeV	- Fill high beam currents (6-8 mA) (if no limit at RF hardware) - Somewhat lower beam-beam limit - Same current as 98 GeV (6 mA): **~ 1.8 pb^{-1} per day** (same average efficiency, less overhead) - For 7.2 mA: **~ 2.3 pb^{-1} per day**
2-on-2 bunches	*see slides*

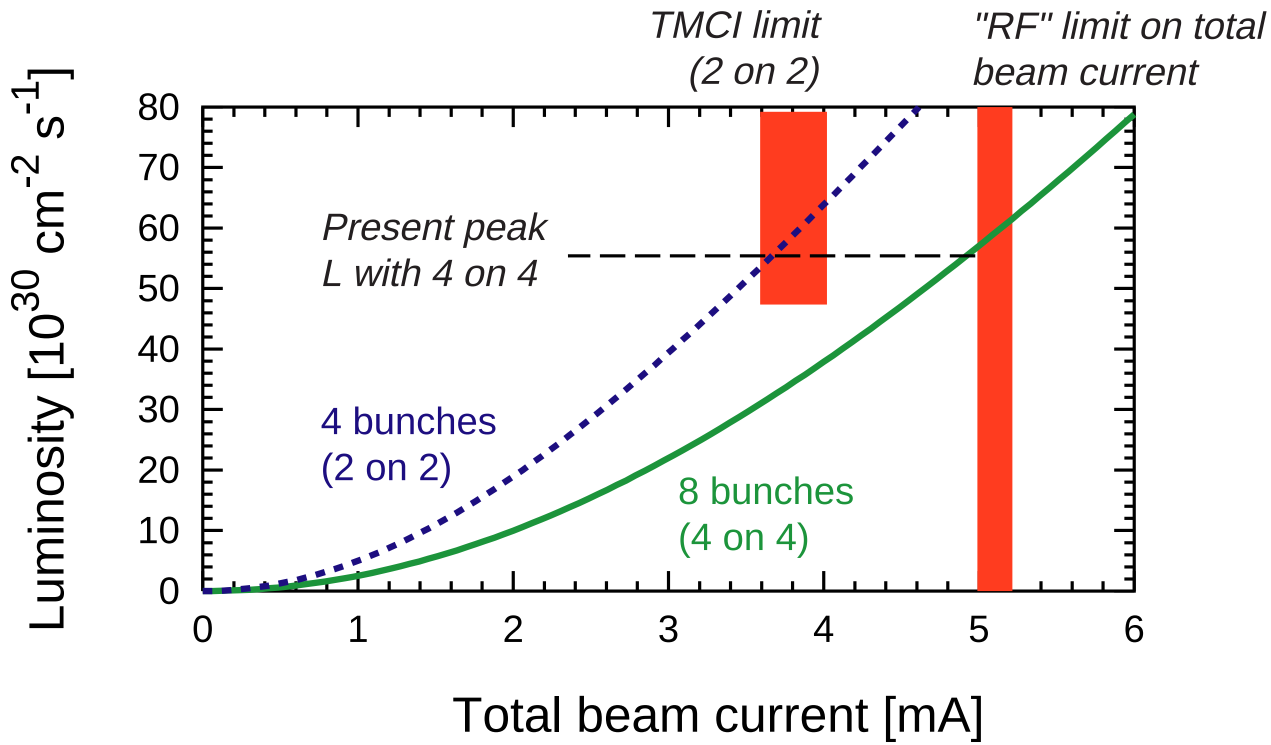
2-on-2 bunches:

Trade-off: Bunch current ⇔ Number of bunches

Luminosity ~ $i^2 \cdot n_b$

Limit on total beam current: **5.2 mA** (in 2000, lower above 104 GeV?)

Limit on single bunch current: **0.9-1.0 mA** (TMCI limit at injection)



Calculation based on:

Beam energy 103 GeV

Beam-beam limit at 0.115

Present emittances

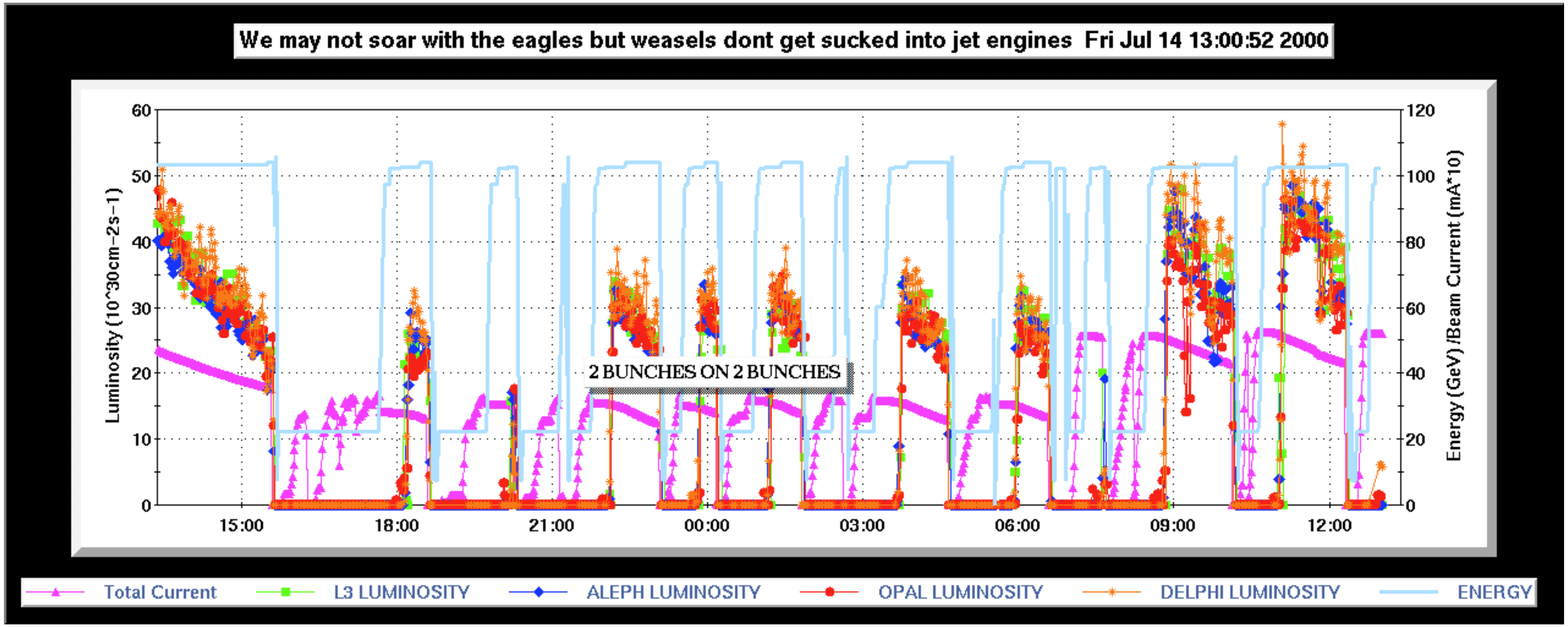
Note:

Beam lifetime is smaller for 2 on 2 (equal luminosity)

2 on 2: A little less luminosity with significantly less total current!

Rate of RF trips scales with: Total beam current?
Luminosity (HOM)?

2 on 2 mode tested (only 3 mA, not fully optimized for luminosity):
With changed strategy: Ramp to > 104 GeV as soon as possible…



RF stability above 104 GeV good during 6 test fills…

Consequences for luminosity production above 104 GeV:

	Standard	"New"	Increase
Fills in 24 hours Fraction at > 104 GeV	**7** **~ 30 %**	**12** **~ 90 %**	**1.7** **3.0**
Length at > 104 GeV (under study)	**14 min**	**29 min (2 on 2)** **(?) min (4 on 4)**	**2.1** **(?)**
Higher L with 2 on 2 (e.g. current limit at 3 mA)			**1.6**

Increase of luminosity rate above 104 GeV: **factor 5** changed strategy

factor 10 + longer time above 104 GeV

(factor 16) + higher L at 3 mA (2 on 2)

L rate above 104 GeV: **0.2** (0.64) **nb^{-1} per day** (so far 0.04 pb^{-1} per day)

Operation will be continuous filling, ramping, colliding…

Conclusion:

LEP operated in "discovery mode":

Beam energy increased by 3.4 GeV

- Increase of RF voltage (additional units, higher gradient)
- Change of operational strategy (ramp during physics fill, …)
- Reduced shift of RF frequency
- Increase of average bending radius

Push beam energy on cost of luminosity

- Reduce beam current (5 mA instead of 6.2 mA)
- Run with small J_x, large horizontal beam size
- Mini-ramp to quantum lifetime limit (zero margin in RF voltage)
- Loose all fills with RF trips

In half the time more physics fills than in 1998 (no time for rest in the LEP control room)

Luminosity production worse than 1999 but under circumstances still excellent: *(2000 still better than 1998)*

- Profit from 1999 improvements in vertical emittance tuning
  (dispersion-free steering, fast luminosity observation, tune working point, turnaround time, …)
- Overhead per fill further reduced by 25%
- Profit from strong transverse damping (unique at LEP)

  … jump 1/3 integer resonance, higher beam-beam limit, ramp colliding beams

Hardware in good shape, RF system shows damage (3 cavities lost in 2000)

How to extend energy reach of LEP further? **Very close to the limit!**

More luminosity above 104 GeV: **0.2-0.64 pb^{-1} / day instead of 0.04 pb^{-1} / day**

(changed strategy, less current with 2-on-2, better RF stability, …)

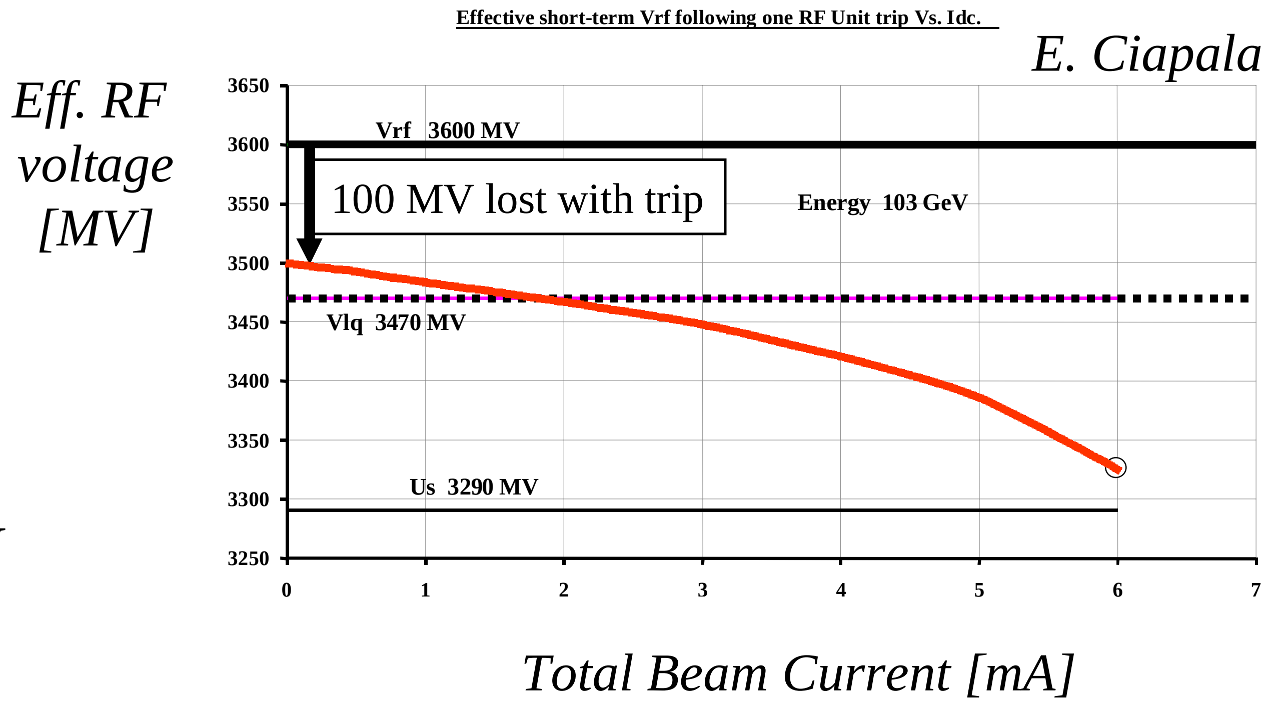
Hoping for a LEP discovery…

Additional slides

Transient effects on RF voltage:

Example:

Loss of one half-unit (100MV) at 103 GeV

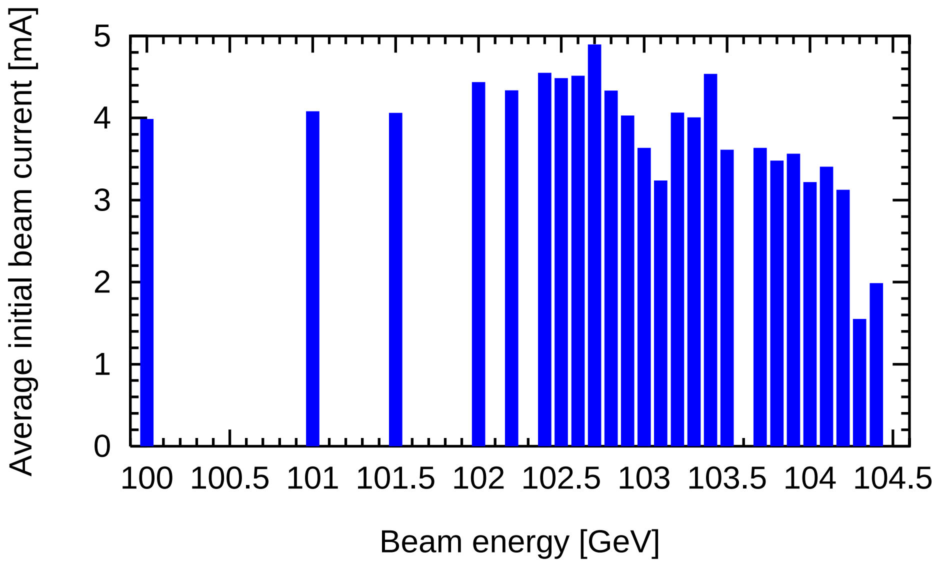


Total beam current	RF voltage	Lost RF voltage
0 mA	3500 MV	- 100 MV
2 mA	3460 MV	- 140 MV
4 mA	3420 MV	- 180 MV
6 mA	3330 MV	- 270 MV

Additional RF voltage reserve for transients required (or lower beam current)…

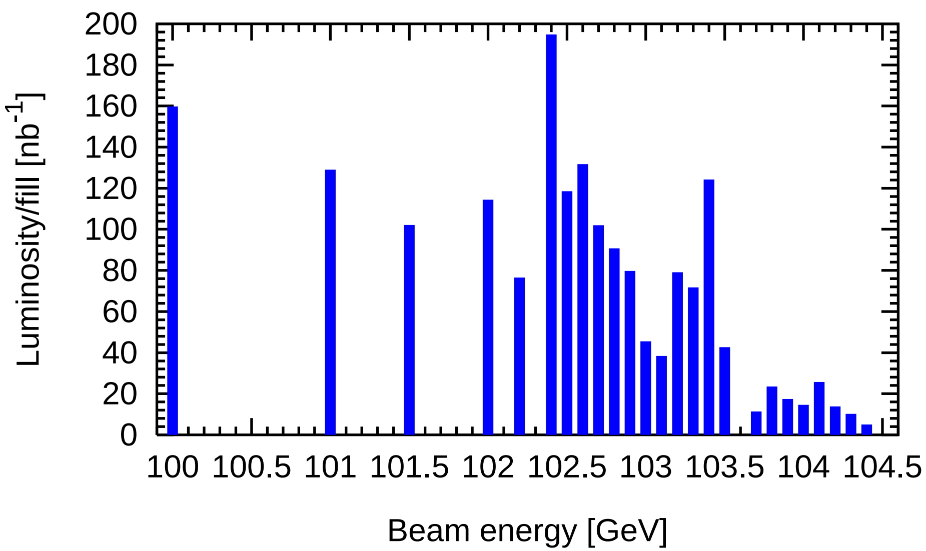
Beam current and luminosity per fill:

Total initial beam current



Higher energies with lower beam currents…

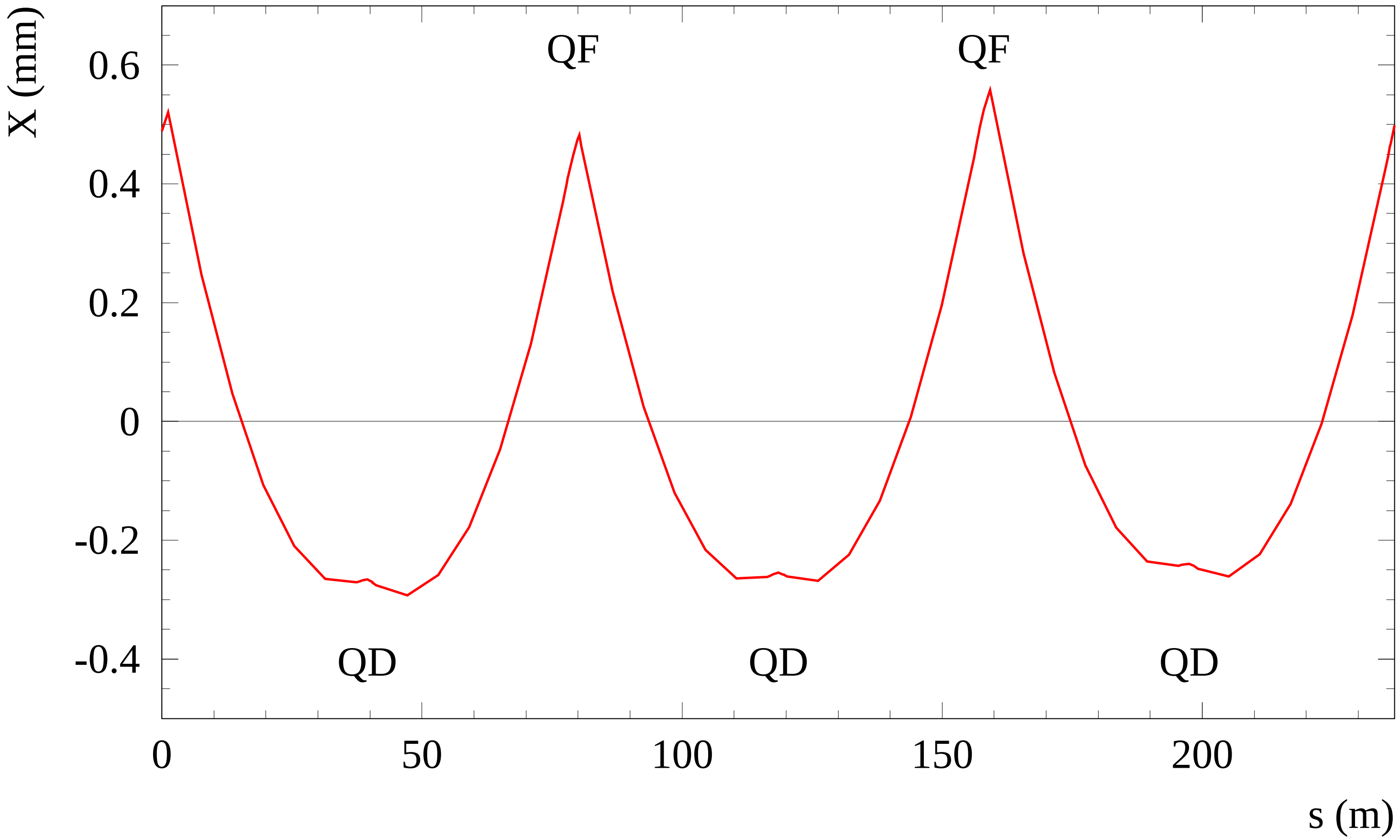
Produced luminosity per fill



Higher energies without margin are soon lost with RF trips…

Quadrupoles contributing to bending:

J. Wenninger



Vertical emittance:

1999/2000: $\beta_y^* = 5$ cm

$$\varepsilon_y \propto \left(C \cdot D_y^{rms} \cdot E\right)^2 + K \cdot \varepsilon_x + \ldots$$

$\propto E$ (solenoids)

- **Initial tuning** of coupling, chromaticity, orbit, dispersion, …
- **Vertical orbit** to get smallest RMS dispersion } *Peak luminosity*
- **Coupling** to get smallest global coupling
- **Local** dispersion, coupling, β-function at IP } *Luminosity balance*

"**Golden orbit**" strategy for optimization: (Lumi. measurements: ⇒ MOP6B04)
Trial and error! Complement with:

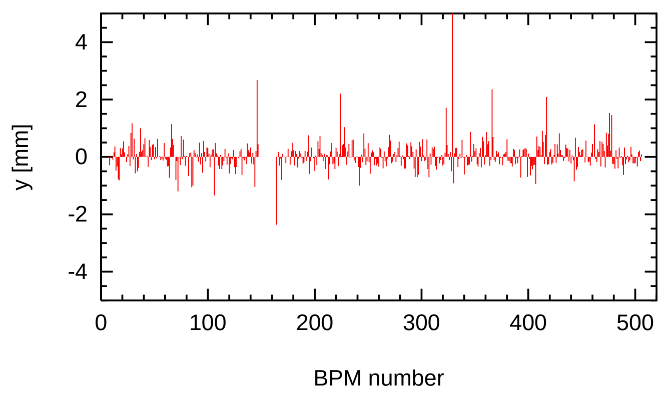
Dispersion-free steering (DFS): ⇒ MOP6B03

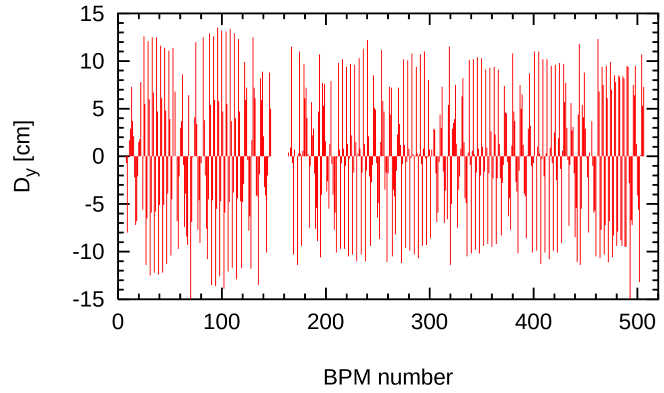
1) Measure orbit and dispersion
2) Calculate correctors to minimize both

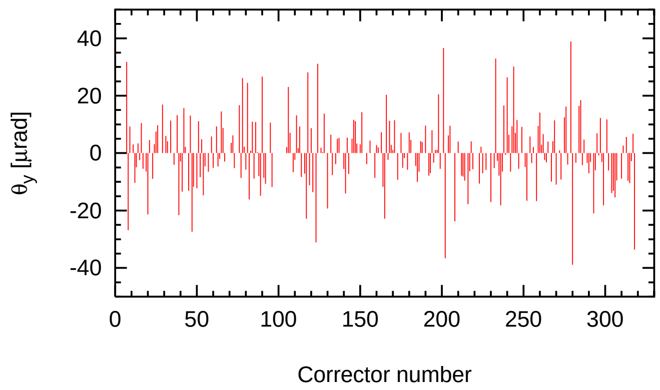
Note: Global correction generally also improves local dispersion/coupling!

Measured single beam performance of DFS in LEP:

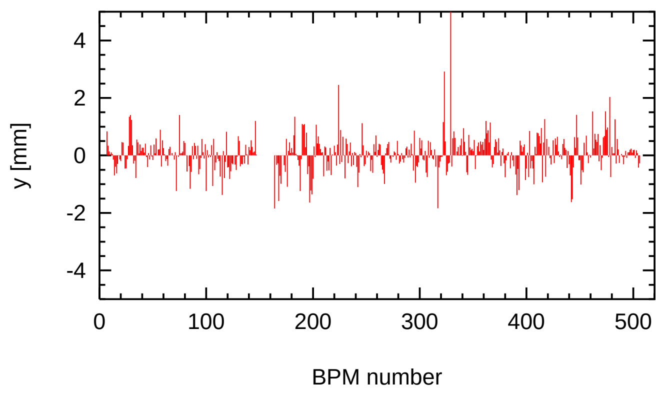
ORBIT | DISPERSION | CORR. KICKS

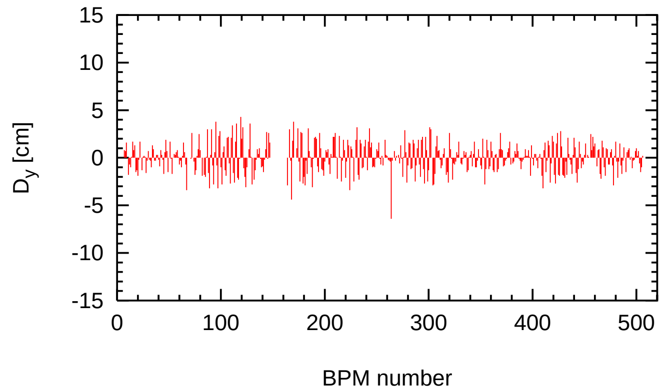


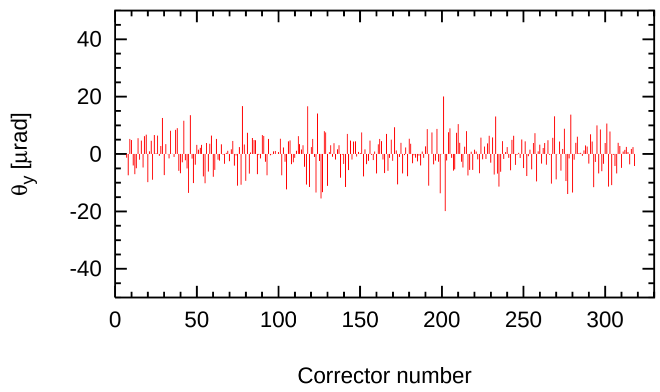




DFS: Simultaneously optimize orbit, disp., corr.





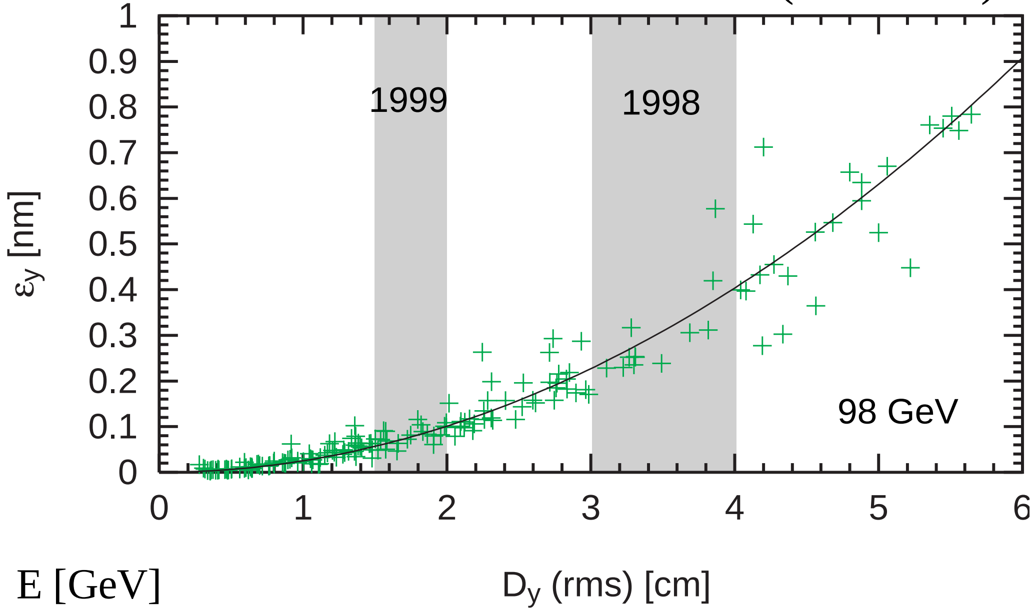


Vertical optimization:

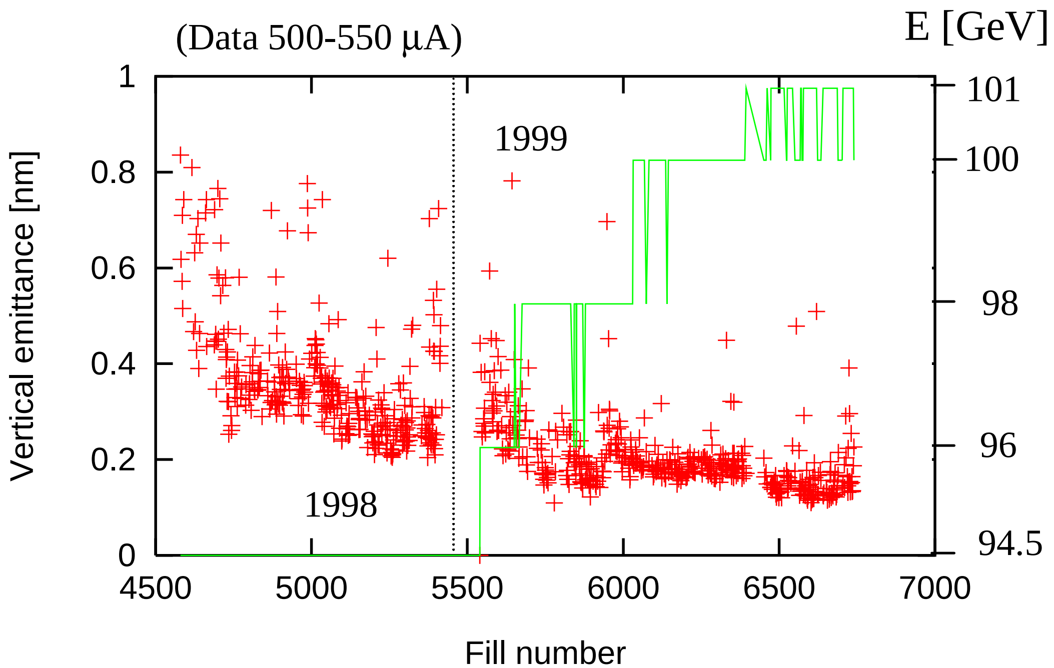
Reduction of RMS dispersion

(DFS + change of separation optics)

(simulated)



(Data 500-550 μA)



Reduction of vertical emittance

Emittance ratio: 0.5%

Vertical beam-beam blow-up:

Simple model used to fit unperturbed emittance and beam-beam limit:

$$\xi_y = \sqrt{\frac{1}{A + (B \cdot i_b)^2}} \cdot i_b$$

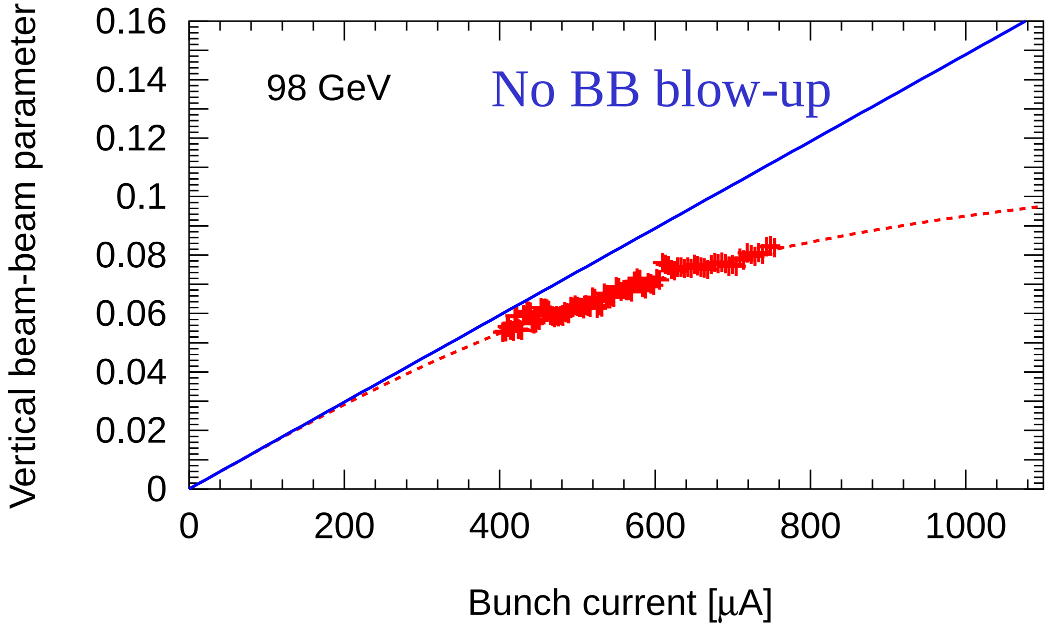
Two fit parameters A and B:

$$A = \left(\frac{2\pi\, e\, f\, \gamma}{r_e}\right)^2 \cdot \frac{\beta_x^*}{\beta_y^*} \cdot \varepsilon_x^0 \cdot \varepsilon_y^0$$

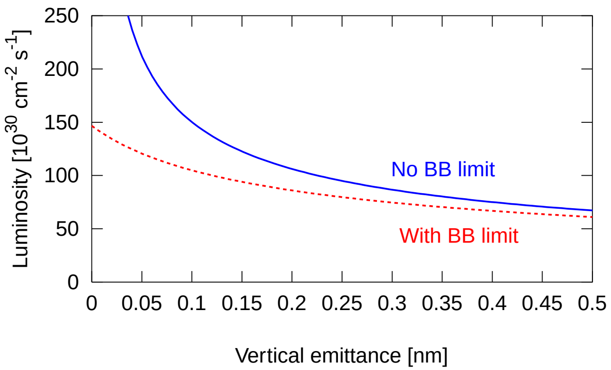
$$B = \frac{1}{\xi_y(i_b \to \infty)}$$

➡ Poster TUP6B01.

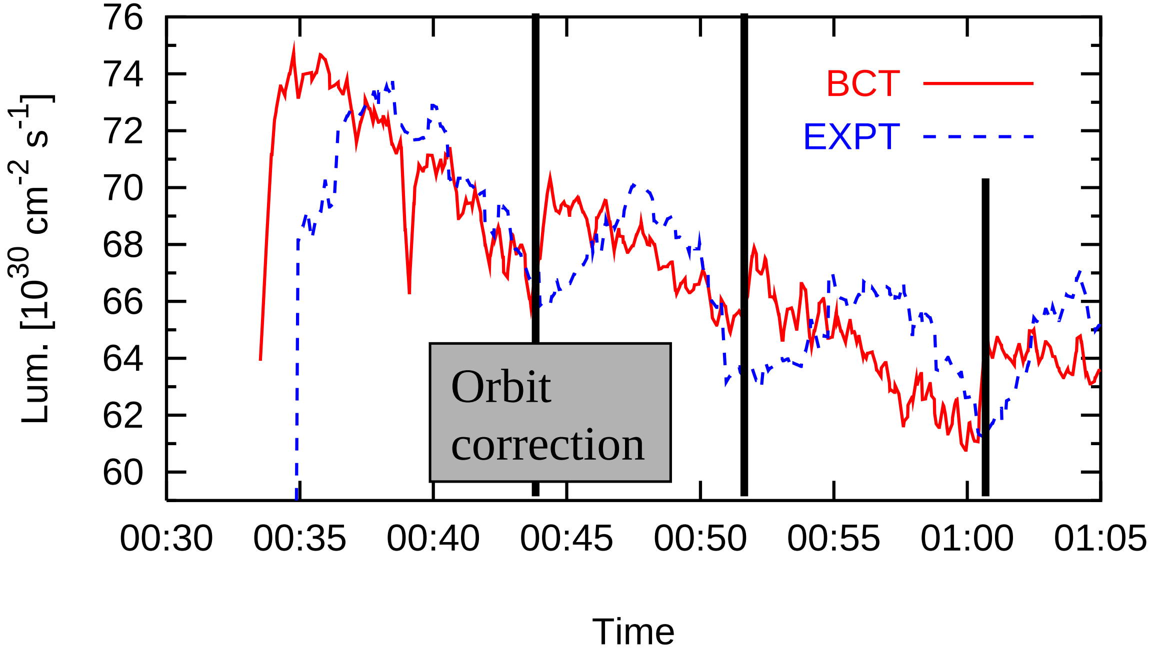
ξ_y (asymp) = 0.115
ε_y (no BB) = 0.1 nm



Limited gain in luminosity with ε_y:



Luminosity decay due to vertical orbit drifts:



$\Delta L \approx 0.3 \cdot 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ per minute

$\Delta \varepsilon \approx 0.002$ nm per minute

Measurement illustrates great sensitivity useful for fast online tuning

Luminosity stabilized with the vertical orbit feedback ("autopilot") every 7-8 minutes (3% effect).

Both visible from experiments and beam lifetime BCT (faster)!

(new operational tool in 1999)

Fast luminosity monitoring from LEP lifetime (BCT):

Different regimes:

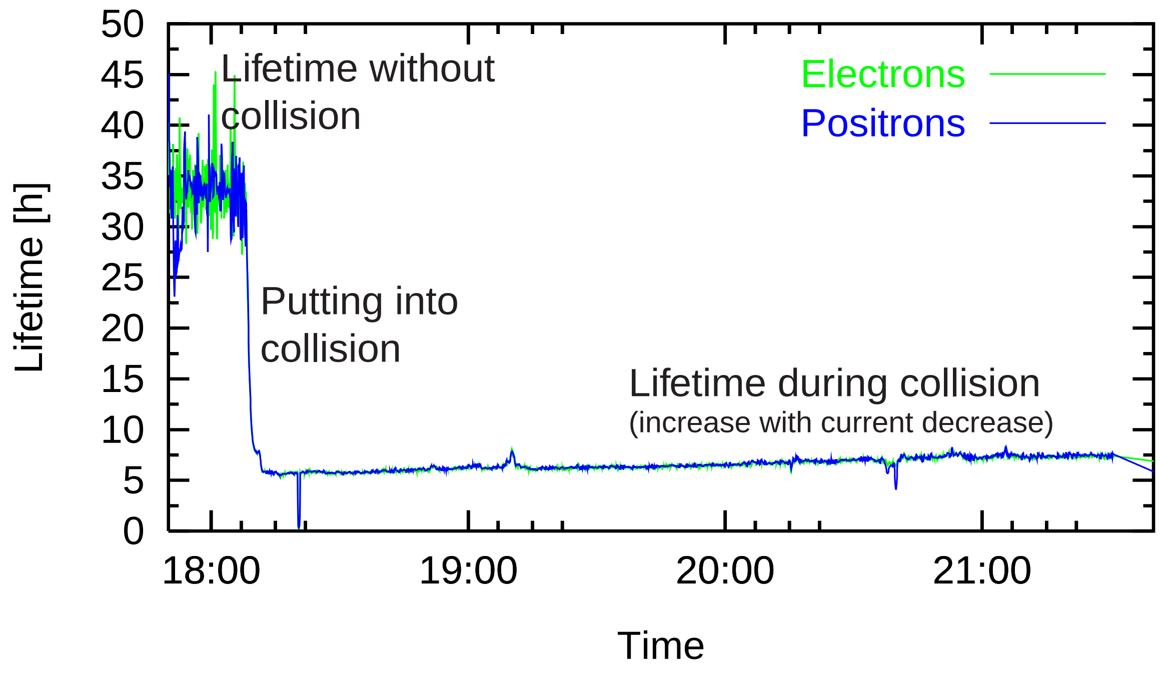
1) Without collision:

Compton scattering on thermal photons, beam-gas scattering.

$\tau_0 = 32$ h.

2) In collision:

Radiative Bhabha scattering or beam-beam bremsstrahlung.



Observe rate particle loss (BCT) → Calculate luminosity

Cross section

Reduction in design vertical dispersion:

DFS 1998 tests successful. Residual dispersion measured:

Single beam:	**1.0 cm**	**WHY the difference?**
Colliding beams:	**3.5 cm**	

Difference explained by separation bumps in odd IP's.

1998 optics:	**2.5 cm**	
1999 modified:	**1.6 cm**	Used for start-up
1999 optimized:	**0.3 cm**	Tested for 30 physics fills in 7/99

New solutions required change of separator polarities…

Trade-off:

Small separation bumps (reduce dispersion from **bumps**) ⟷ Large separation bumps (reduce dispersion from **residual beam-beam kicks**)

New working point for horizontal tune:

Strategy from 1998: Put Q_x as high as possible (~ 0.3)
Lower Q_y to ~ 0.18

Limits for Q_x: Third integer resonance at 1/3

Sensitivity to background storms closer to 1/3

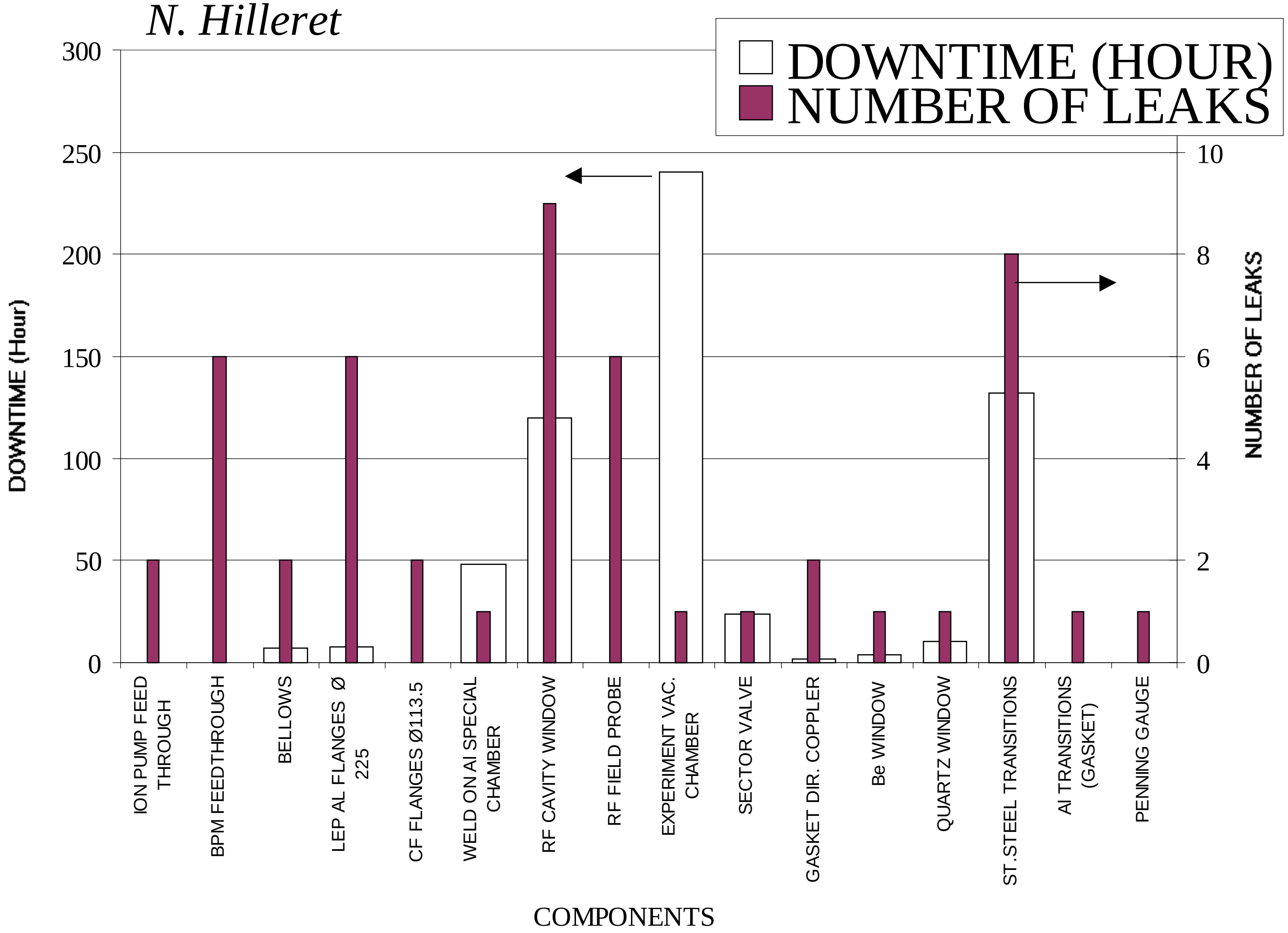
June 1999: **Jump the 1/3 resonance with Q_x to ~ 0.36**

Observation: Higher luminosity

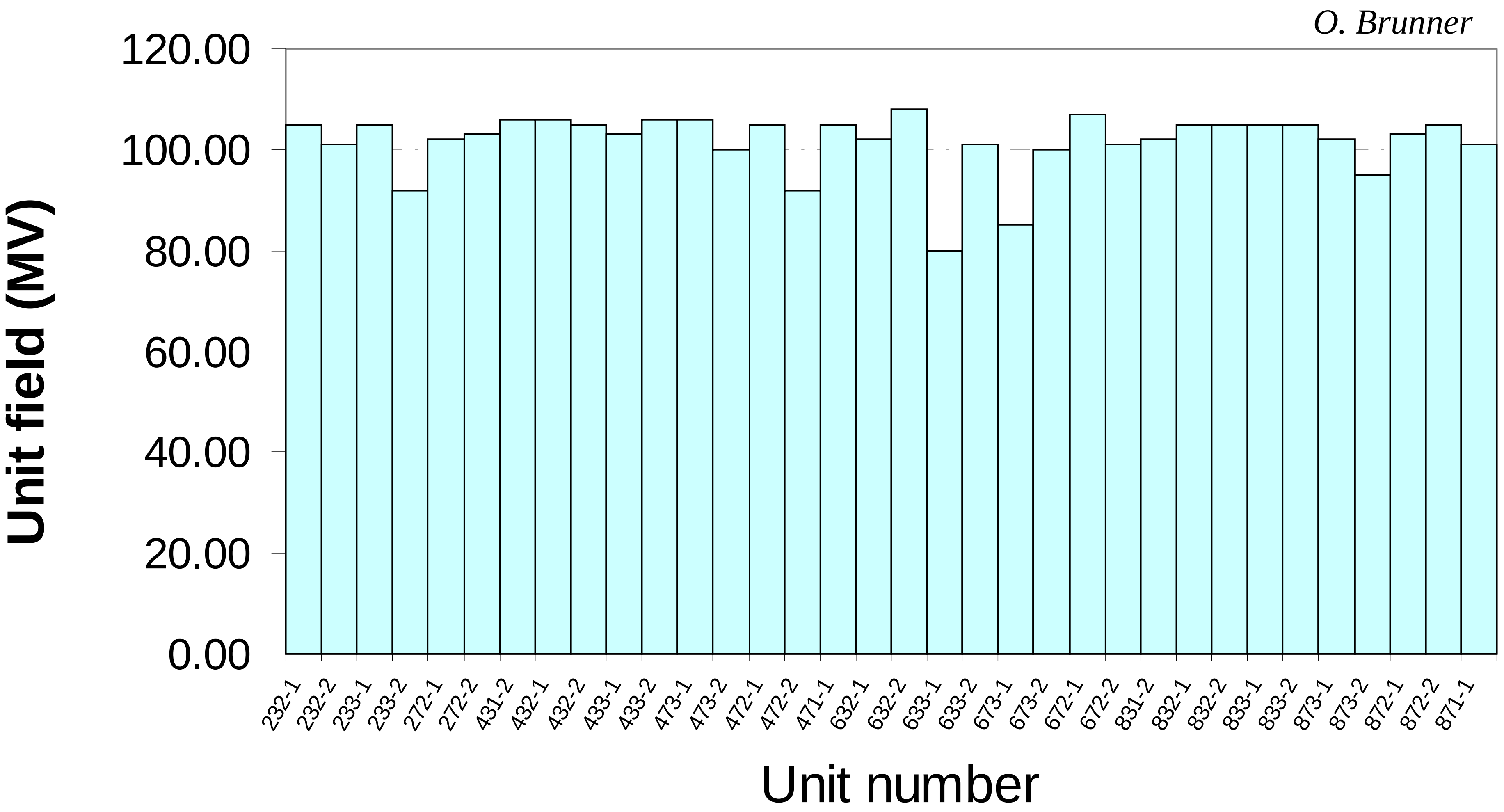
No background storms with $J_x = 1.5$

Details of vacuum leaks:

N. Hilleret



Nb/Cu SC units - Maximum field after conditioning (2000):



Horizontal beam size:

$$\sigma_x = \sqrt{\beta_x \varepsilon_x} \propto \sqrt{\beta_x / J_x} \cdot D_x^{rms} \cdot E$$

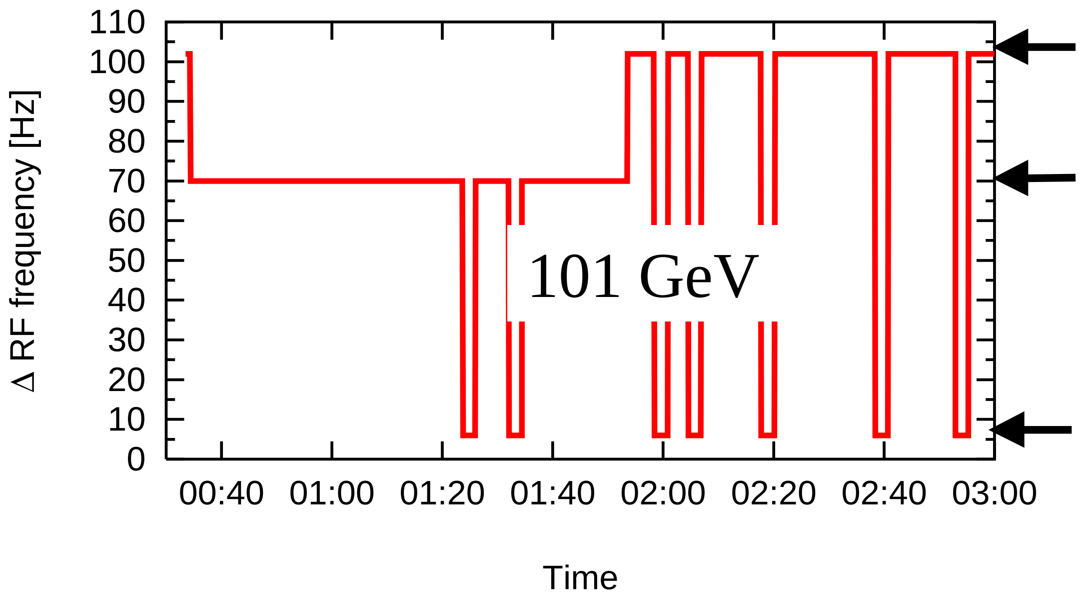
Compensate increase with energy (smaller luminosity, larger background):

1) **High Q_x optics** with smaller D_x^{rms} (D. Brandt et al, PAC99)

2) **Smaller β_x^*** (2.0 m - 1.5 m - 1.25 m)

3) **Increase** damping partition number **J_x** via RF frequency

Automatic control
$J_x = function\ (U_{RF})$



$J_x = 1.6$ (smaller σ_x)

$J_x = 1.4$

Safety setting $J_x = 1.04$ (larger σ_x)