Colliding Beams
How to make them

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Texas A&M University

- Motivations for high energy physics
- Beam cooling
- $\bar{p}p$ collider
- pp collider
- $\mu^+\mu^-$ collider

MEPAS is a feast for your mind.

Beam dynamics

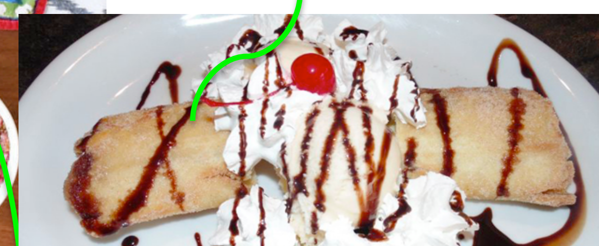
Magnets

Synchrotron light

Cavities

Colliders

FELs



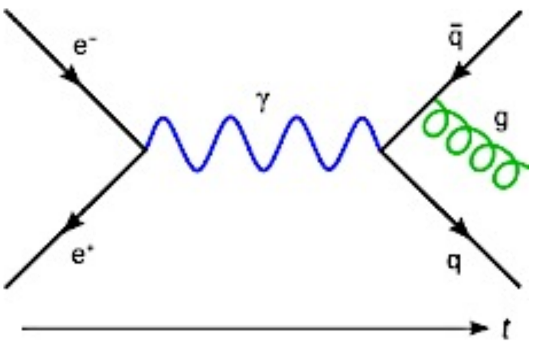
Particle sources

Instrumentation

Cryogenics

John and I will be presenting your dessert!

Accelerators and Colliders



- The name of the game: access new Bosons and new Fermions by ***colliding Fermions together***.
- Analyze collision dynamics as a 4-vector:

$$\prod = \left[(E_1 + E_2), (\vec{p}_1 + \vec{p}_2) \right]$$

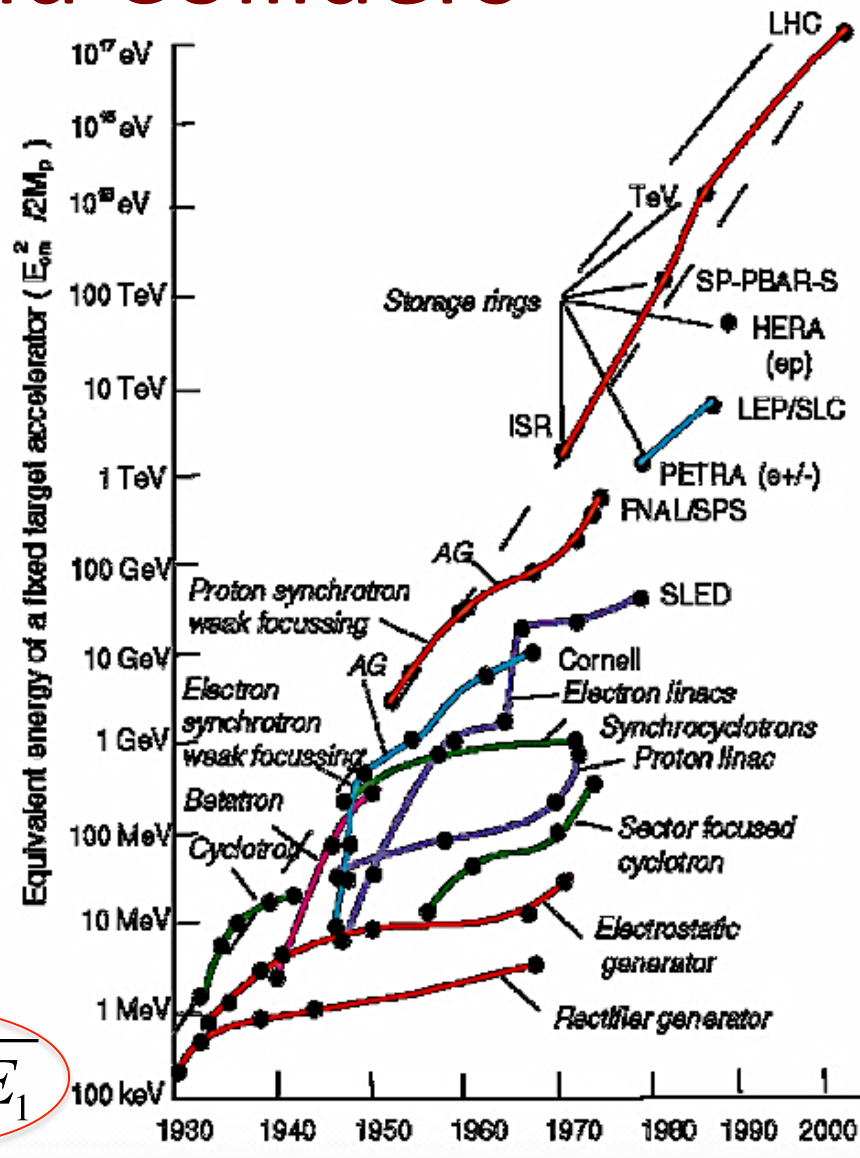
$$\prod^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

- Two ways to do it:
  - ✦ Collide beam on target

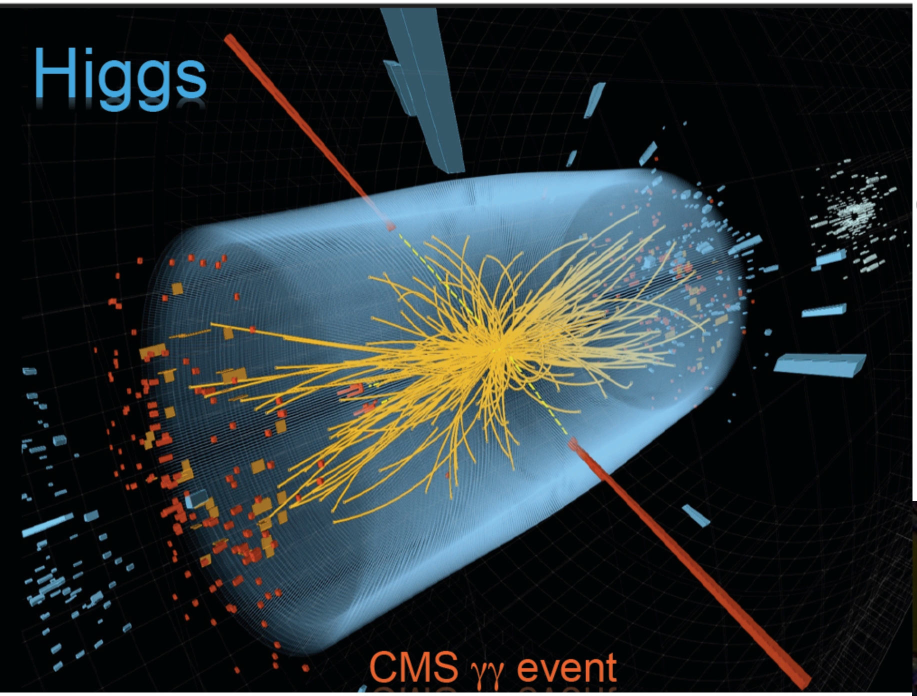
$$E_2 = m_2, \qquad p_2 = 0, \qquad \sqrt{\prod^2} = \sqrt{2m_2 E_1}$$

  - ✦ Collide beams head-on

$$E_1 = E_2 = E, \qquad \vec{p}_1 = -\vec{p}_2 \cong E, \qquad \sqrt{\prod^2} = 2E$$



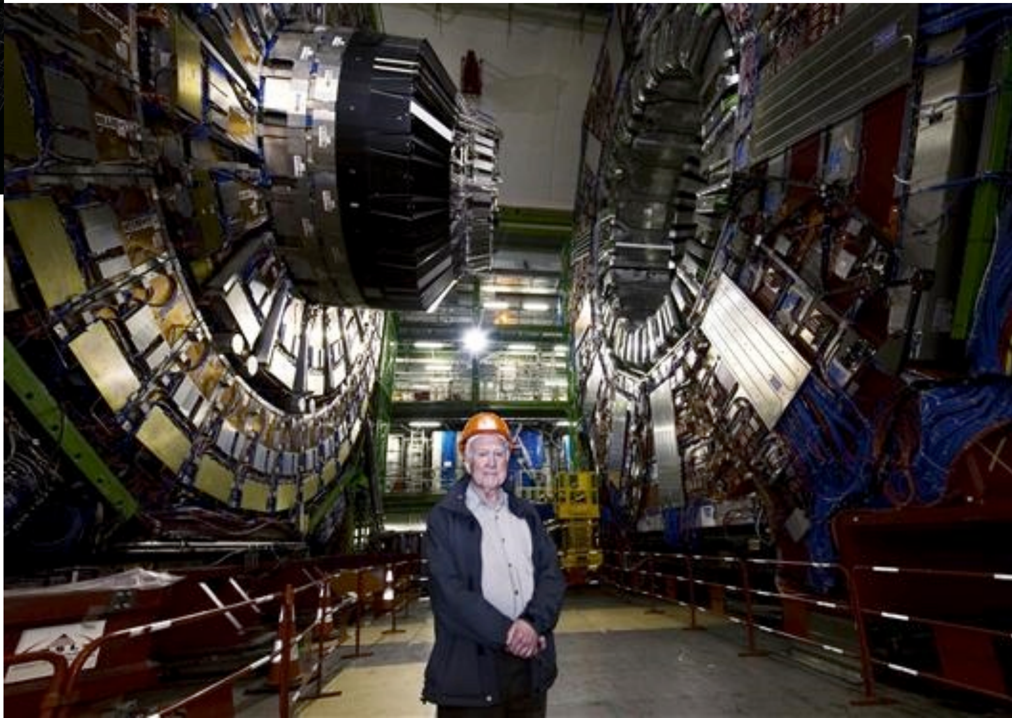
Present state of the art



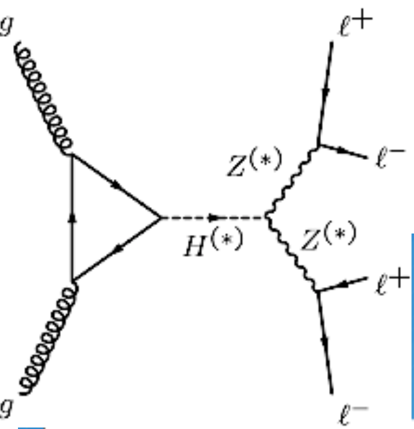
LHC produces collisions at

Collision energy $\sqrt{s} = 13\ TeV$

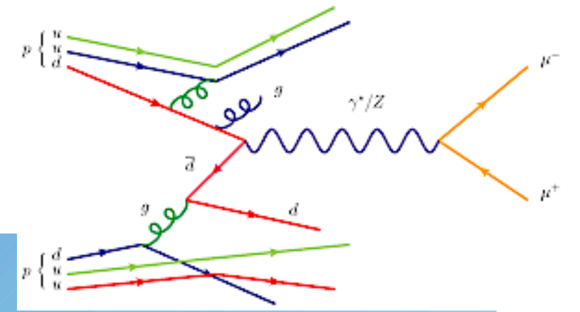
Luminosity $\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

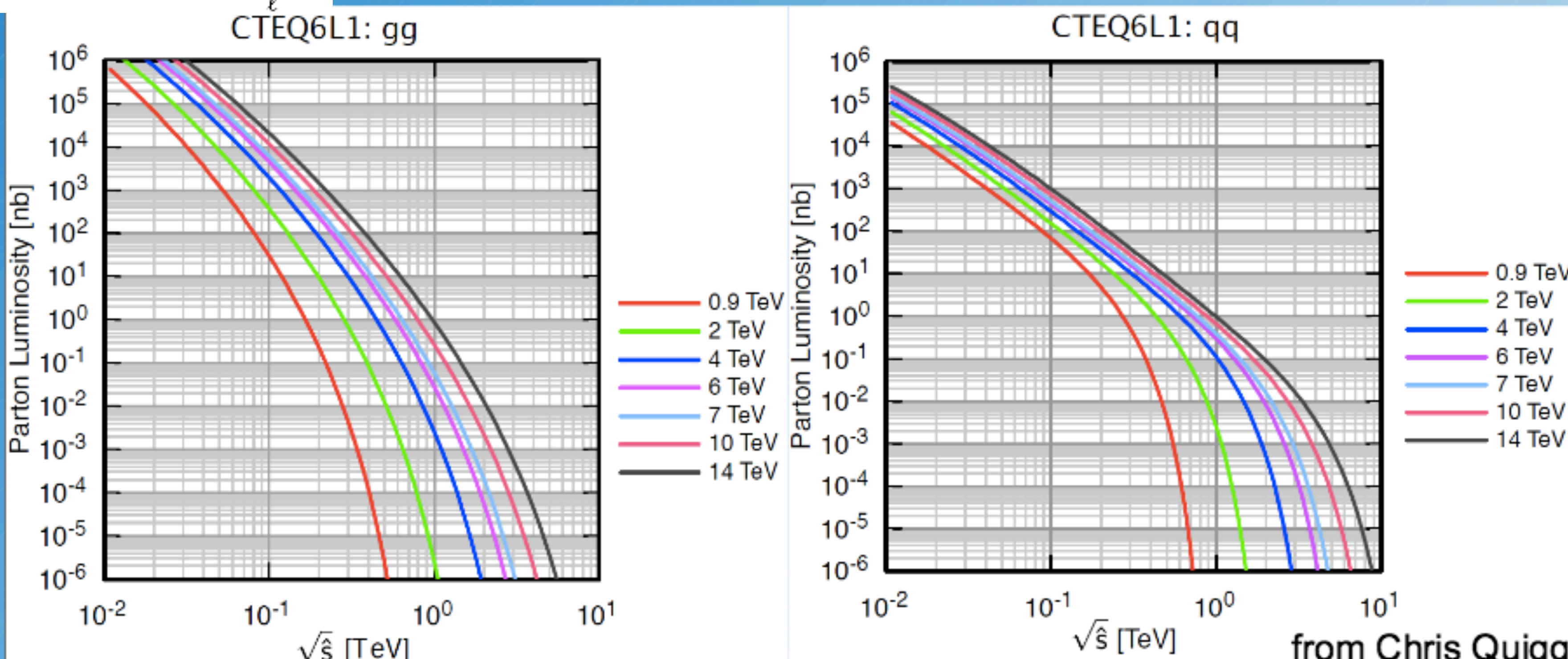


On July 4, 2012 the LHC experiments discovered the Higgs boson with mass $\mathcal{M} = 125\ \mathrm{GeV/c^2}$



Parton Luminosity





from Chris Quigg

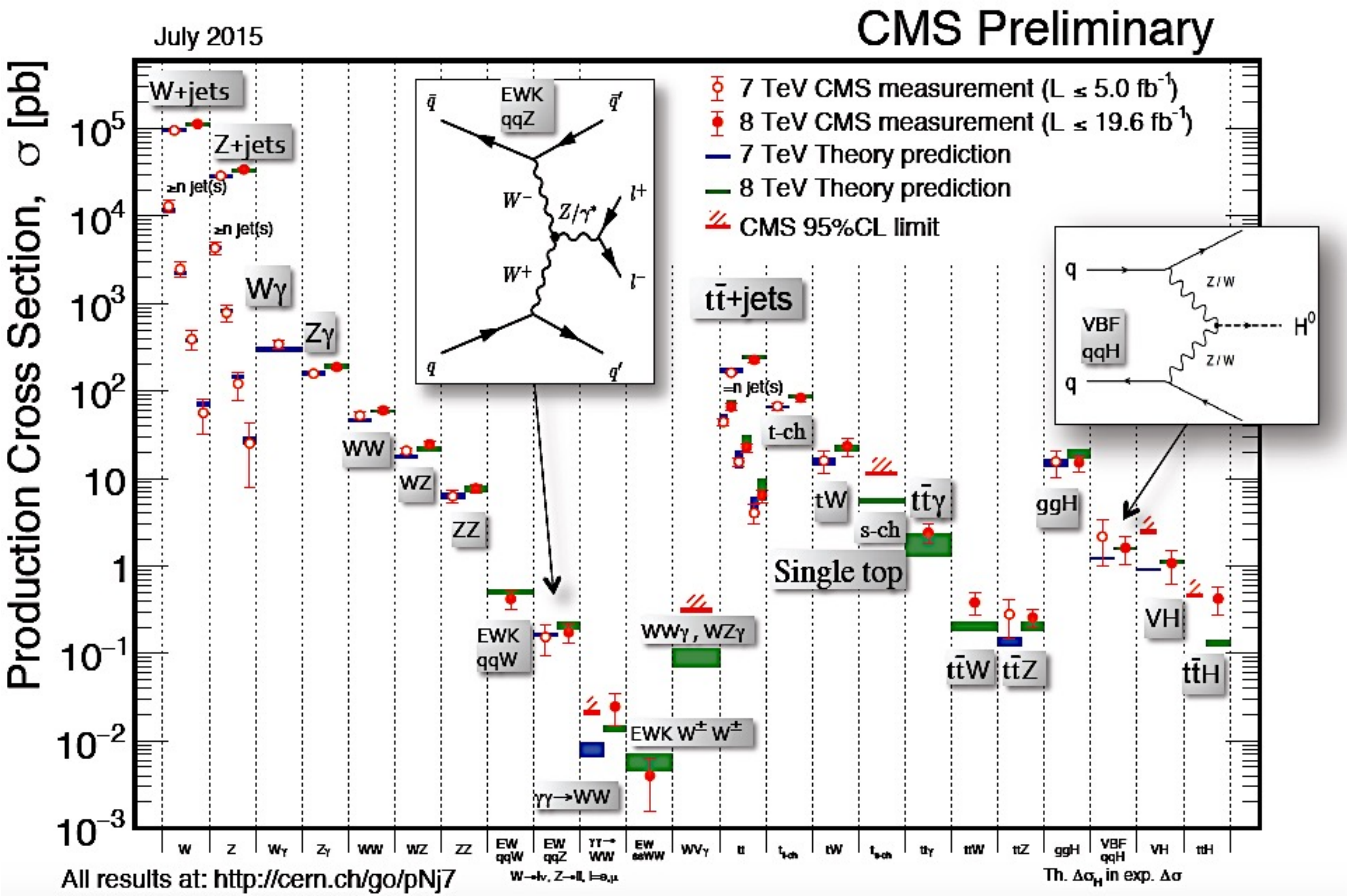
Example: $s^{1/2}$ = **14 TeV**, $\hat{s}^{1/2}$ = 1 TeV

cross section: $\sigma \sim 0.01^2$ parton luminosity ~ 0.1 pb (if couplings ~ 0.01)

luminosity $L = 10\ pb^{-1}$ → $N_{event} = L\,\sigma = 1$ event

New Physics channels for Run 2

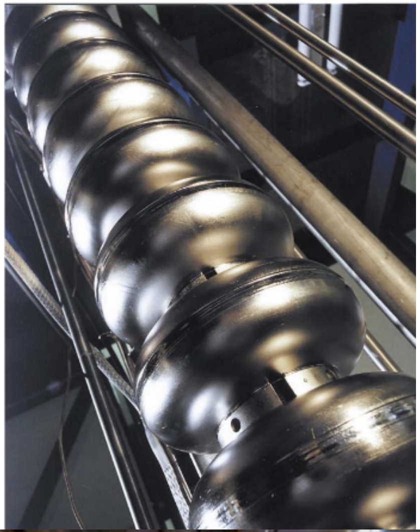
Need Maximum possible luminosity



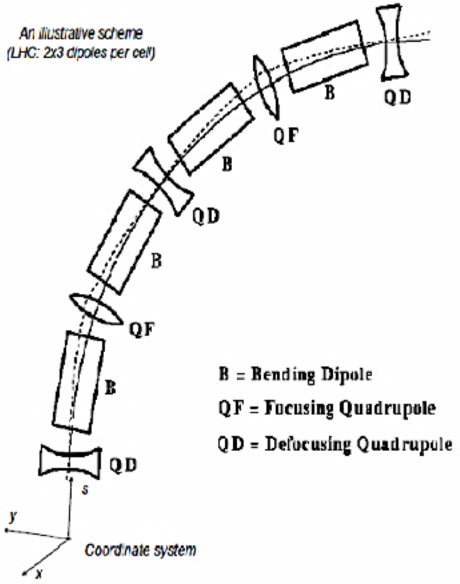
Need Maximum possible collision energy

Accelerators: Linacs and Synchrotrons

- Linacs:



β < 1: drift tube linac



Bending and focusing beams

The physics of accelerators builds upon a common framework, in which three elements are arranged in sequence:

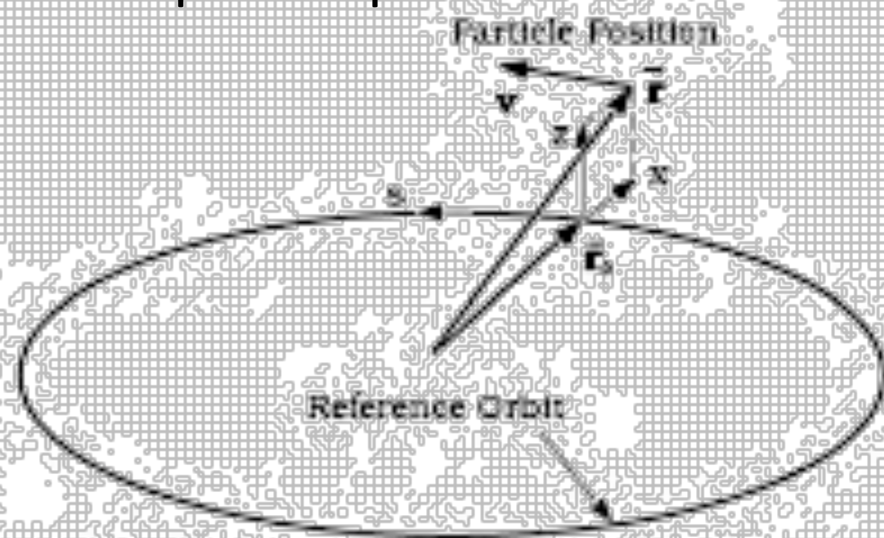
- dipole magnets to bend the bunches in a circular orbit (omitted for a linac);
- Quadrupole magnets to focus the bunches and confine them in transverse phase space;
- RF cavities to accelerate the bunches and confine them in bunches in longitudinal phase space.

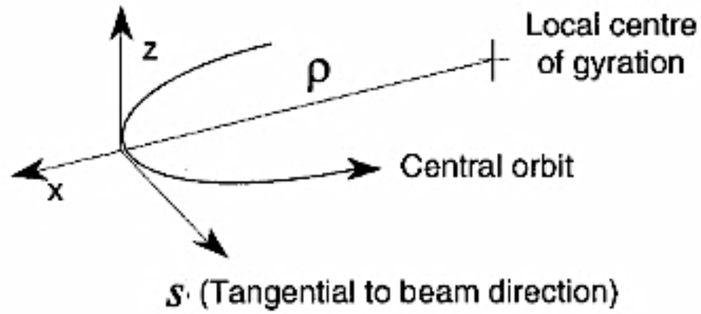
$$\frac{d\vec{P}}{dt} = e(\vec{E} + \vec{v}\times\vec{B})$$

$$\vec{E} = -\nabla\Phi - \frac{\partial\vec{A}}{\partial t}, \quad \vec{B} = \nabla\times\vec{A}$$

$$H = e\Phi + c\sqrt{m^2c^2 + (\vec{P} - e\vec{A})^2}$$

$$\dot{x} = \frac{\partial H}{\partial P_x}, \quad \dot{P}_x = -\frac{\partial H}{\partial x}, \quad \text{etc.}$$





Taylor series expansion

$$\phi = \sum_{n=1}^{\infty} \phi_n r^n \sin n\theta$$

Field in polar coordinates:

$$B_r = -\frac{\partial \phi}{\partial r}, \quad B_\theta = \frac{1}{r}\frac{\partial \phi}{\partial \theta}$$

$$B_r = \phi_n n r^{n-1} \sin n\theta, \quad B_\theta = \phi_n n r^{n-1} \cos n\theta$$

To get vertical field

$$B_z = B_r \sin\theta + B_\theta \cos\theta$$

$$= -\phi_n n r^{n-1}[\cos\theta \cos n\theta + \sin\theta \sin n\theta]$$

$$= \phi_n n r^{n-1} \cos(n-1)\theta = \phi_n n x^{n-1} \quad (\text{when } y = 0)$$

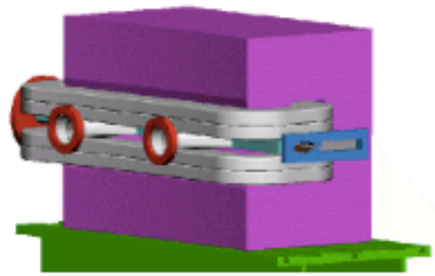
Taylor series of multipoles

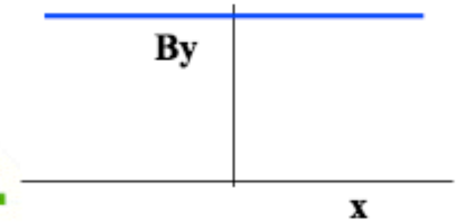
$$B_z = \phi_0 + \phi_2 .2x + \phi_3 .3x^2 + \phi_4 .4x^3 + \ldots\ldots$$

$$= B_0 + \frac{1}{1!}\frac{\partial B_z}{\partial x}x + 2\frac{\partial^2 B_z}{\partial x^2}x^2 + \frac{1}{3!}\frac{\partial^3 B_z}{\partial x^3}x^3 + \ldots$$

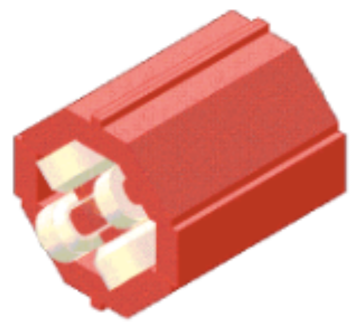
Dip. Quad Sext Octupole

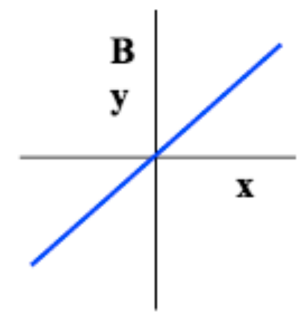
Magnet types



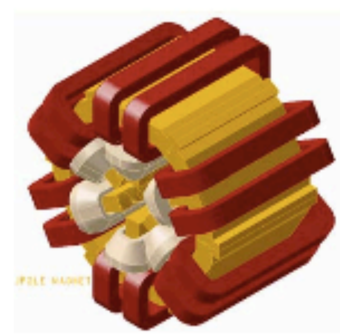


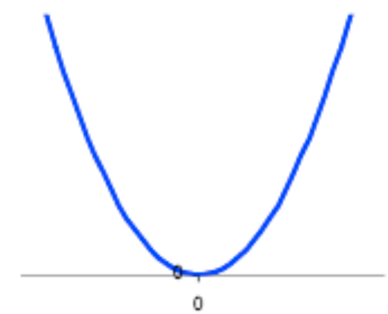
- Dipoles bend the beam





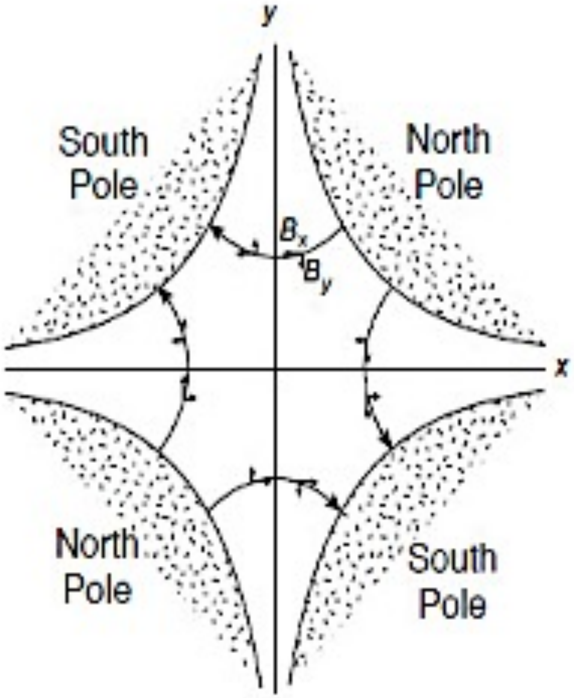
- Quadrupoles focus it





- Sextupoles correct chromaticity

Equation of motion in each coordinate



Magnetic field [T] : $B_y = \frac{\partial B_y}{\partial x} \times x$

Field gradient [T m^{-1}] : $g = \frac{\partial B_y}{\partial x}$

Normalized grad. [m^{-2}] : $K = \frac{g}{p_0/e} = \frac{1}{f}$

$$x'' + K(s)x = 0$$

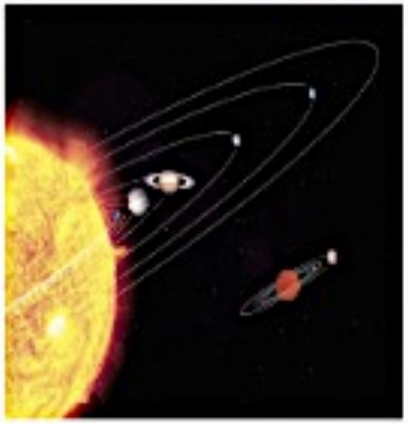
Hill's equation

K(s) describes the distribution of focusing strength along the lattice.

Alternating Gradient focusing → pseudo-harmonic oscillator with *s*-dependent spring constant *K(s)*.

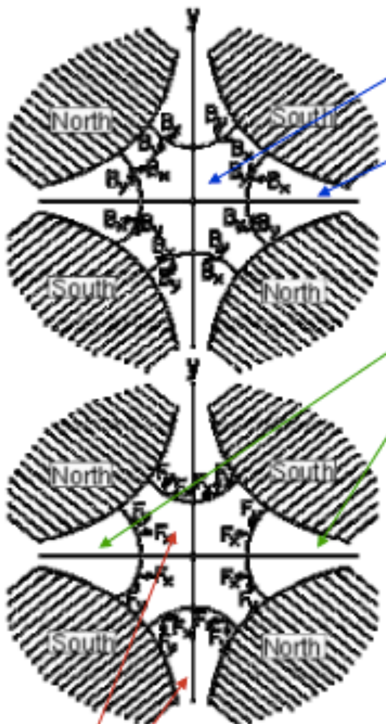
The general linear magnet lattice can be parameterized by a 'varying spring constant', *K=K(s)*

Note that dipoles give a "weak focusing" term in the horizontal plane, $K(s) = K(s)+1/\rho^2$



Transverse focusing

Fields and force in a quadrupole



Focuses in horizontal plane

(hence is linear)

Force restores

Gradient → $\frac{\partial B_y}{\partial x}$

Normalized:

$$k = -\frac{1}{(B\rho)} \cdot \frac{\partial B_y}{\partial x}$$

POWER OF LENS

$$\ell k = -\frac{\ell}{(B\rho)} \cdot \frac{\partial B_y}{\partial x} = \frac{1}{f}$$

Defocuses in vertical plane

Equation of motion in transverse co-ordinates

- Hill's equation (linear-periodic coefficients)

$$\frac{d^2 y}{ds^2} + k(s)y = 0$$

where $k = -\frac{1}{(B\rho)} \frac{dB_z}{dx}$ at quadrupoles

like restoring constant in harmonic motion

- Solution (e.g. Horizontal plane)

$$y = \sqrt{\beta(s)}\sqrt{\varepsilon}\sin[\phi(s) + \phi_0]$$

- Condition

$$\varphi = \int \frac{ds}{\beta(s)}$$

- Property of machine $\sqrt{\beta(s)}$
- Property of the particle (beam) ε
- Physical meaning (H or V planes)

Envelope $\sqrt{\varepsilon\beta(s)}$

Maximum excursions

$$\hat{y} = \sqrt{\varepsilon\beta(s)} \qquad \hat{y}' = \sqrt{\varepsilon / \beta(s)}$$

Each quadrupole lens couples position and angle in each transverse direction

The most general representation of the matrix **M**(s) with **unit modulus** is given by the Courant-Snyder parameterization.

$$\mathrm{M}(s)=\begin{pmatrix}\cos\Phi+\alpha\sin\Phi & \beta\sin\Phi\\ -\gamma\sin\Phi & \cos\Phi-\alpha\sin\Phi\end{pmatrix}=I\cos\Phi+J\sin\Phi$$

$$I=\begin{pmatrix}1&0\\0&1\end{pmatrix},\quad J=\begin{pmatrix}\alpha&\beta\\-\gamma&-\alpha\end{pmatrix},\quad J^2=-I,\ \text{ or }\ \beta\gamma=1+\alpha^2$$

The ambiguity in the sign of sin can be resolved by requiring β to be a positive definite number if |Trace(M)| ≤ 2, and by requiring Im(sinΦ)>0 if |Trace(M)| > 2. The definition of the phase factor is still ambiguous up to an integral multiple of 2π. This ambiguity will be resolved when the matrix is tracked along the accelerator elements. Using the property of matrix J, we obtain the De Moivere' theorem:

$$\mathbf{M}^k=(\mathbf{I}\cos\Phi+\mathbf{J}\sin\Phi)^k=\mathbf{I}\cos k\Phi+\mathbf{J}\sin k\Phi,$$
$$\mathbf{M}^{-1}=\mathbf{I}\cos\Phi-\mathbf{J}\sin\Phi.$$

Drift section or dipole magnet:

$$M=\begin{pmatrix}1&L\\0&1\end{pmatrix}$$

Focusing quadrupole:

$$M=\begin{pmatrix}1&0\\ \frac{1}{f}&1\end{pmatrix}$$

Example: FODO cell

A FODO cell is a basic block in beam transport, where the transfer matrices for dipoles (B) can be approximated by drift spaces, and QF and QD are the focusing and defocusing quadrupoles.

$$\mathbf{M}=\begin{pmatrix}1&0\\-\frac{1}{2f}&1\end{pmatrix}\begin{pmatrix}1&L_1\\0&1\end{pmatrix}\begin{pmatrix}1&0\\\frac{1}{f}&1\end{pmatrix}\begin{pmatrix}1&L_1\\0&1\end{pmatrix}\begin{pmatrix}1&0\\-\frac{1}{2f}&1\end{pmatrix}$$
$$=\begin{pmatrix}1-\frac{L_1^2}{2f^2} & 2L_1(1+\frac{L_1}{2f})\\ -\frac{L_1}{2f^2}(1-\frac{L_1}{2f}) & 1-\frac{L_1^2}{2f^2}\end{pmatrix}$$

$$\mathrm{M}(s)=\begin{pmatrix}\cos\Phi+\alpha\sin\Phi & \beta\sin\Phi\\ -\gamma\sin\Phi & \cos\Phi-\alpha\sin\Phi\end{pmatrix}$$

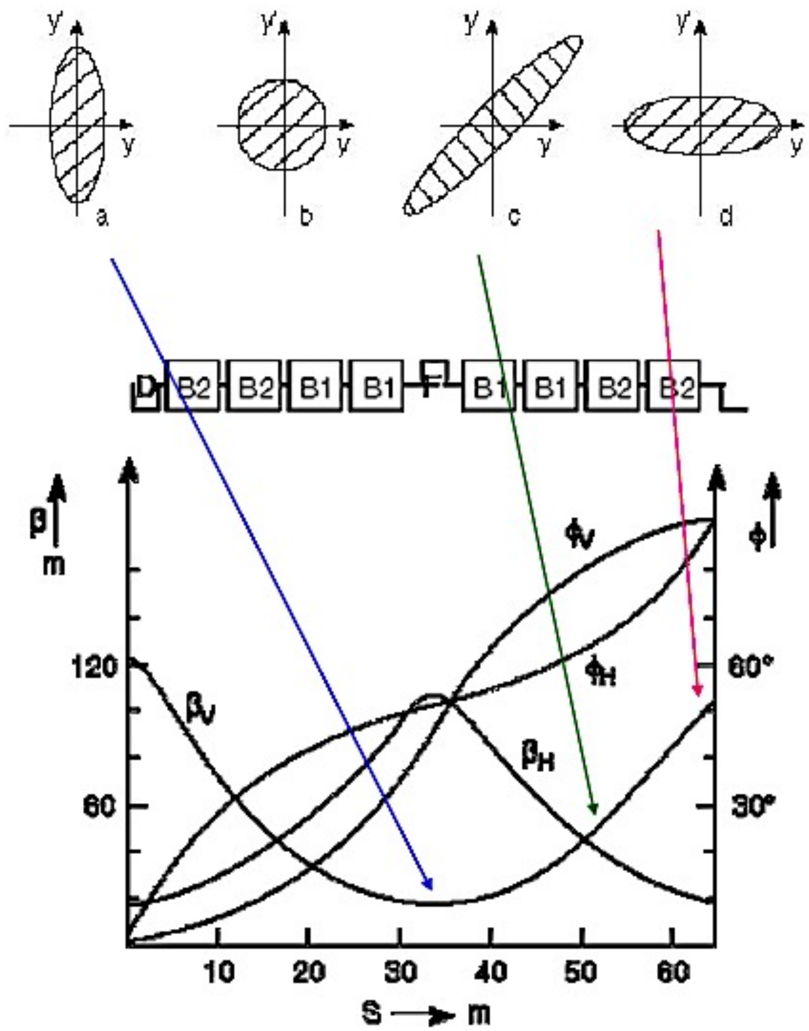
$$\cos\Phi=\tfrac{1}{2}\mathrm{Tr}(\mathrm{M})$$

$$\cos\Phi=1-\frac{L_1^2}{2f^2},\quad \sin\frac{\Phi}{2}=\frac{L_1}{2f}$$

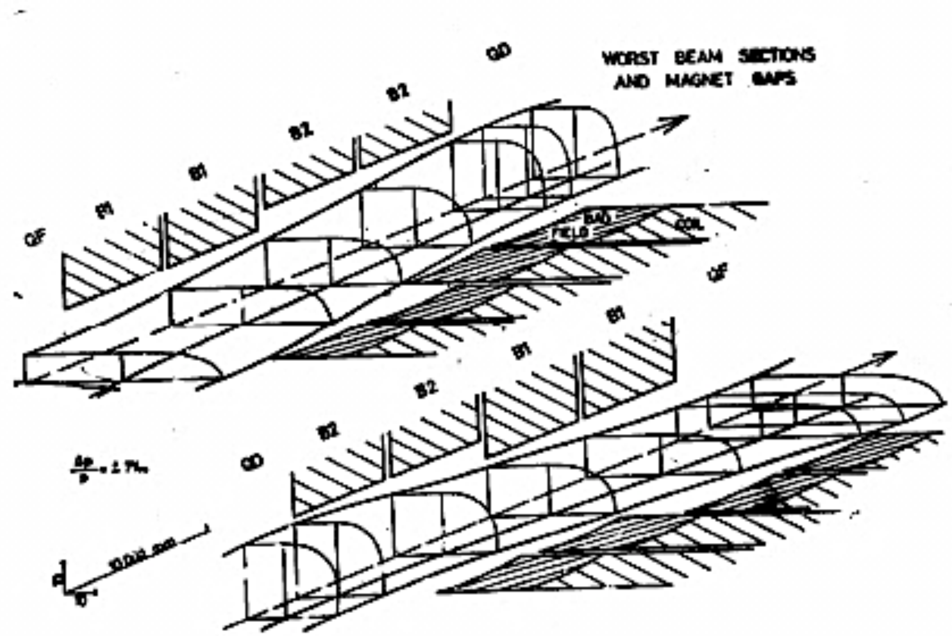
$$\beta=\frac{2L_1(1+\frac{L_1}{2f})}{\sin\Phi}=\frac{2L_1(1+\sin\frac{\Phi}{2})}{\sin\Phi}$$
$$\alpha=0$$

This description works just as well for a linac as for a synchrotron or storage ring – main difference is that chromaticity and dispersion play an important role for circular machines.

Betatron phase space at various points in a lattice



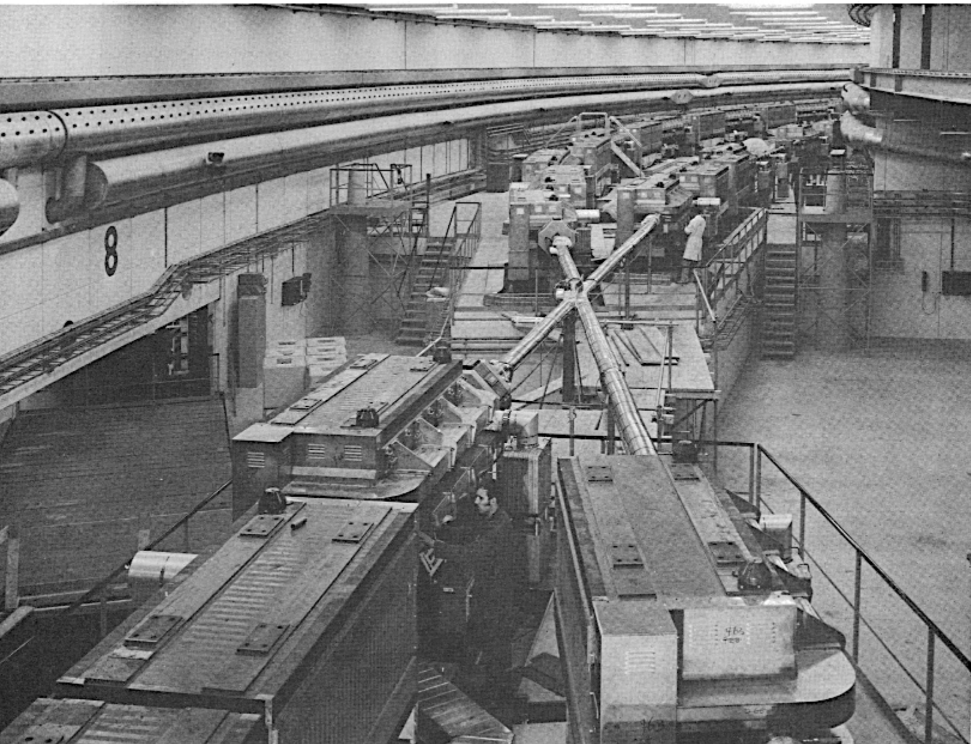
Beam sections



I will present this as a personal tour through colliders I have known.

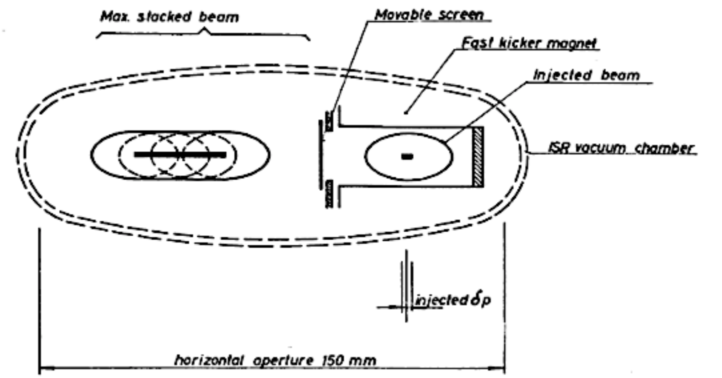
I began my career (I was once your age!) as a scientist on an experiment at CERN's Intersecting Storage Rings (ISR).

The ISR made p-p collisions up to 60 GeV collision energy, luminosity to 10^{30} cm^{-2}s^{-1}



The ISR did not produce a single important HEP discovery, but it ushered in several pivotal developments of accelerator physics and technology:

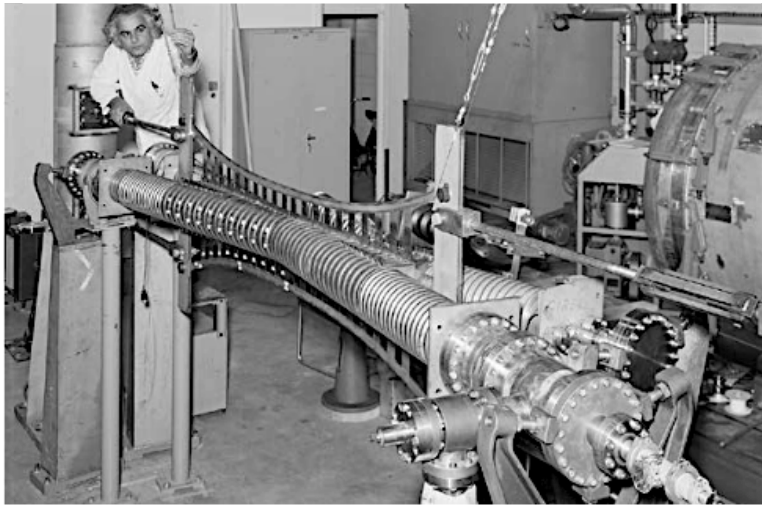
The ISR used momentum stacking to accumulate ~100 fills from PS – 20 A circulating d.c. current @ 30 GeV.



It required ultra-high vacuum for ~week-long lifetimes.

Benvenuti invented

- getter pumping, later NEG
- plasma discharge cleaning for UHV



The crowning glory from ISR was stochastic cooling

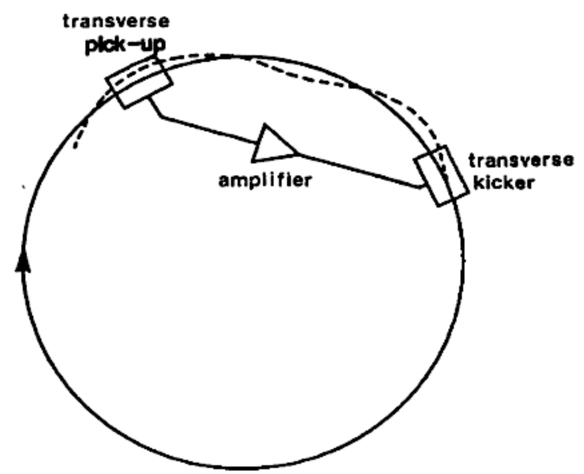


FIG. 2. Cooling of the horizontal betatron oscillation of a single particle.

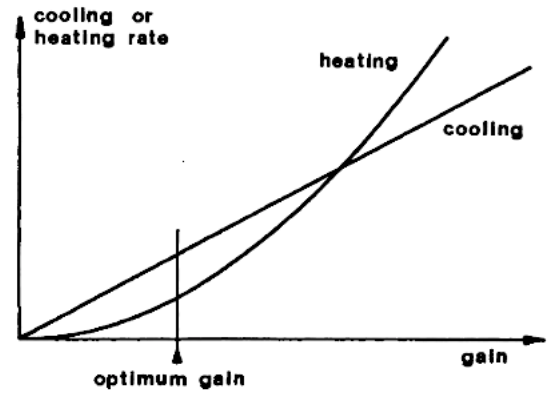


FIG. 3. Variation with system gain of the coherent cooling and incoherent heating effect.

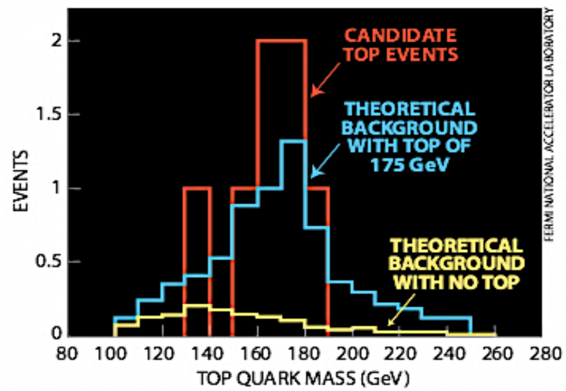
Simon van der Meer

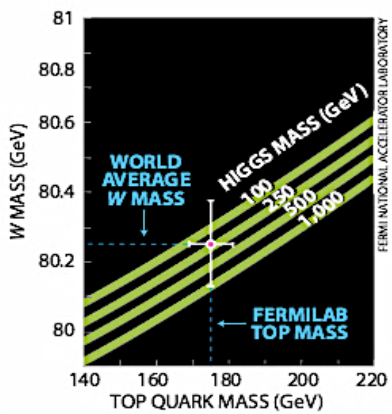
Invented stochastic cooling to cool protons in the ISR

Used it to cool 5x10^{10}/hr antiprotons to discover the weak bosons in the $Sp\bar{p}S$

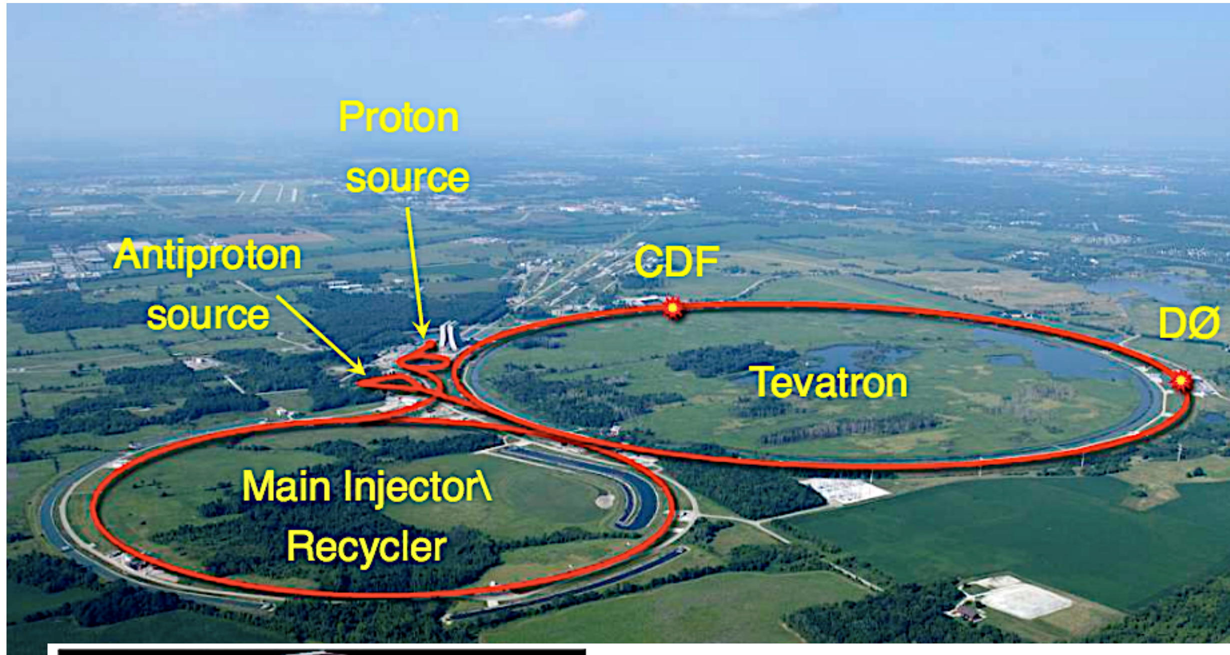
The Tevatron:
Anchor for a generation of HEP discoveries

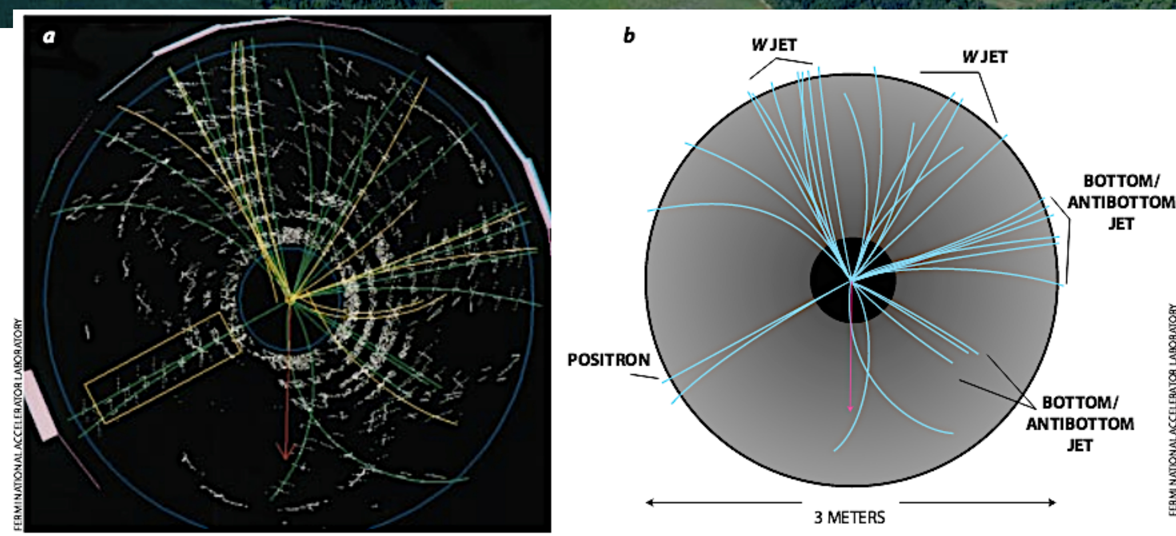
One can still obtain a mass bump from a new particle, even at 175 GeV/c^2 mass!



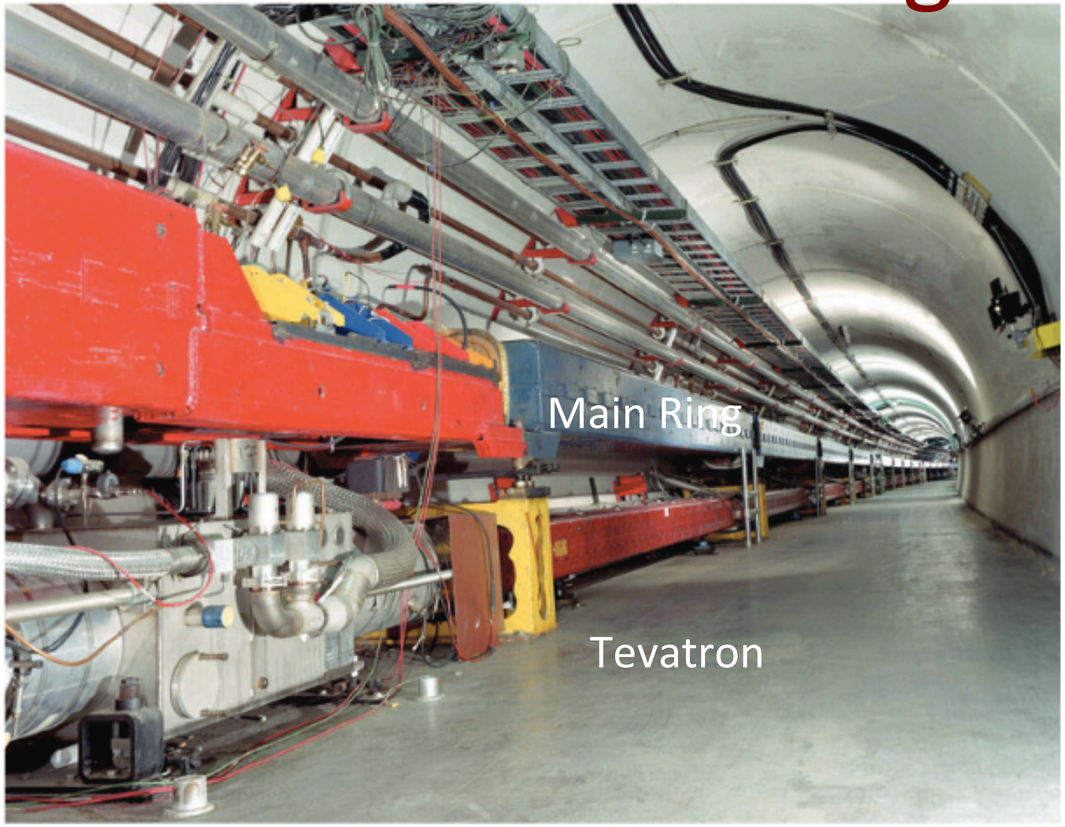


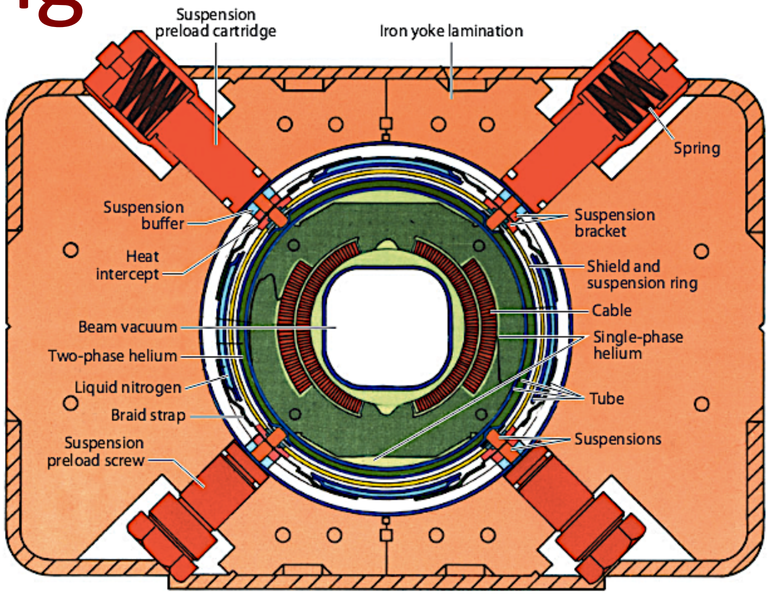
The top quark and the Higgs are intimately related through gauge couplings: – a_{scalar}~m_f



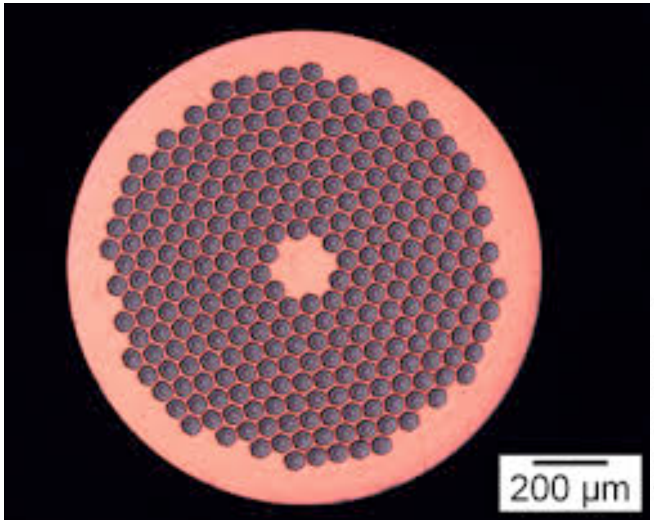


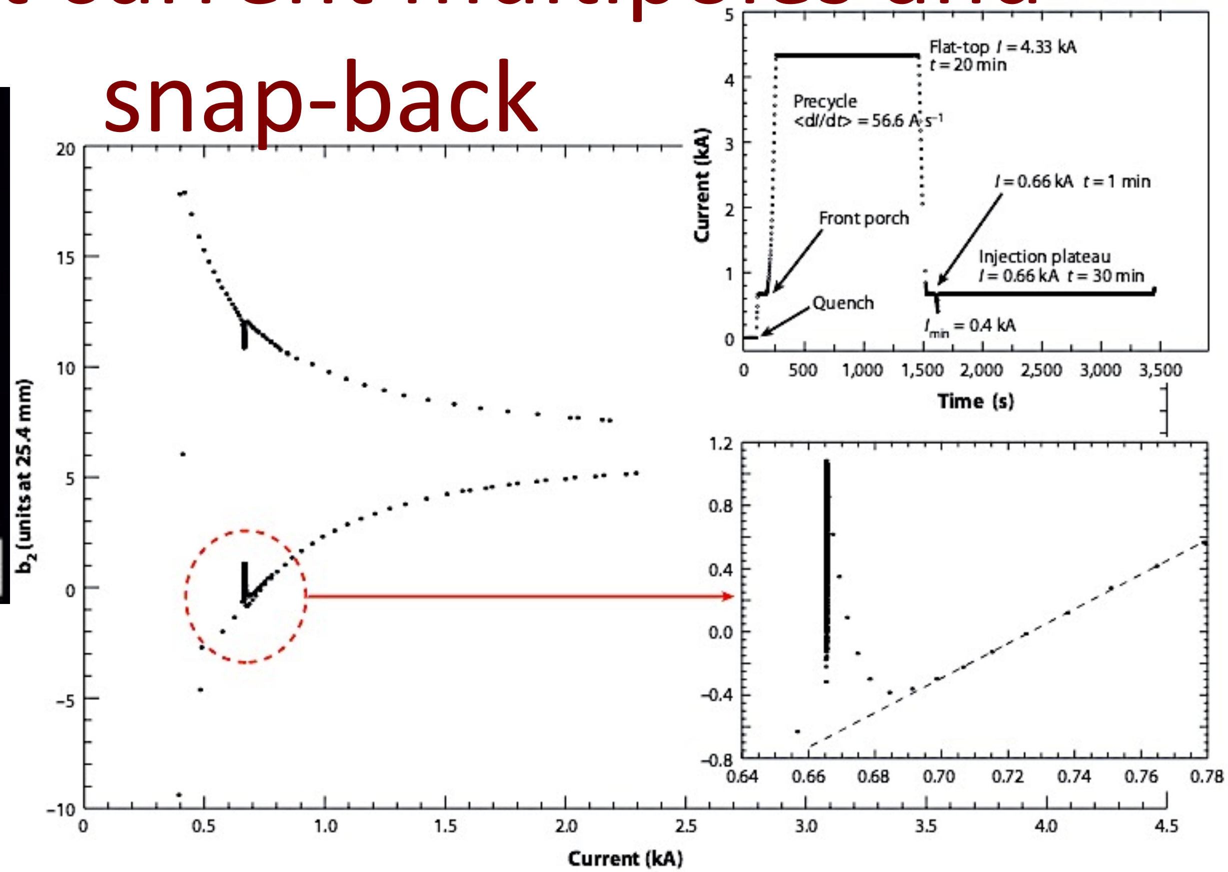
Tevatron the first-ever superconducting storage ring

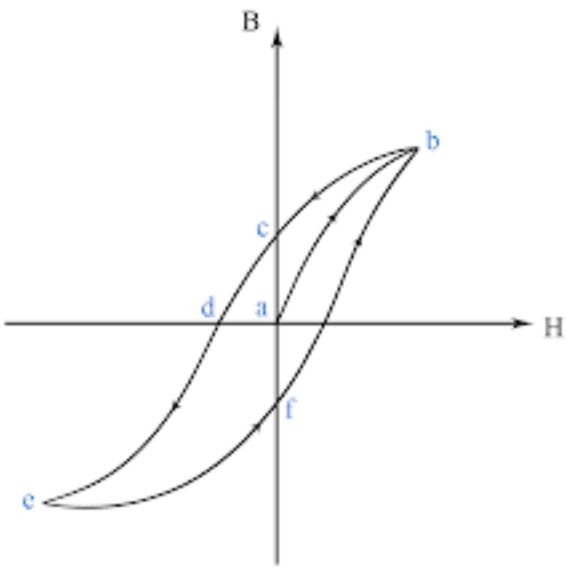




Persistent current multipoles and snap-back





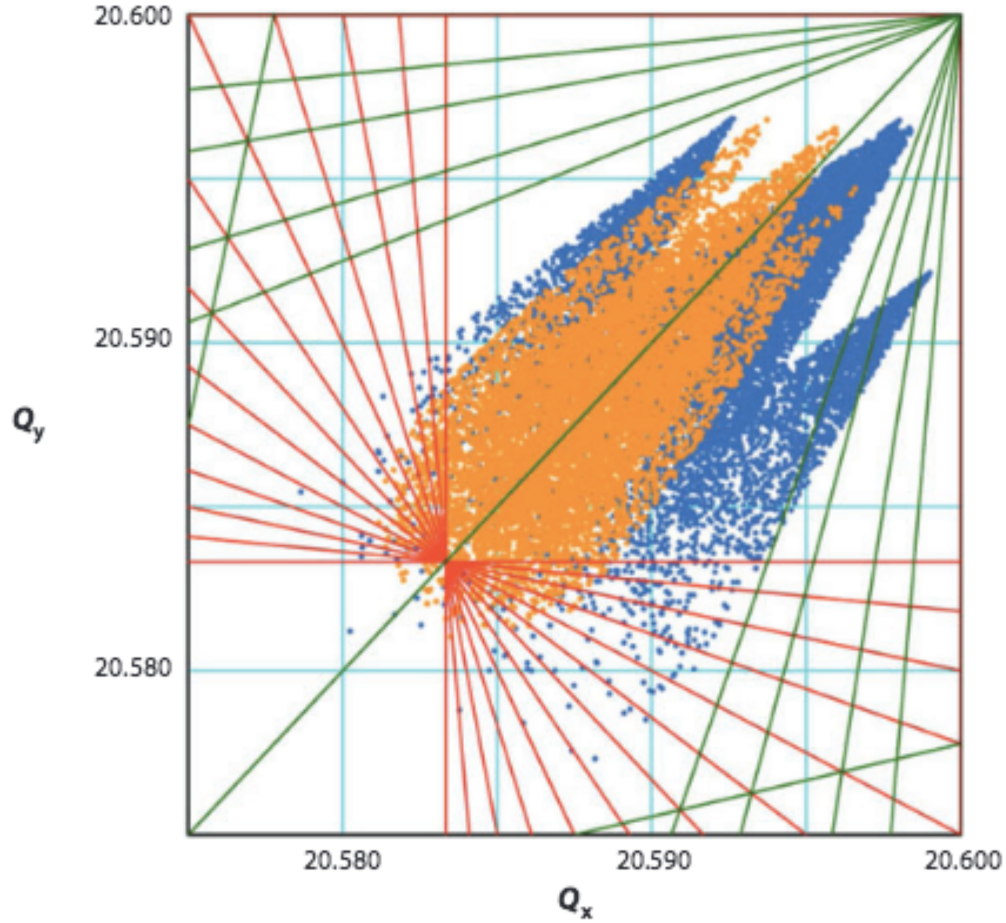


One significant challenge for superconducting colliders is snap-back. When the dipole is ramped down to injection field, the superconducting currents within each filament are set on the discharging side of hysteresis loop.

When new beam is injected and the up-ramp begins, the currents re-distribute to the charging side: snap-back.

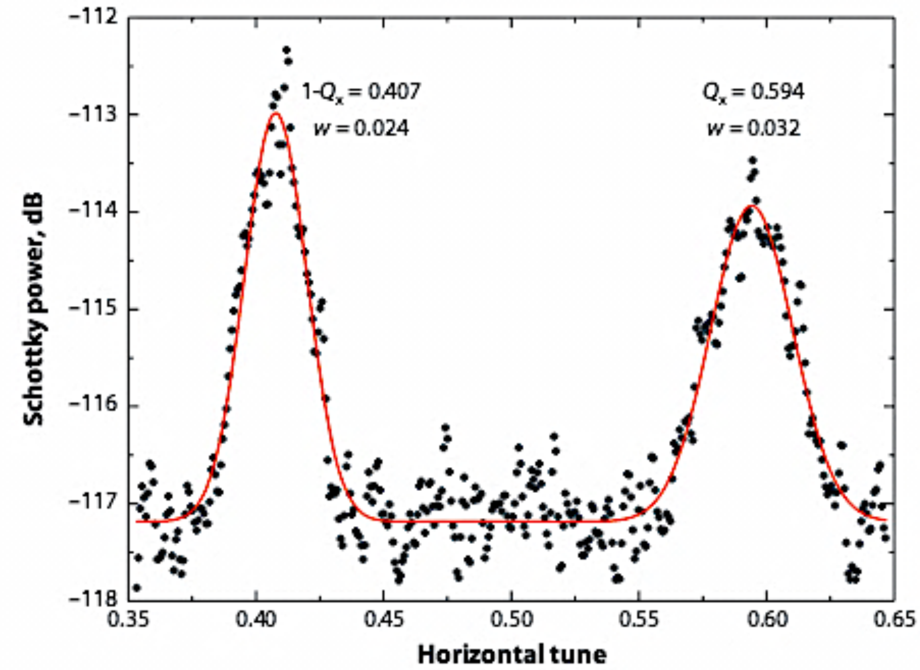
The sextupole component creates an instantaneous change in chromaticity that can be enough to blow the beam out of orbit.

Beam-beam tune shift



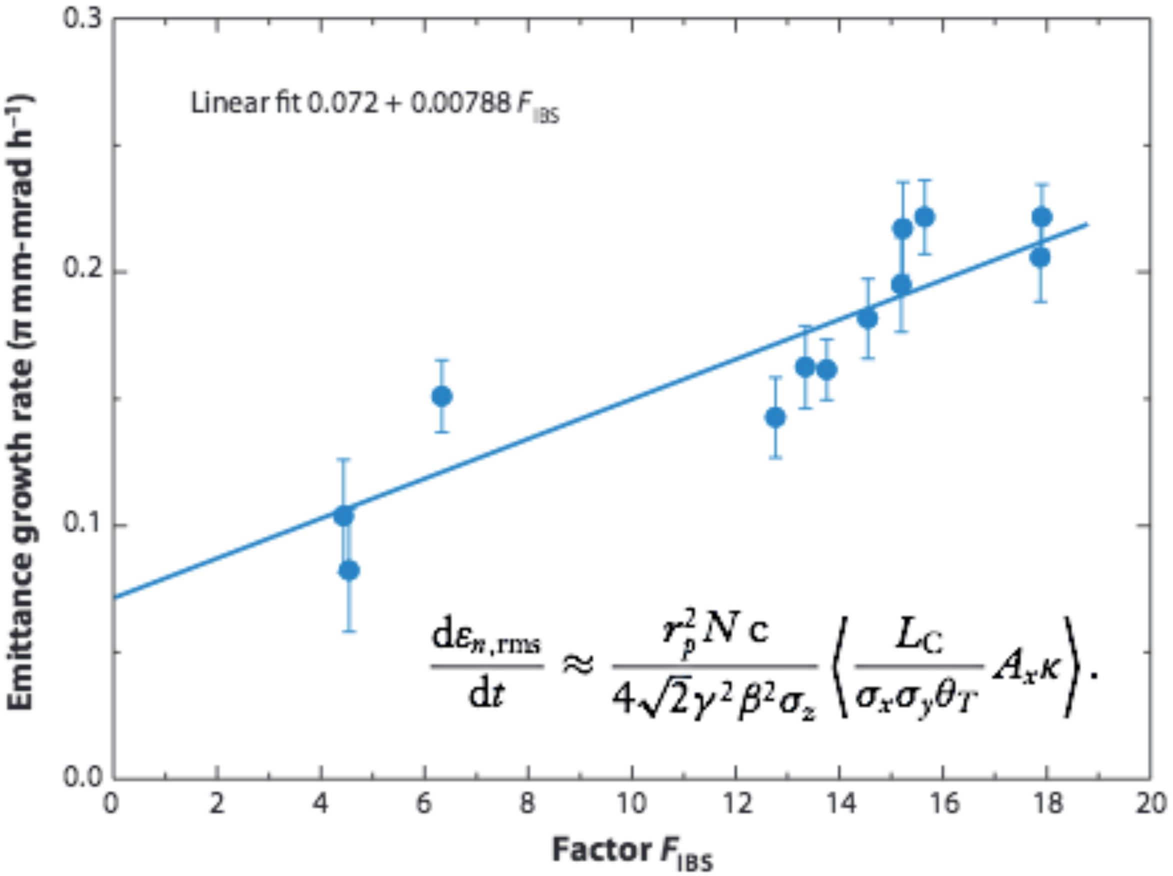
Red and green lines are sum and difference resonances up to 12th order.
Yellow dots are tunes or proton bunches. Blue dots are tunes of antiproton bunches.

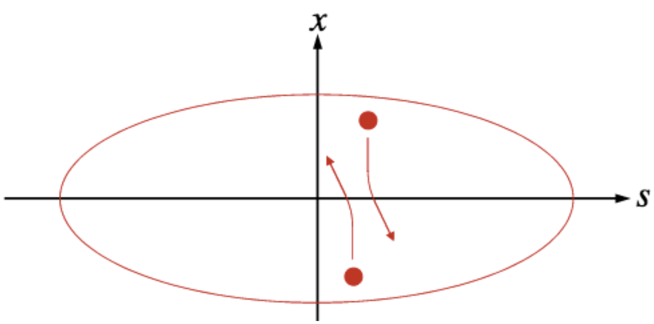
Schottky scans in the Tevatron



As a proton passes through a slot-gap electrode, it induces a potential across the electrode that is proportional to its displacement from the axis.
The particles of each bunch induce a noise frequency spectrum that is proportional to $\sqrt{N}$. The protons are also undergoing betatron oscillations, so the Schottky spectrum is modulated to form sidebands.
A 1.7 GHz Schottky pickup was used to measure the betatron tunes of each individual bunch every day. The measurements were used to correct the tunes to keep maintain optimal working point.

Intrabeam scattering





The longitudinal and transverse emittances of each bunch are equivalent to temperatures in the frame of the bunch. The bunch is a gas with non-equilibrium temperatures.

$T_\perp << T_\ell$ as a natural consequence of acceleration (homework).

In the bunch frame, the particles Coulomb scatter, and the scattering is heat transfer from the hot dimension to the cold dimension.

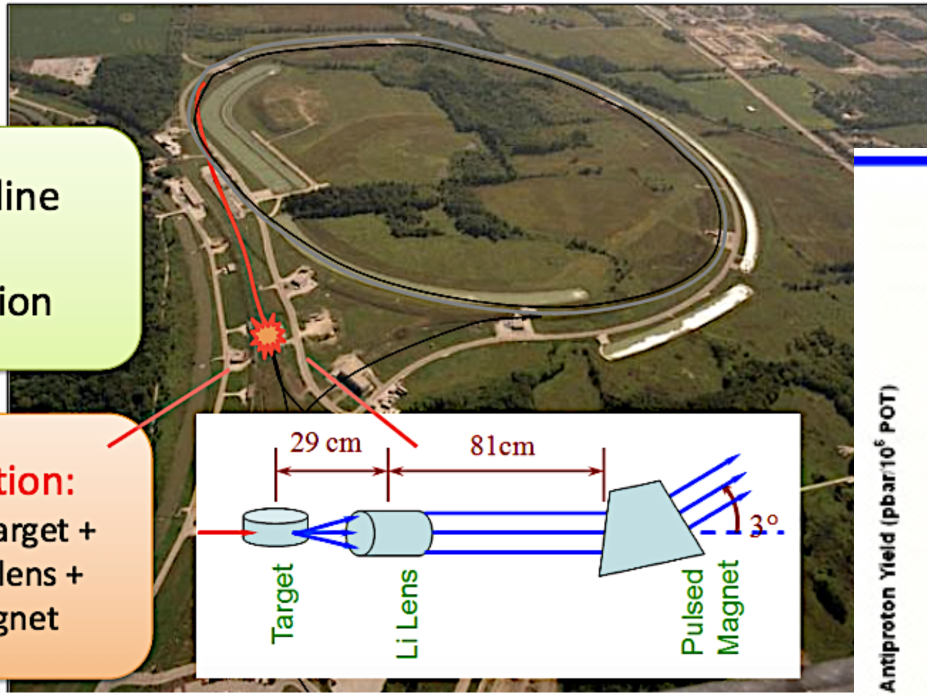
Challenges for collider operation

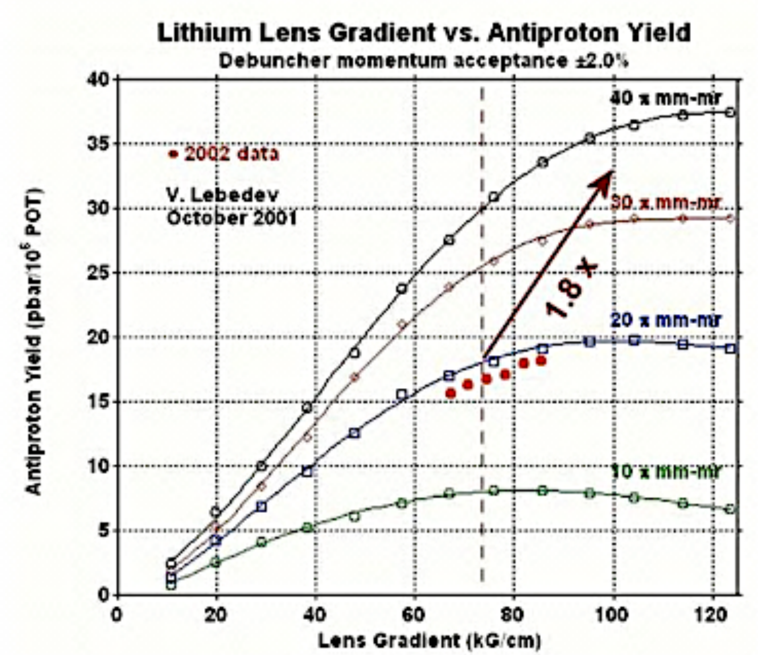
Example of the Tevatron magnet alignment (not common, but)

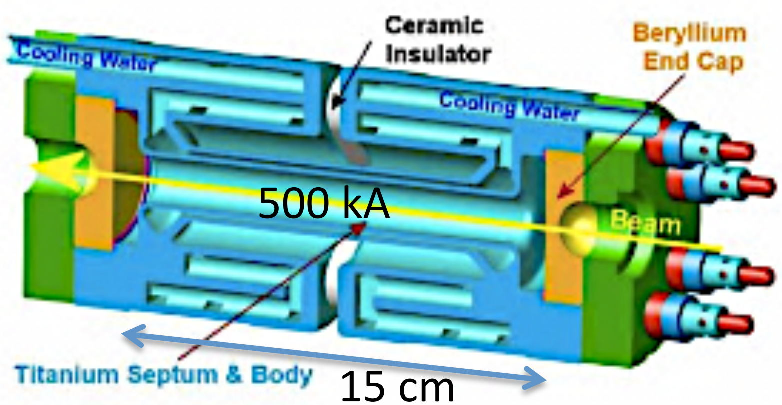
Making antiprotons

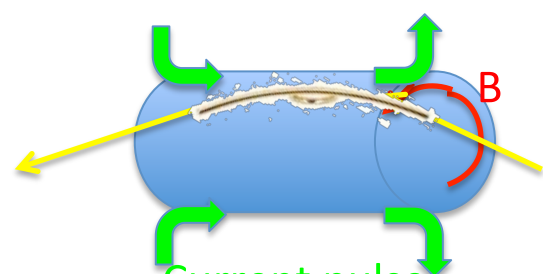
Transport line
to the
Target station

Target station:
Ni (Inconel) target +
Li collection lens +
Pulsed magnet

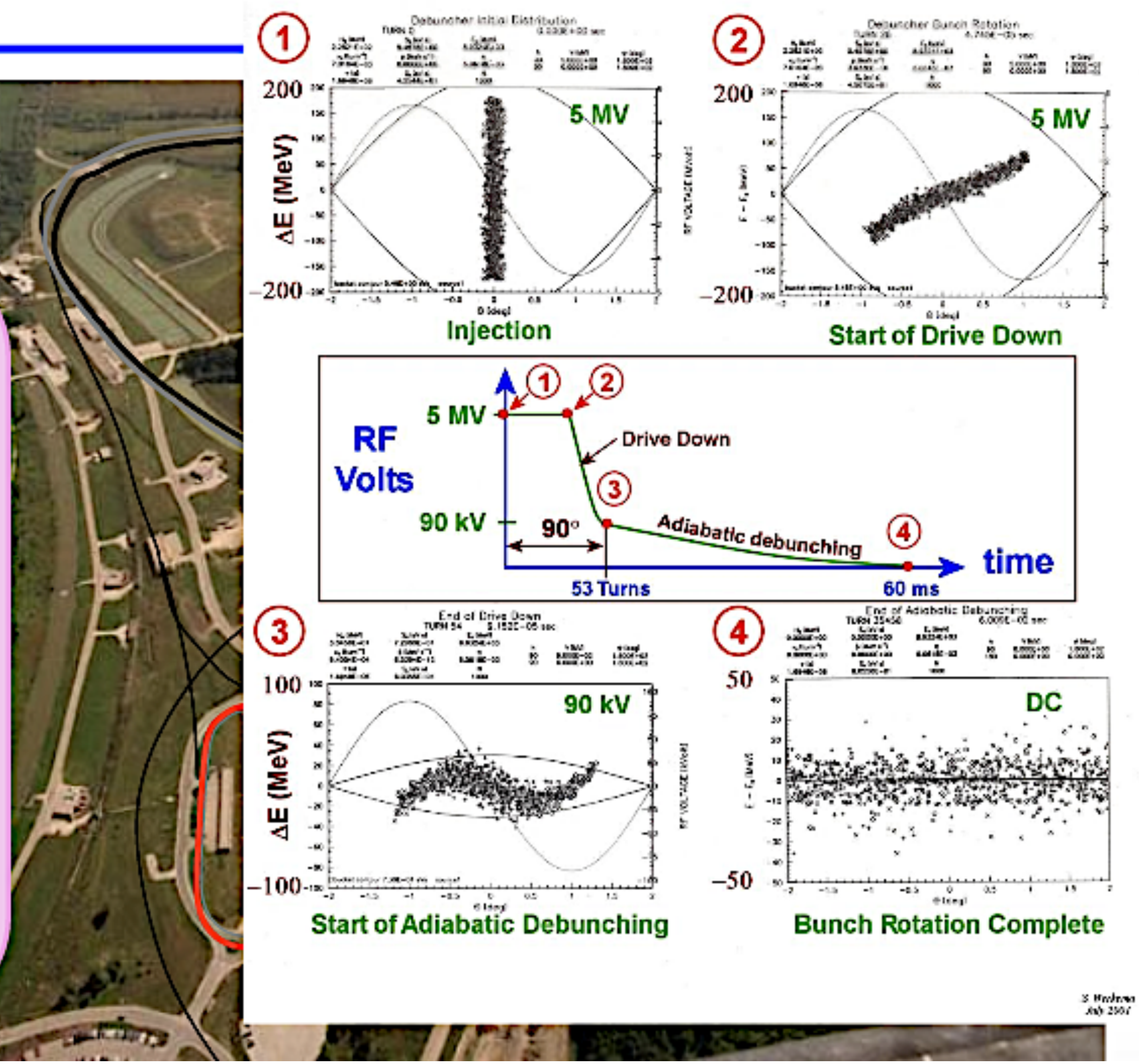








Phase Rotation & Debunching



Debuncher ring:

~2e8 pbars/cycle

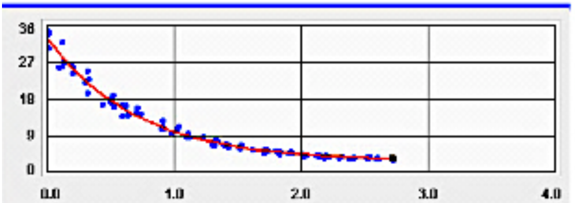
Large acceptance

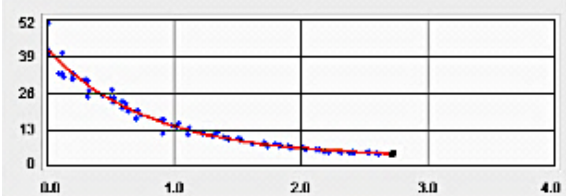
Fast compression (2sec):

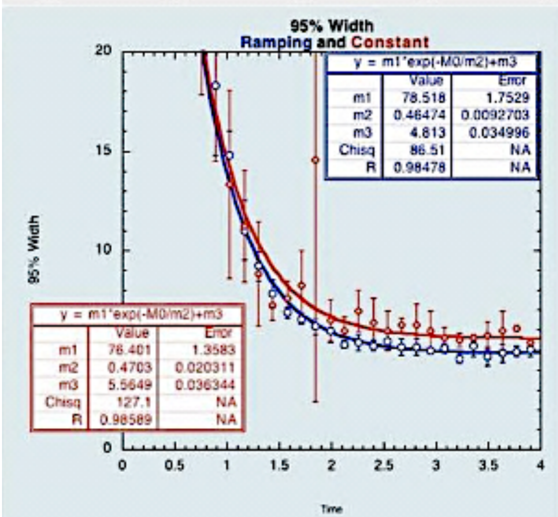
- Debunching
- Stochastic cooling
- ~10x10x10

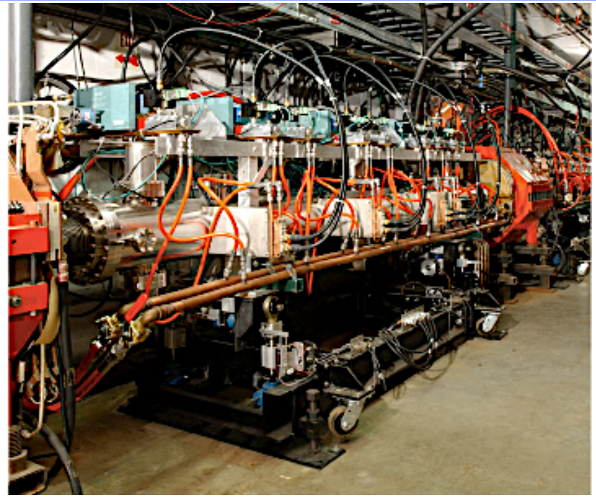
Fast Stochastic Cooling in the Debuncher

- fast – 2 sec cycle time
- wide acceptance in dP
- very low signal – cryogenic
- 8 PU bands, 4 kicker bands, 4-8 GHz

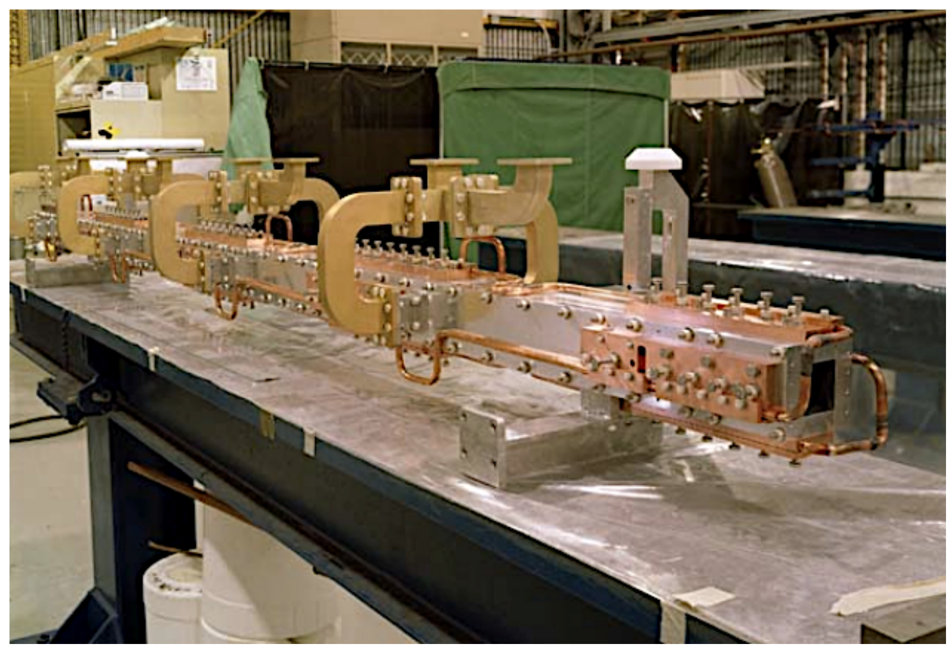




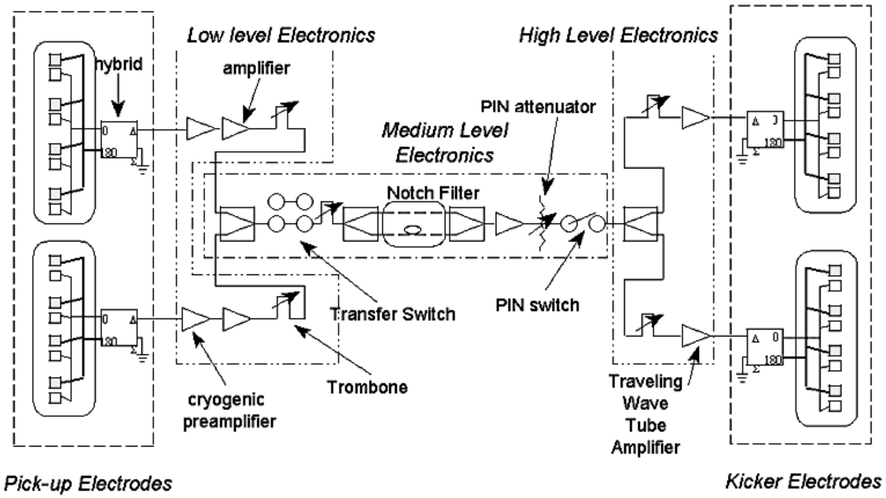




Debuncher stochastic cooling kicker tank



Antiproton accumulator



Stacktail notch filter assemblies

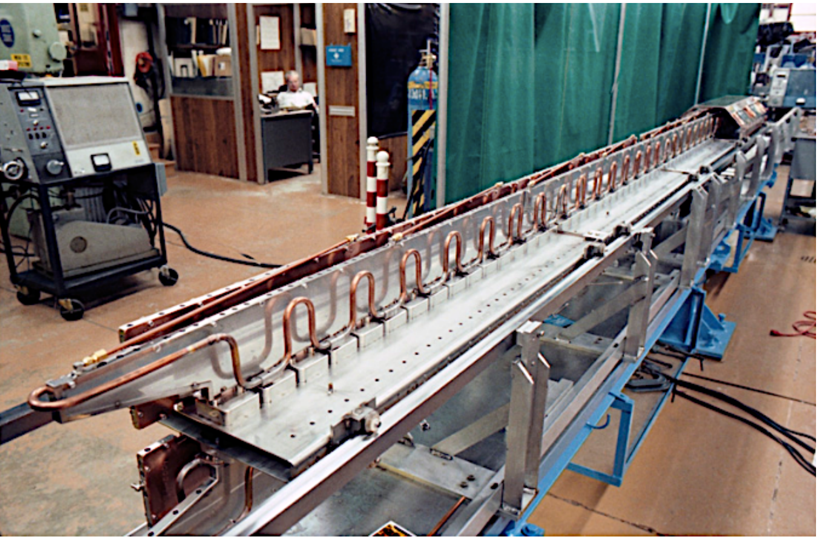


Figure 2. Stacktail 1–2 GHz 3-D pickup loop array. Horizontal aperture is 30 cm.

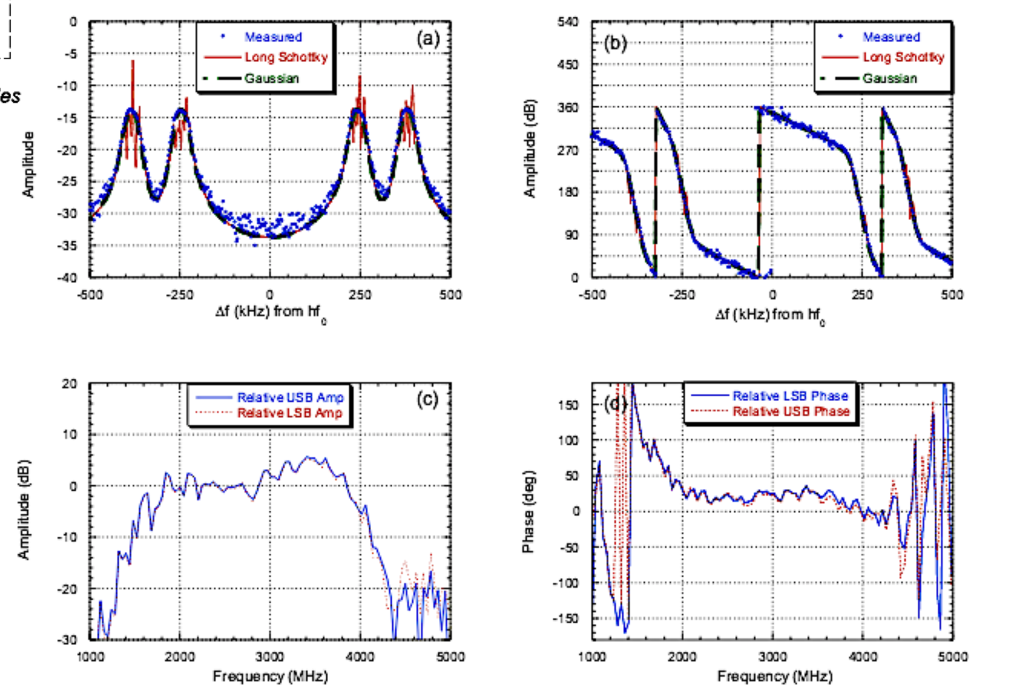


Figure 2. A network analyzer open loop gain (BTF) measurement of the Fermilab Accumulator 2-4 GH stochastic cooling system. The amplitude (a) and phase (b) response of a single Schottky band at harmoni 4305 is shown (dots). The curves are calculations of the response using a measurement of the longitudina Schottky beam profile. The amplitude (c) and phase (d) response sampled over the system bandwidth ar also shown.

Stochastic Cooling: Accumulate $2x10^{11}\overline{p}$/hr

Accumulator ring:

Inject to +80 MeV

RF move to deposition

Moving to Core: -60 MeV

with Stochastic cooling

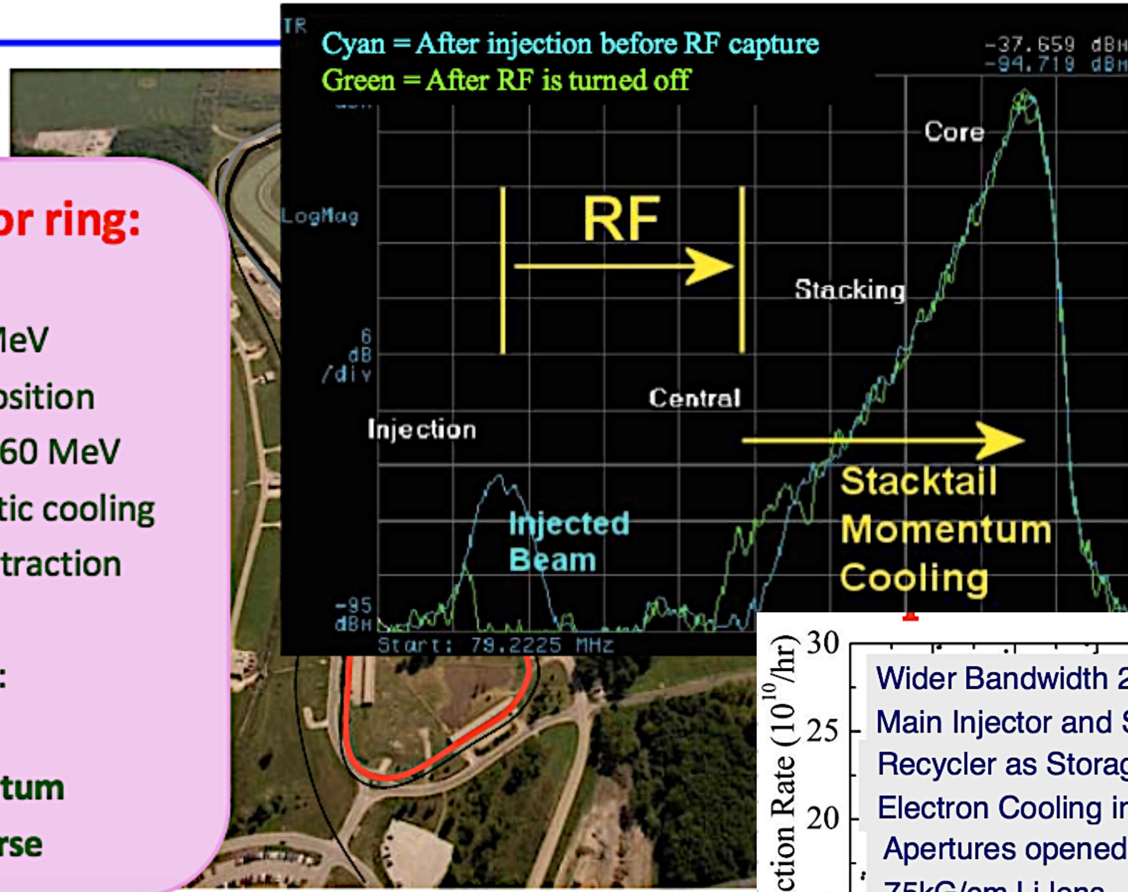
RF unstack for extraction

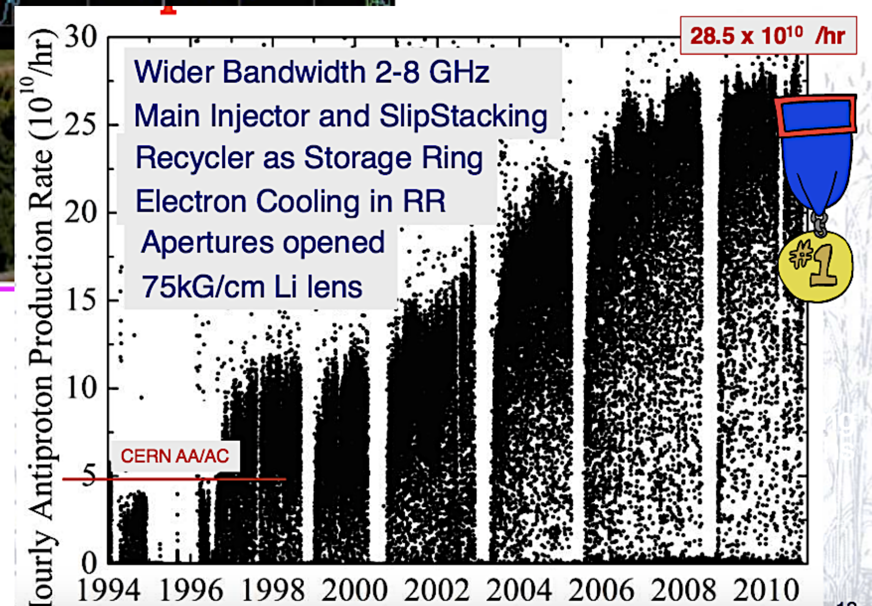
Stochastic cooling:

Stack- tail

Core momentum

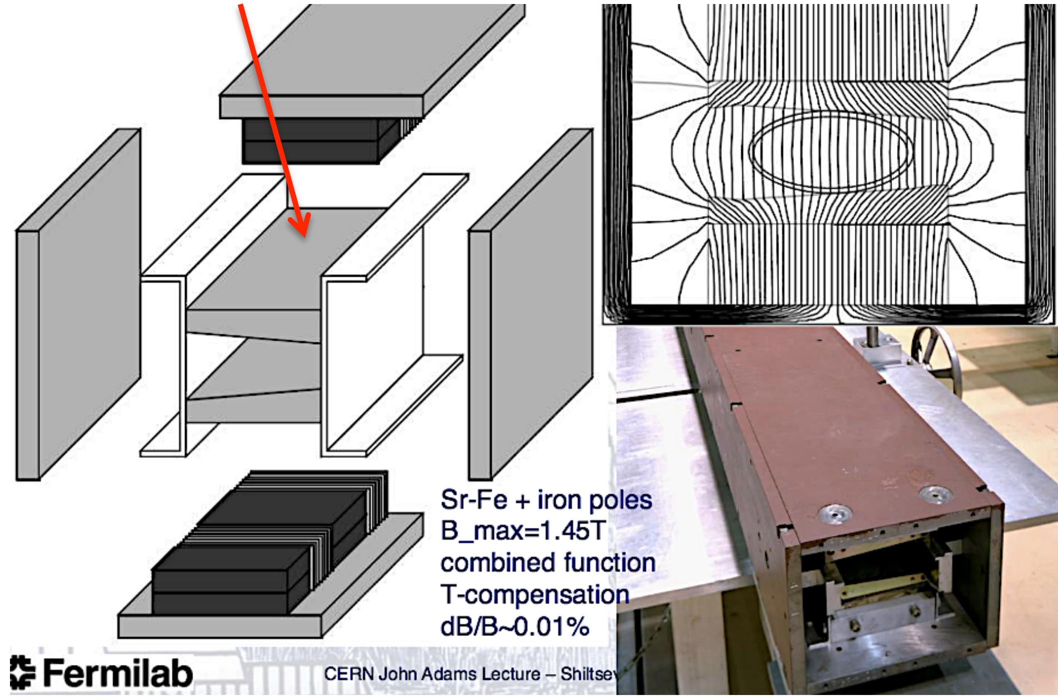
Core transverse





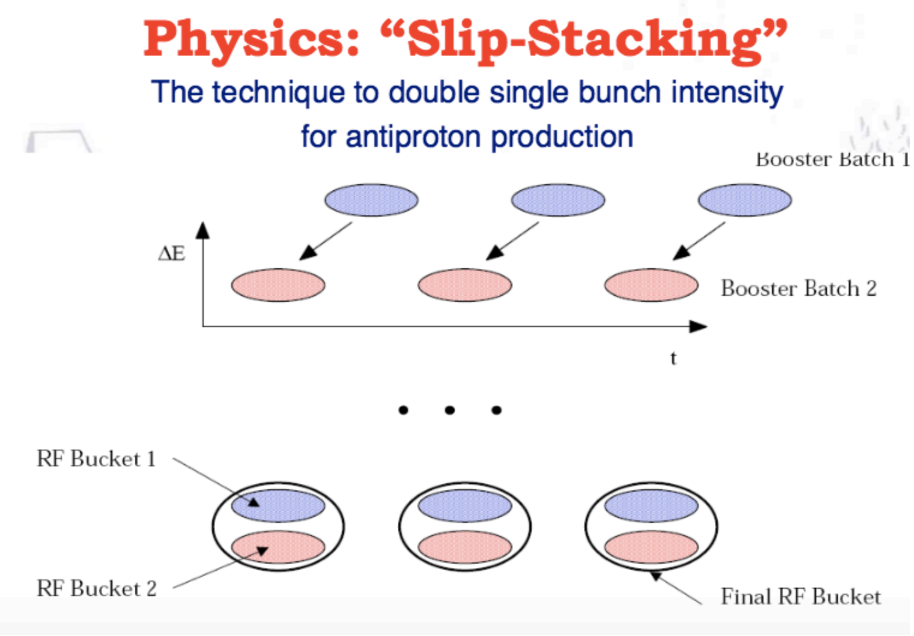
Main Injector & Recycler

Recycler = 8 GeV fixed-energy storage ring – *combined-function permanent magnets*

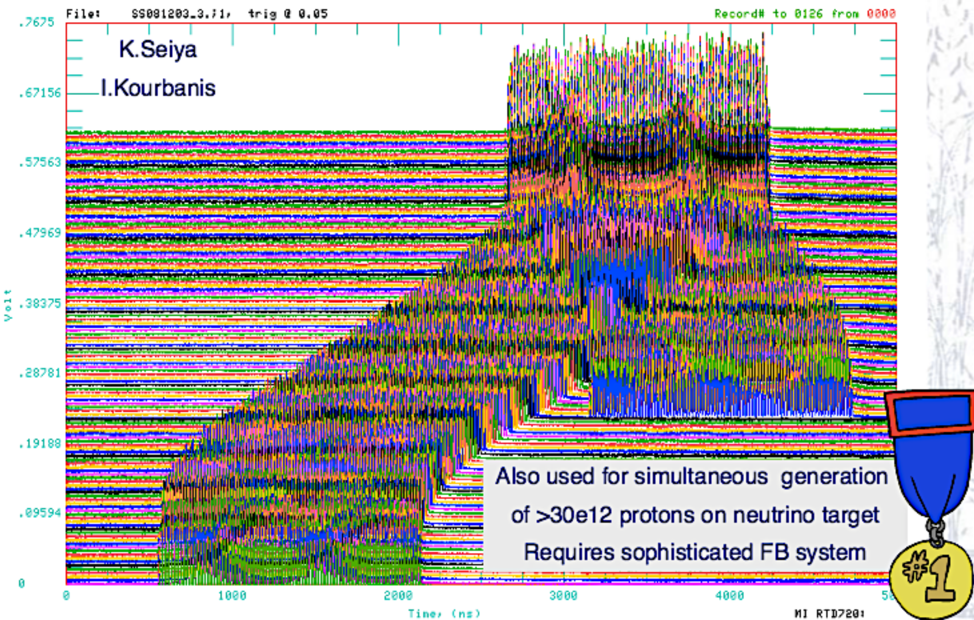


Main Injector = 150 GeV rapid-cycling synchrotron
– deliver protons to $\overline{p}$ target

Creating proton superbunches for $\overline{p}$ targetry



4.1e12+4.1e12 =8.2 e12 protons on target per 2.2 s MI cycle



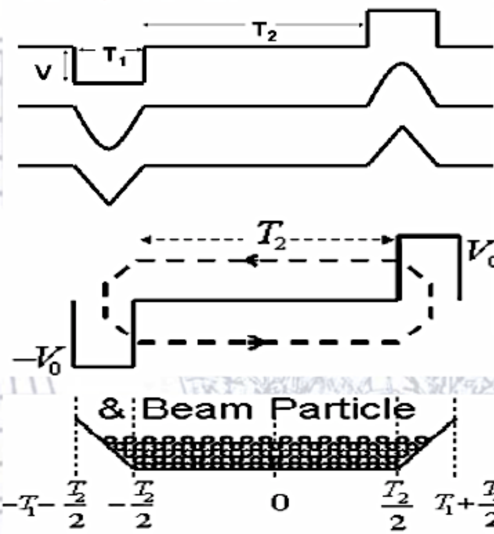
RF barrier buckets were used to coalesce protons, manipulate mom spread

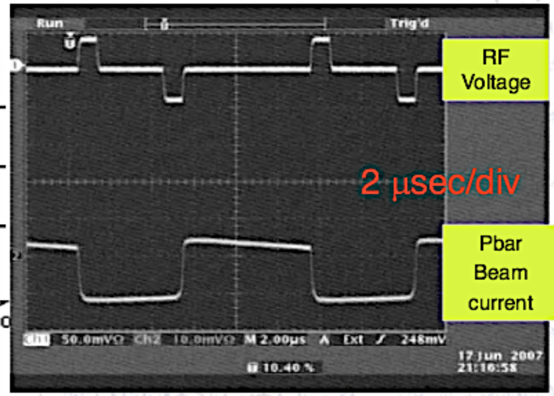
To manipulate with pbars in Recycler: create bunch structures, etc

C.Bhat

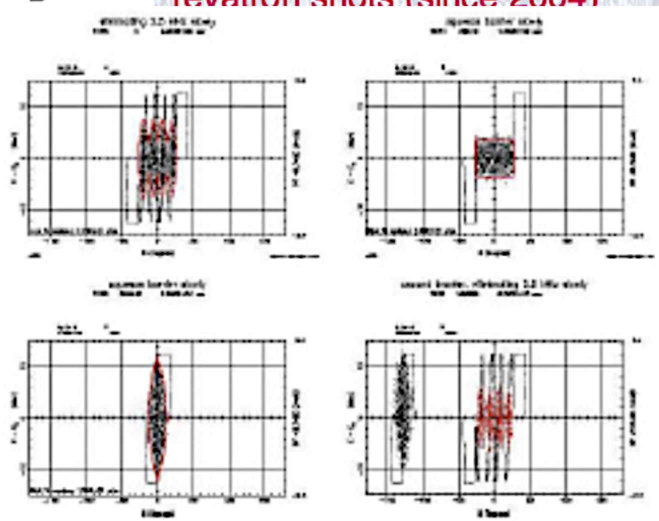
Broad band ~1kV RF, ferrite loaded

J.Griffin, FNAL 1983





Longitudinal momentum mining in the Recycler to generate constant emittance, constant intensity pbar bunches for the Tevatron shots (since 2004)



RF Chopper Cavity made of Finemet (Fermilab/KEK)

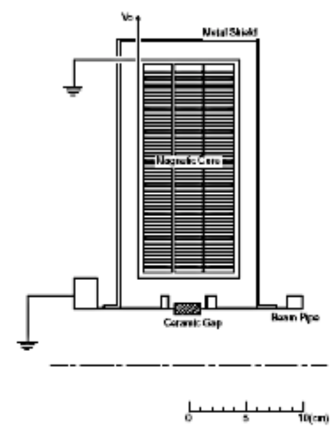


Figure 2: A test cavity used in the measurements. It consists of a magnetic core, a metal shield, a one-turn coil and a stainless steel beam pipe with a ceramic gap.

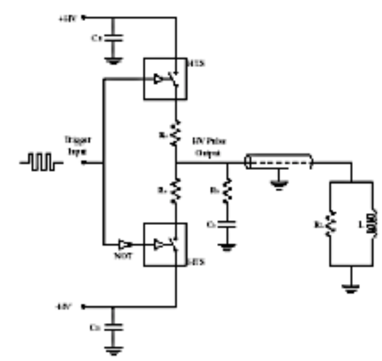


Figure 5: A circuit diagram of a bipolar (push–pull) high voltage source using two HTS transistors as the switches.

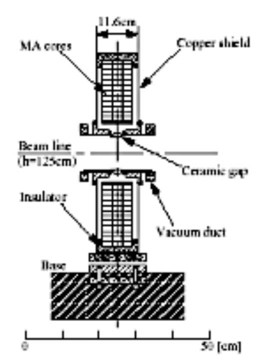


Figure 2: Side view of the chopper. Three magnetic-alloy cores with 504mm o.d. x 158mm i.d. x 25mm thickness are used. An one-turn coil is wound around the cores.

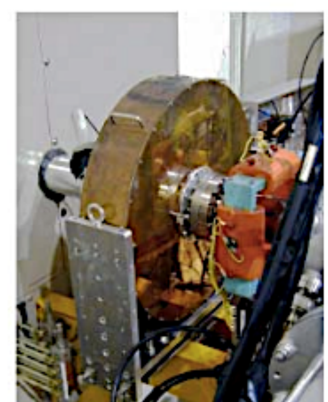
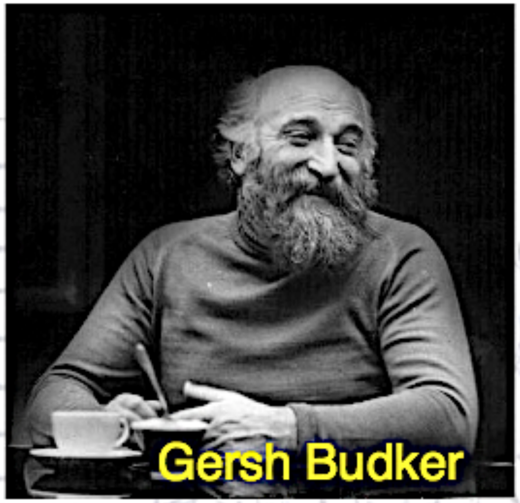
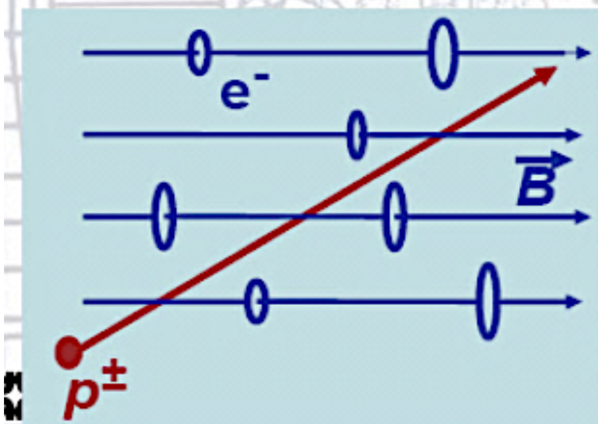


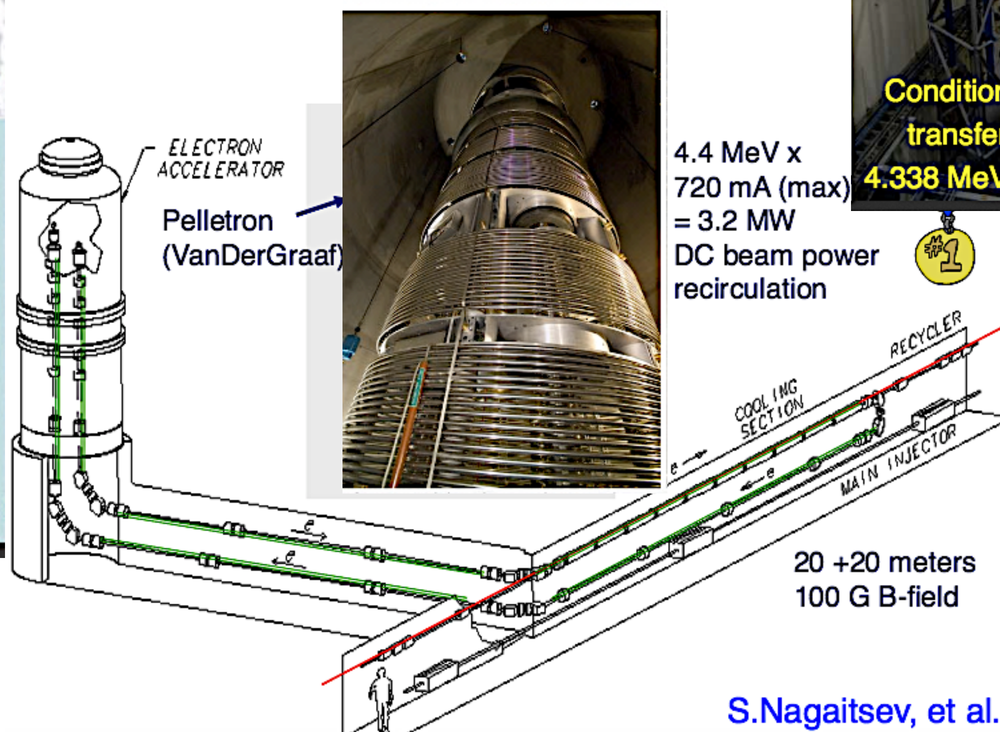
Figure 1: Chopper cavity installed at the HIMAC facility. A constant-energy beam from an ion source comes from the right-hand side, and its energy is modulated by +-5% at the chopper cavity. The downstream RFQ is located at the left-hand side, which is at the other side of the wall.

Electron Cooling Antiprotons @ 8 GeV



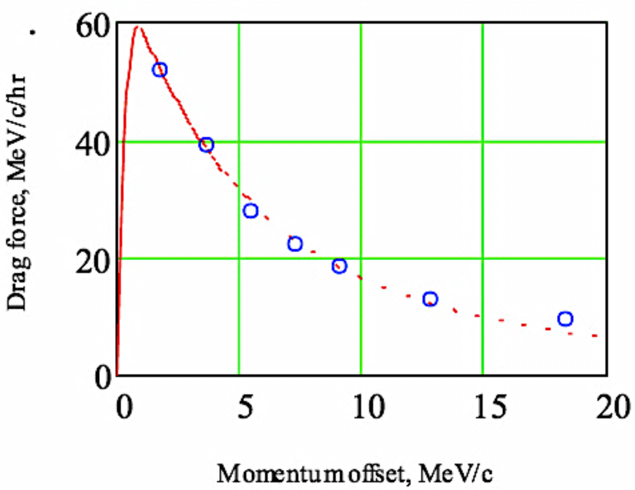
Ions in a bath of cold electrons

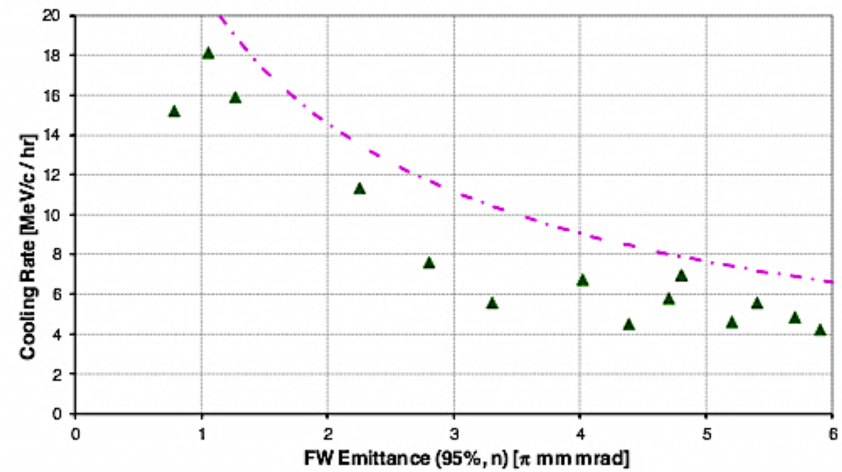


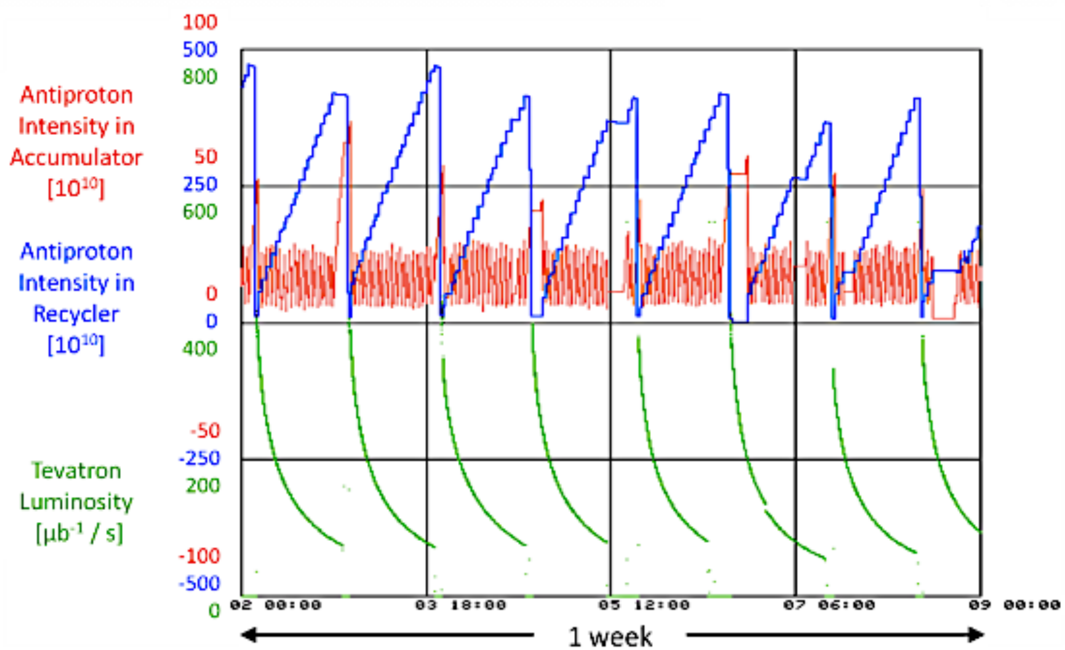


S.Nagaitsev, et al.

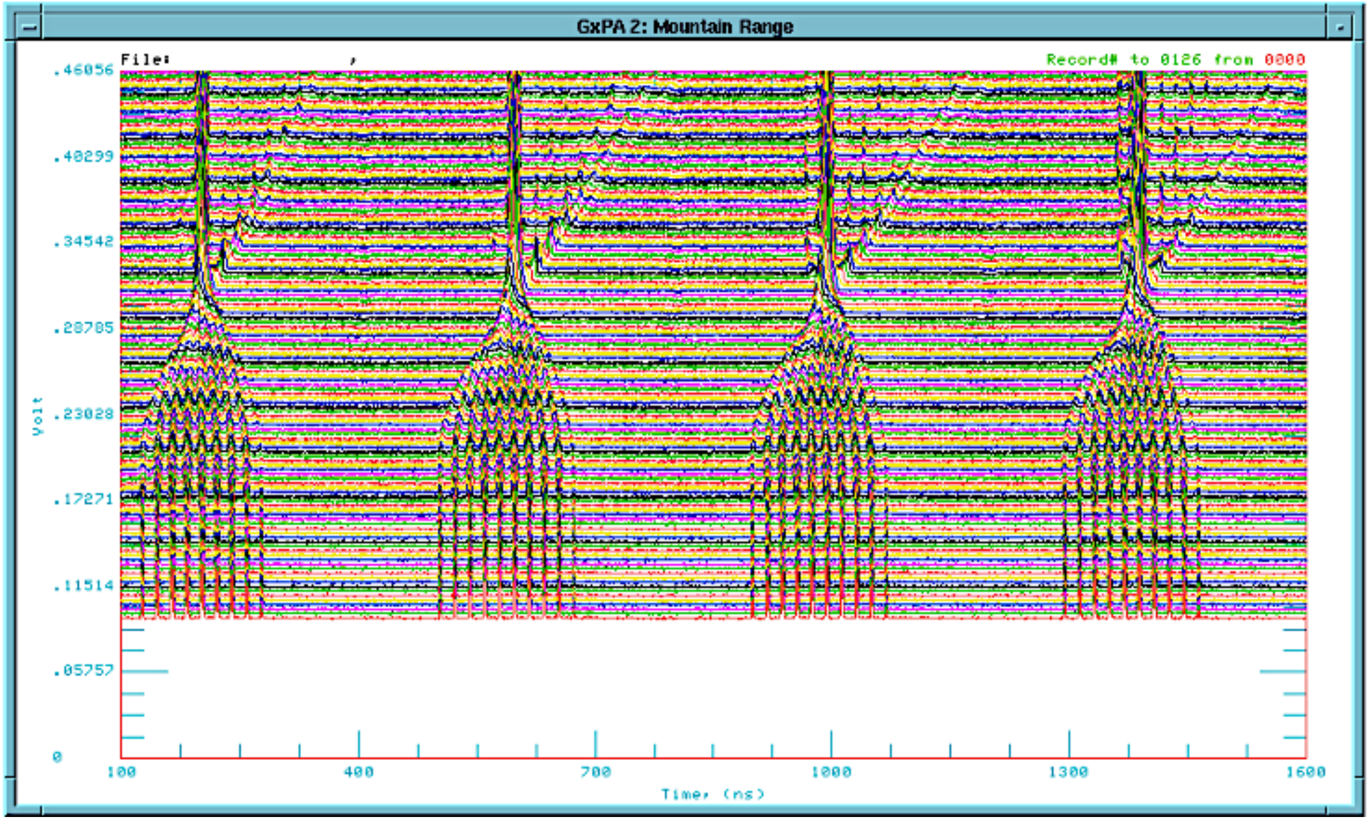
Electron Cooling increased $\bar{p}$ stack x10 beyond what accumulator could hold







Coalescing antiproton bunches in the Main Injector for transfer to Tevatron



Beam Beam Tune Shift

The luminosity of collisions and the beam-beam tune shift have the same dependences on the beam emittance:

$$L = \frac{N^2 f}{4\pi\sigma_x\sigma_y} \qquad \xi = \frac{N r_p}{4\pi\epsilon_n} \qquad L = \frac{\gamma\xi N f}{\beta_x r_p}$$

Simple example: round Gaussian beams

- Assumption 1: $\sigma_x = \sigma_y = \sigma$, $Z_1 = -Z_2 = 1$
- Assumption 2: very relativistic → $\beta \approx 1$
- Only components E_r and B_Φ are non-zero
- Force has only radial component, i.e. depends only on distance r from bunch centre (*where:* $r^2 = x^2 + y^2$) (see proceedings)

$$F_r(r) = -\frac{Ne^2(1+\beta^2)}{2\pi\epsilon_0 \cdot r}\left[1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right]$$

Beam-beam kick:

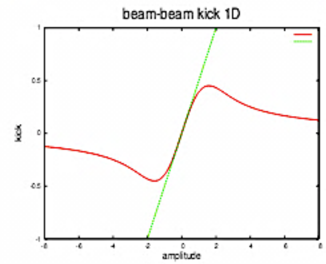
- Kick ($\Delta r'$): angle by which the particle is deflected during the passage
- Integration of force over the collision, i.e. time of passage Δt (assuming: $m_1 = m_2$ and $Z_1 = -Z_2 = 1$):

$$\text{Newton's law:} \quad \Delta r' = \frac{1}{mc\beta\gamma}\int_{-\frac{\Delta t}{2}}^{+\frac{\Delta t}{2}} F_r(r,s,t)\,dt$$

with:

$$F_r(r,s,t) = -\frac{Ne^2(1+\beta^2)}{\sqrt{(2\pi)^3}\epsilon_0 r\sigma_s}\left[1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right]\cdot\left[\exp\left(-\frac{(s+vt)^2}{2\sigma_s^2}\right)\right]$$

Beam-beam force/kick



- For small amplitude: tune shift
- For large amplitude: amplitude dependent tune shift

There is a fundamental difference in the significance of beam-beam tune shift for an e^+e^- collider and a hadron collider:

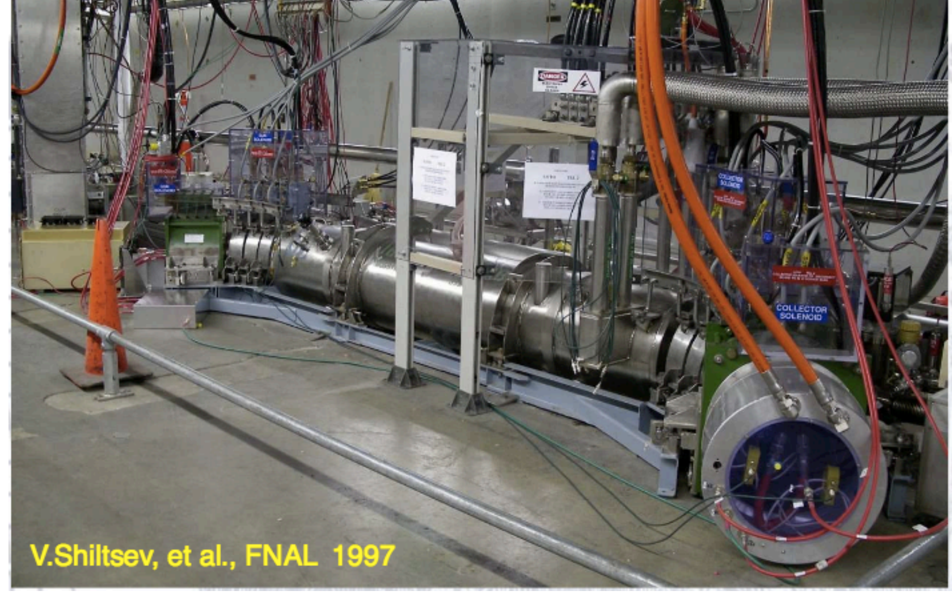
LEP - LHC

	LEP (e^+e^-)	LHC (pp)
Beam sizes	160 - 200μm · 2 - 4μm	16.6μm · 16.6μm
Intensity N	4.0 · 10^{11}/bunch	1.15 · 10^{11}/bunch
Energy	100 GeV	7000 GeV
ϵ_x · ϵ_y	(≈) 20 nm · 0.2 nm	0.5 nm · 0.5 nm
β_x^* · β_y^*	(≈) 1.25 m · 0.05 m	0.55 m · 0.55 m
Crossing angle	0.0	285 μrad
Beam-beam parameter(ξ)	0.0700	0.0037

The electron emittance is damped by synchrotron damping. Each electron in LEP 'forgets' what harm was done to it on the last orbit.

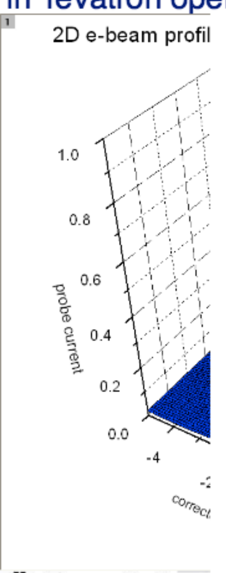
But the protons in LHC have very little synchrotron damping. They remember all the harm done, on all the orbits, for a day! Comparable to the Earth's orbits in its history…

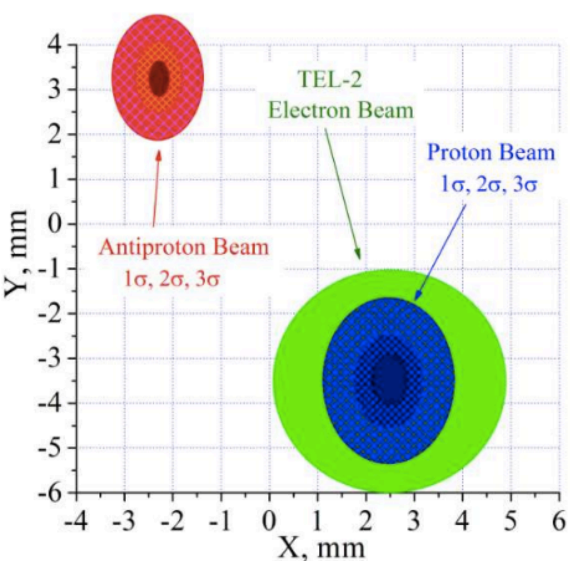
Electron Lens was used on Tevatron for two purposes:



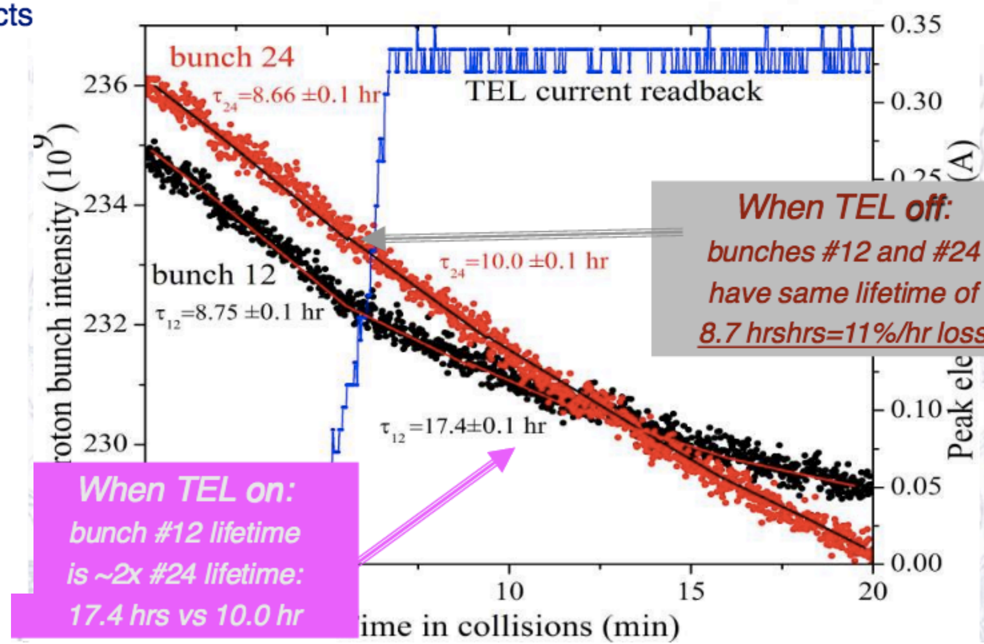
1. Gaussian-profile e-beam compensates beam-beam tune shift:

in Tevatron operation - TELs compensated of long range BB effects

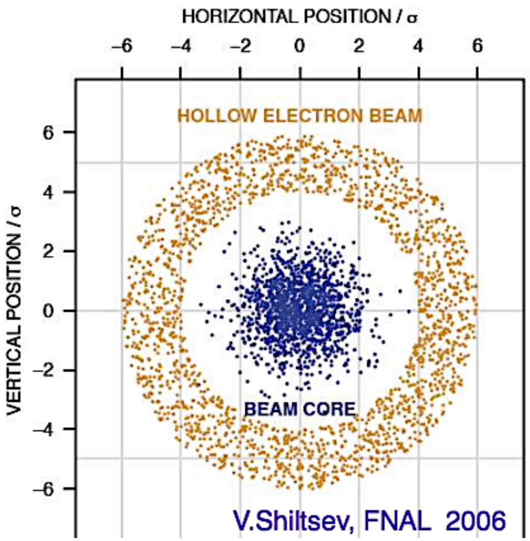




TEL2 on One "Bad" Bunch (P12)

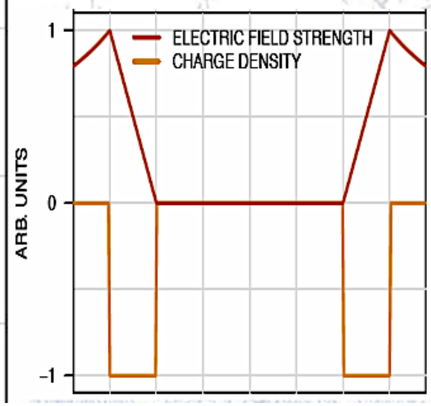


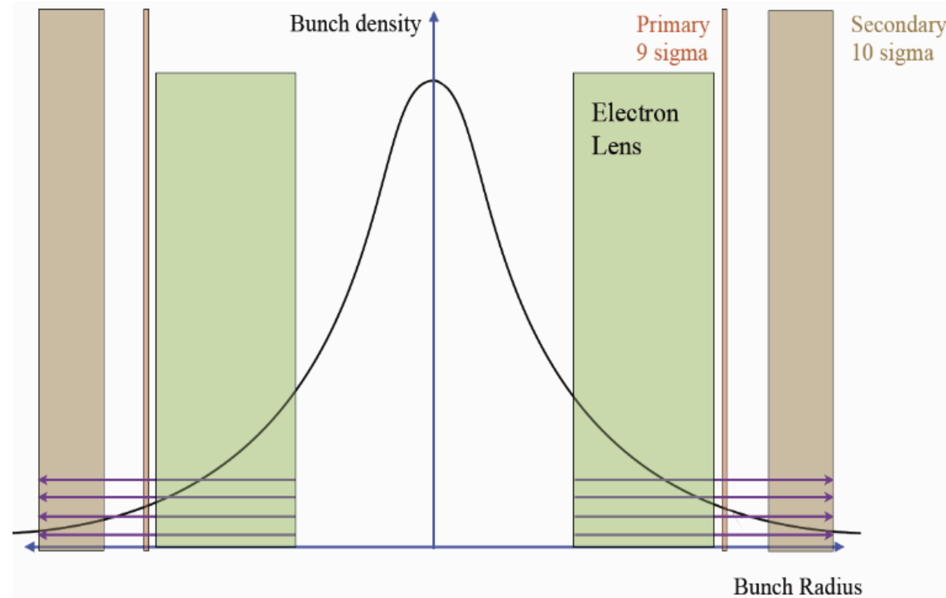
2. Hollow e-beam, notched on during gap, removes d.c. beam



No EM field inside

Strong field outside

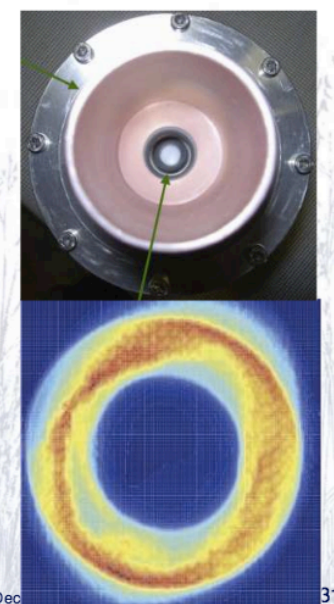




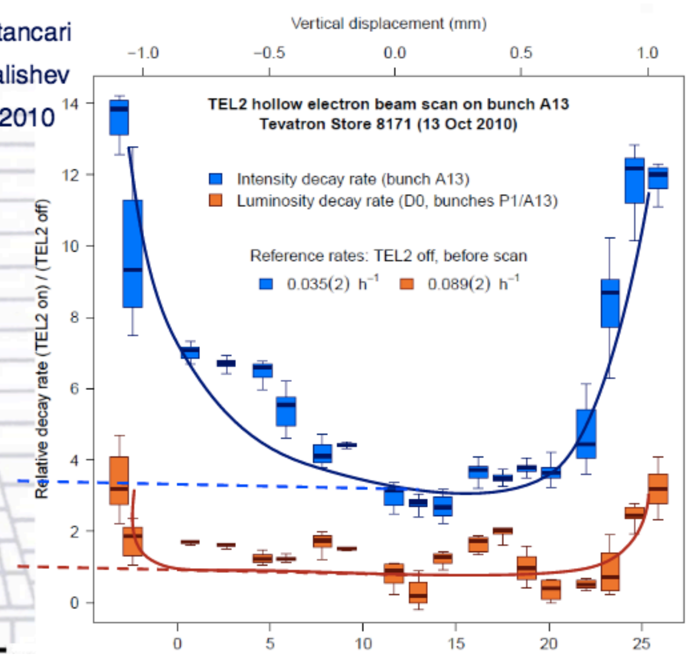
Tevatron HEB-Collimator

To explore advantages:

- Kicks are small but not random
- Halo diffusion enhancement ("smooth" scraper)
- Resonant excitation is possible (pulsed e-beam)
- No material damage
- No ion breakup
- Low impedance
- Position control by magnetic field (no motors or bellows)
- Established e-lens technology



G.Stancari
A.Valishev
Oct.2010



Presented is **RATIO** of decay rates with TEL on/TEL off:

Intensity losses are **UP**

Luminosity **INTACT!!!**

That IS collimation!

And now for the LHC

Large Hadron Collider (CERN)

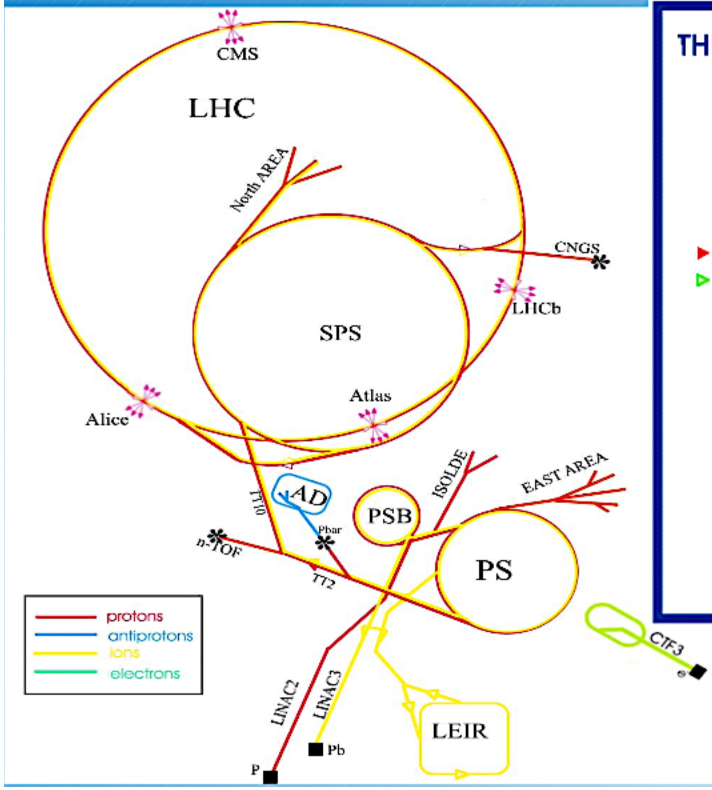
LHC (pp) 7(14) TeV

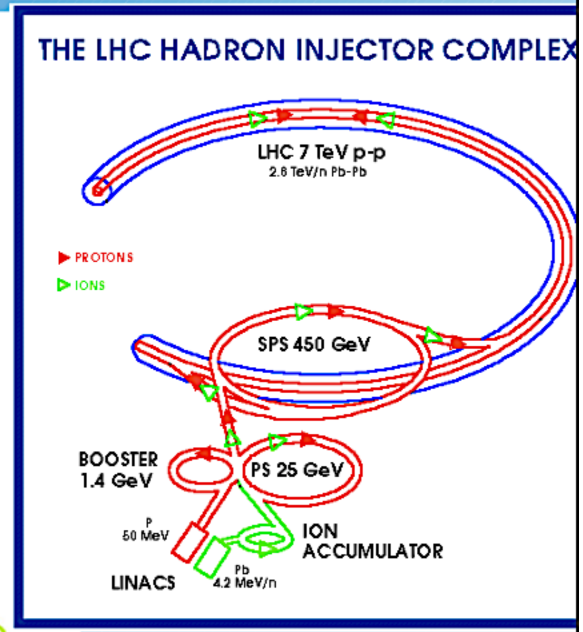
operation started in 2008

26.7 km circumference!

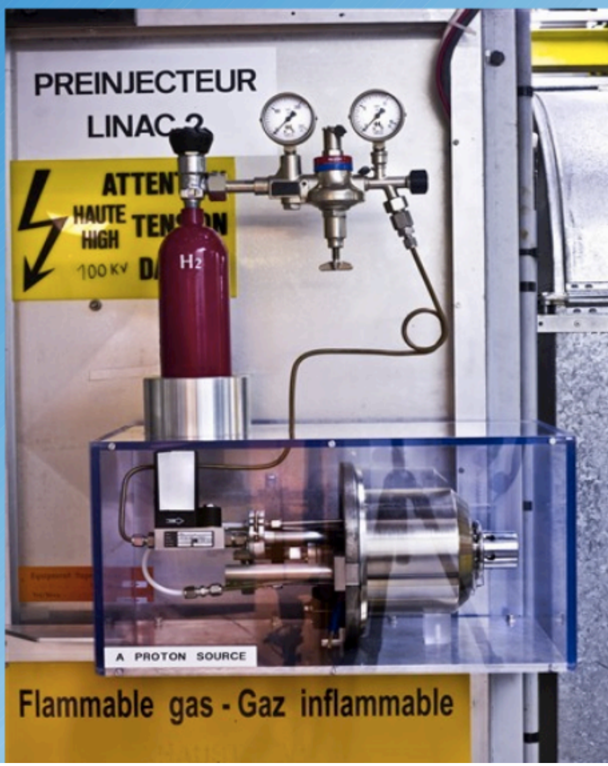
		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5^{a}
Transverse normalized emittance	[μm rad]	3.5^{b}	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	3.56×10^{30}
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	[10^{-4}]	3.06	1.129
RMS bunch length	[cm]	11.24	7.55
Longitudinal emittance growth time	[hours]	30^{a}	61
Horizontal emittance growth time	[hours]	38^{a}	80
Total beam and luminosity lifetimes[b]			
Luminosity lifetime (due to beam-beam)	[hours]	-	29.1
Beam lifetime (due to rest-gas scattering)[c]	[hours]	100	100
Beam current lifetime (beam-beam, rest-gas)	[hours]	-	18.4
Luminosity lifetime (beam-beam, rest-gas, IBS)	[hours]	-	14.9
Synchrotron Radiation			
Instantaneous power loss per proton	[W]	3.15×10^{-16}	1.84×10^{-11}
Power loss per m in main bends	[Wm^{-1}]	0.0	0.206
Synchrotron radiation power per ring	[W]	6.15×10^{-2}	3.6×10^{3}
Energy loss per turn	[eV]	1.15×10^{-1}	6.71×10^{3}
Critical photon energy	[eV]	0.01	44.14
Longitudinal emittance damping time	[hours]	48489.1	13
Transverse emittance damping time	[hours]	48489.1	26

Overview Accelerator Chain

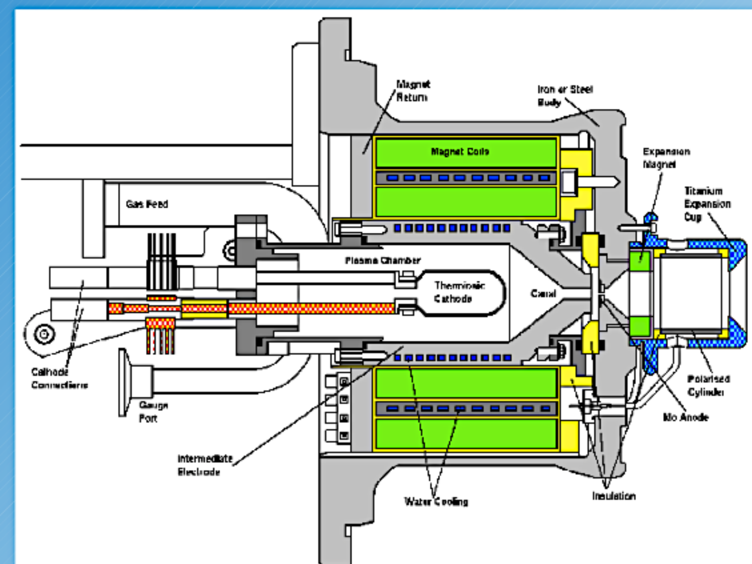




The Proton Source

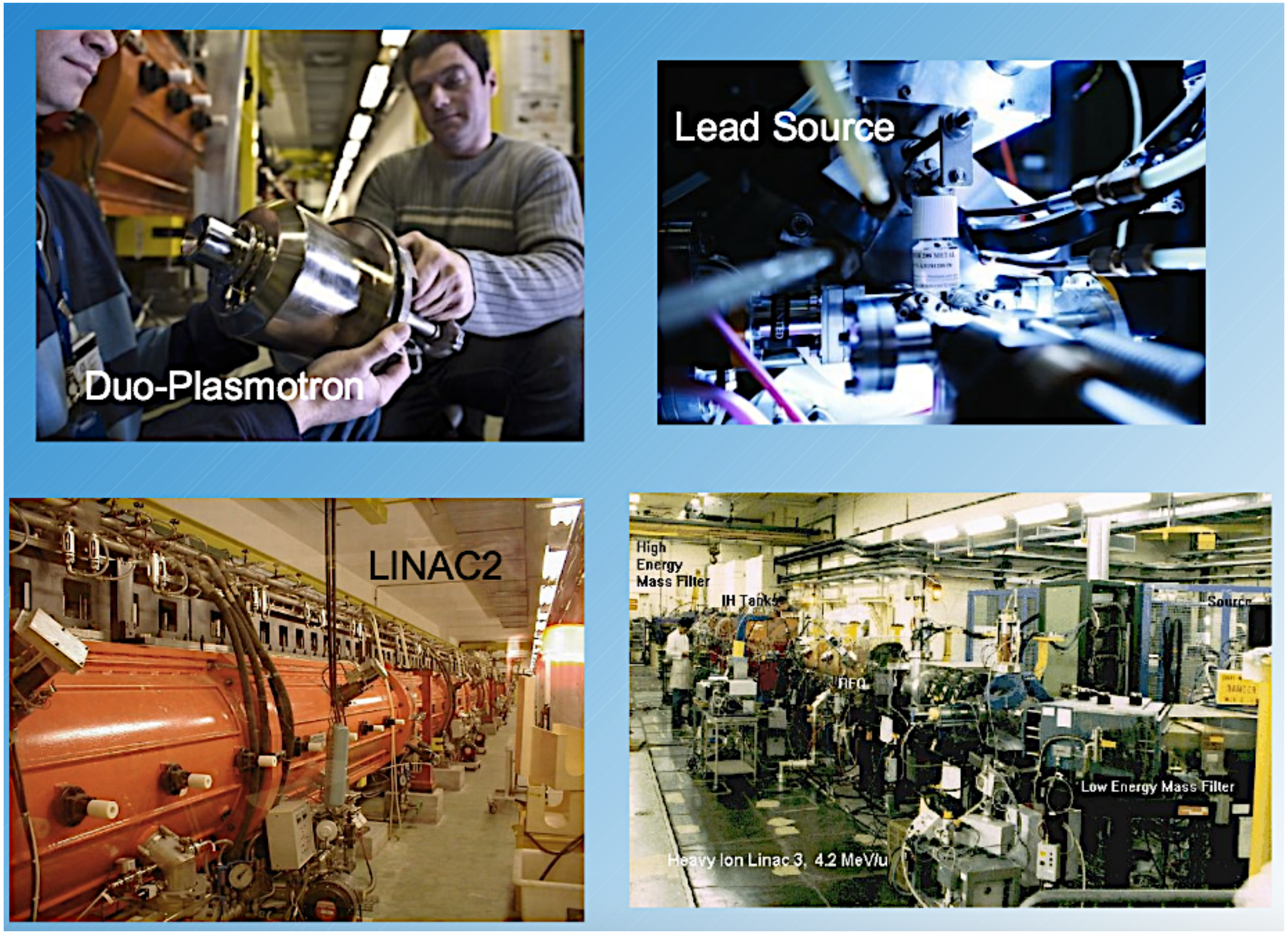


Duo-Plasmotron

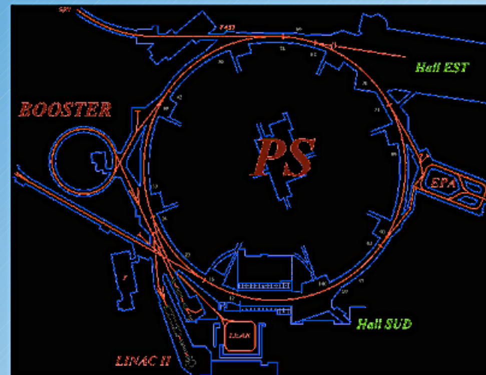


hydrogen (metal) plasma used to create protons (ions)

LHC Injector



CERN PS (24 GeV)

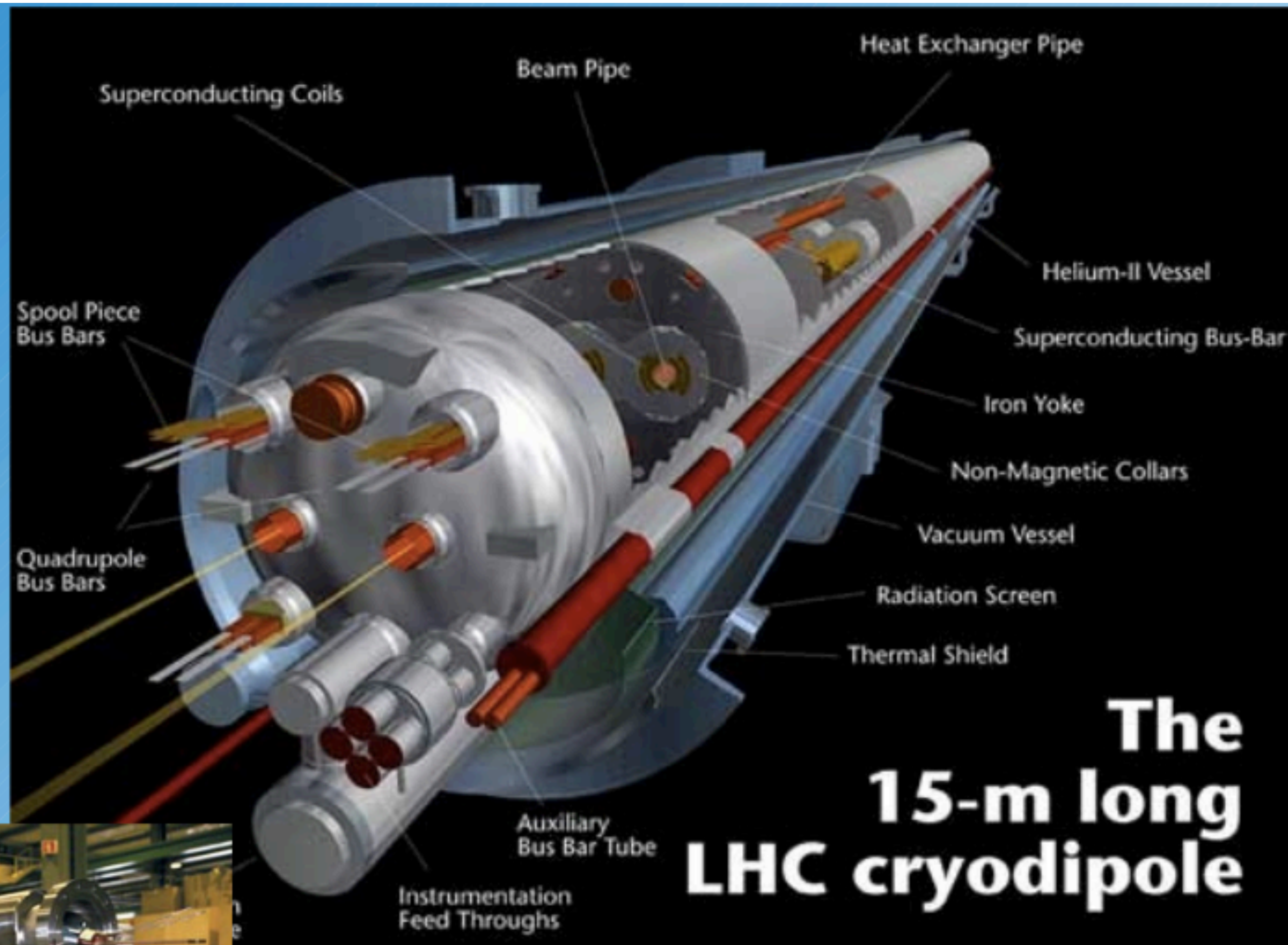


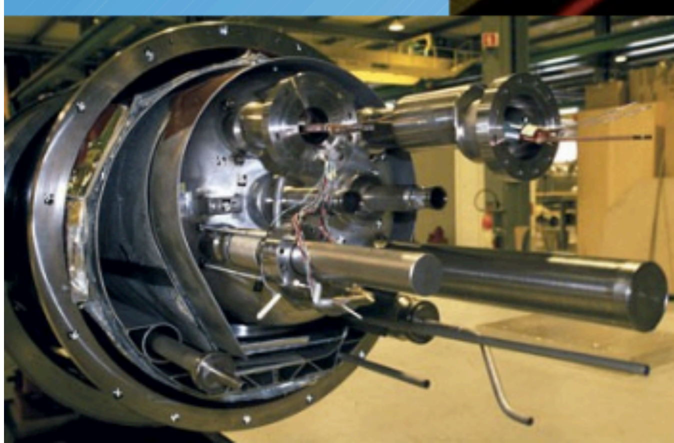
Parameter name	Unit	Value
Injection kinetic energy	GeV	1.4
Maximum momentum	GeV/c	26
Dipole field at 26 GeV/c	T	1.26
Radius	m	100.000
Curvature radius	m	70.079
g_t		~ 6.1
Pipe half height	cm	3.5
Pipe half width	cm	7.0

CERN SPS 450 GeV (since 1976)

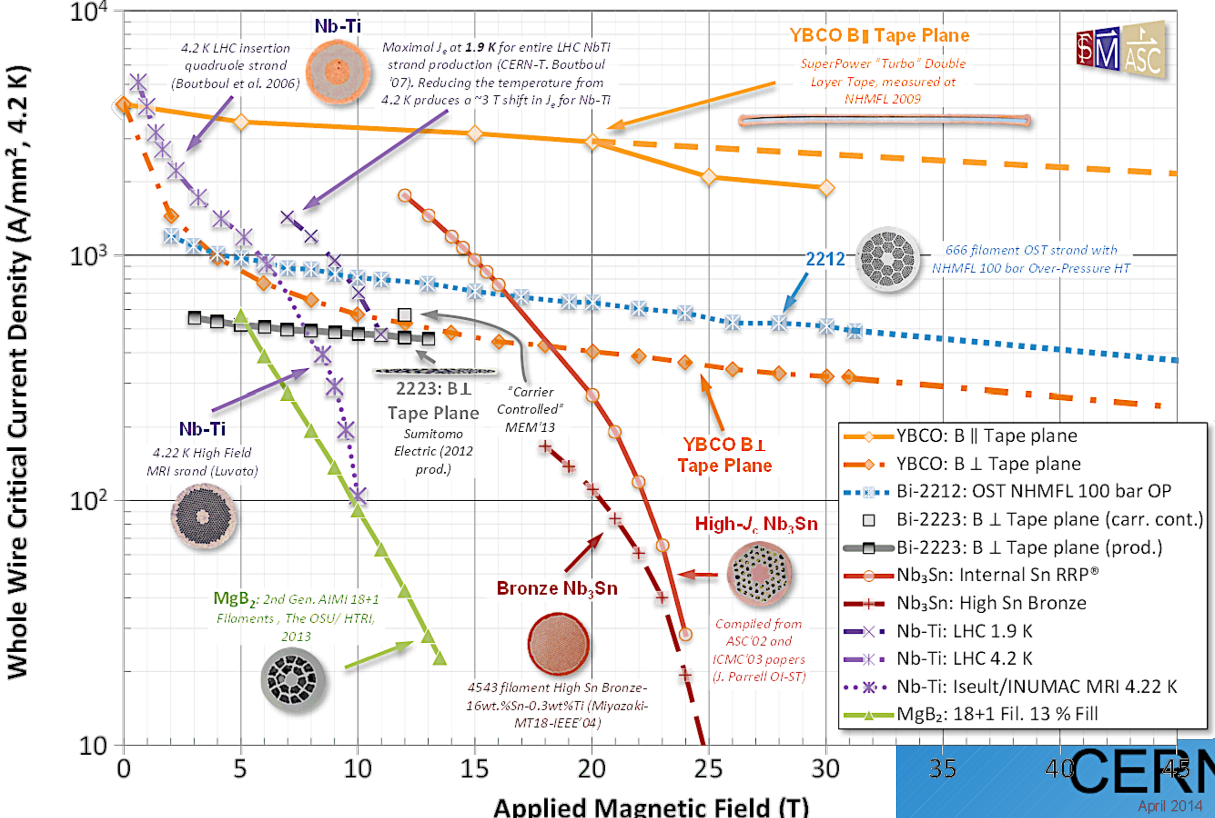
Super Proton Synchrotron, CERN

Note, a proton synchrotron (fixed orbit, varying magnetic dipole fields) have a limited range of operation (magnetic saturation, beam stability)



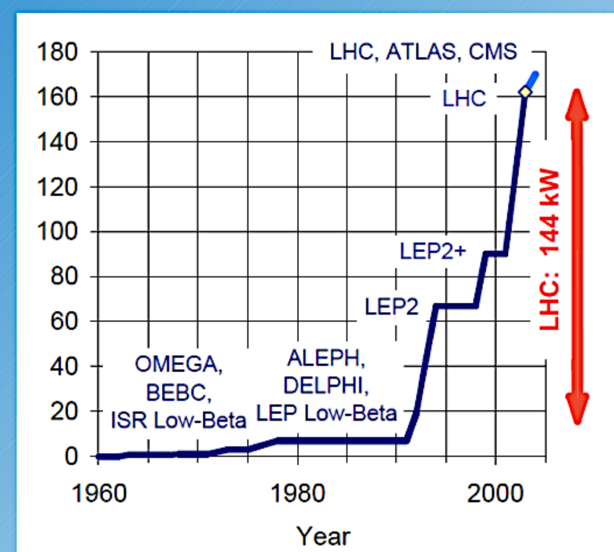


~ 1400 modules



LHC operates at 1.8 K in order to get 8 T from NbTi. The performance comes at a stiff price.

CERN Cryogenic power

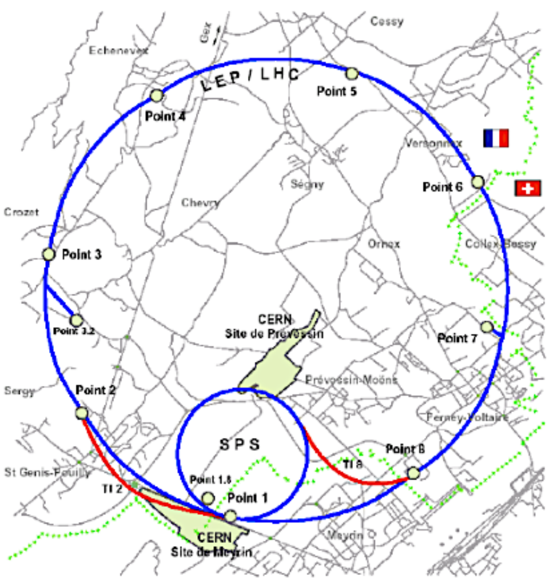


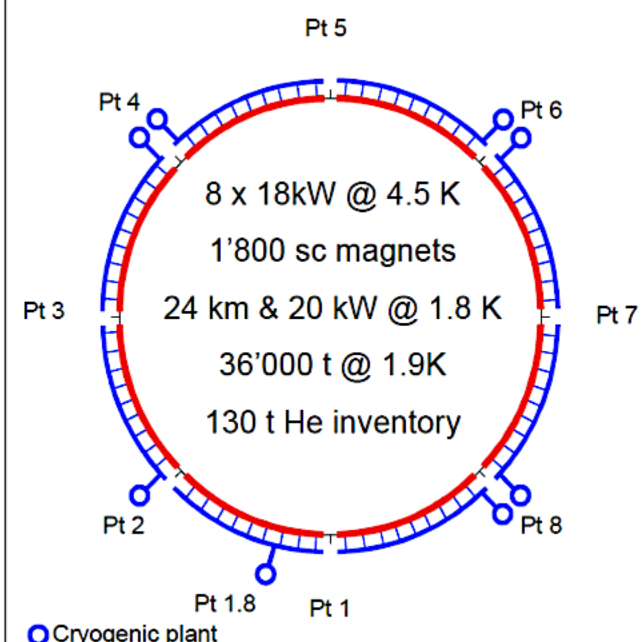
from S.Claudet

LHC Superfluid Cryogenic Plant – the largest LHe capacity in the world

LHC Cryogenic System

...um (2K)

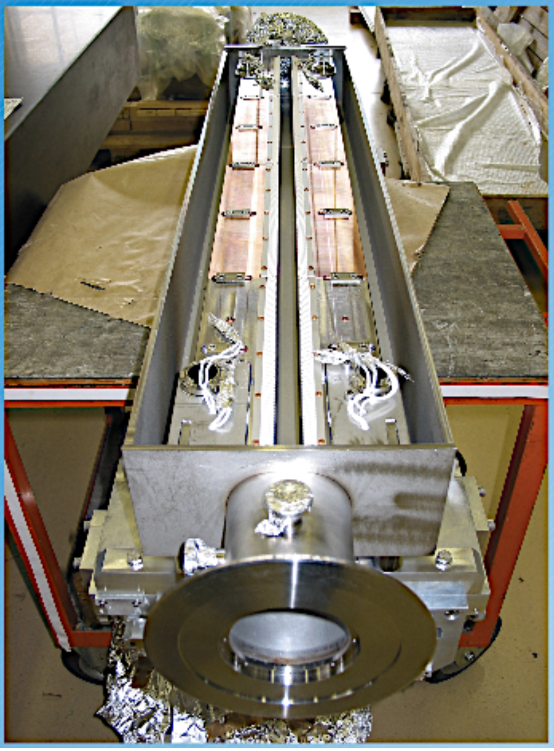


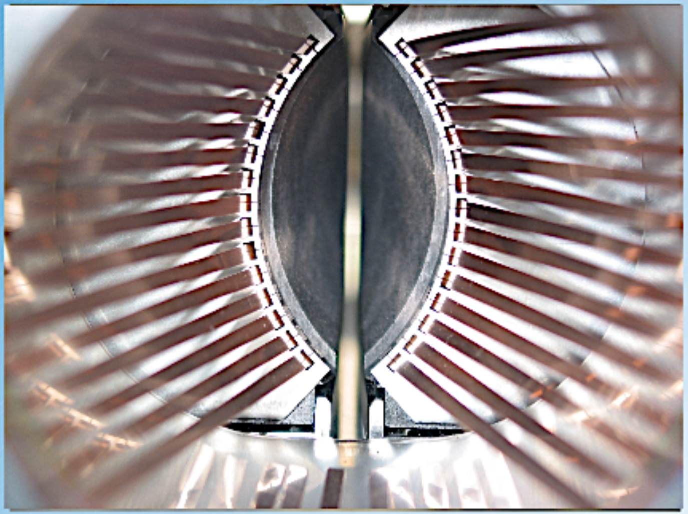


from S.Claudet

LHC Collimators

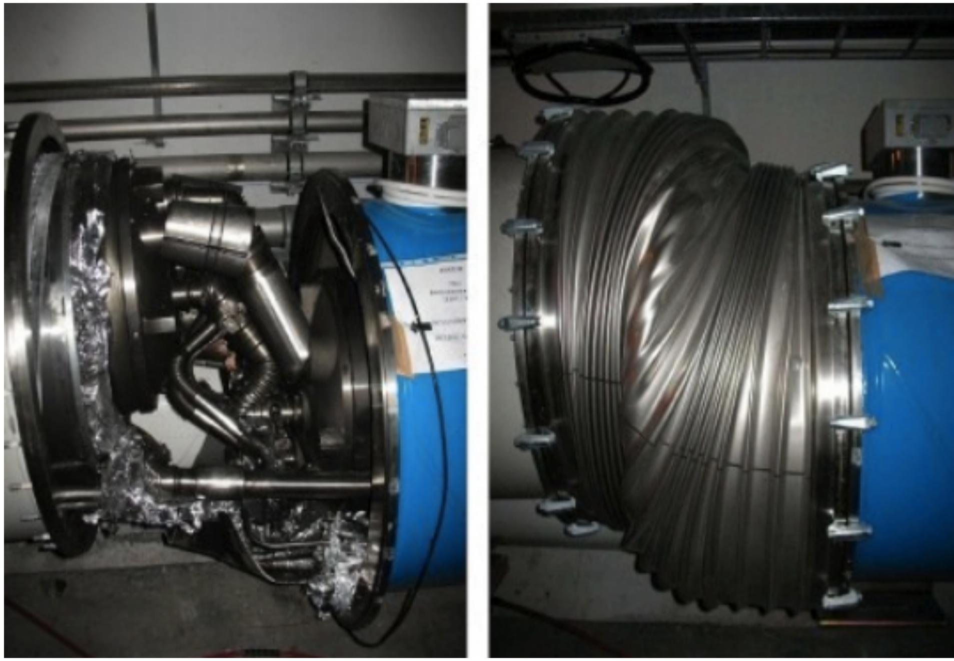
Task: absorb halo proton and neutrons straying around the beam





movable jaws (with RF shield)

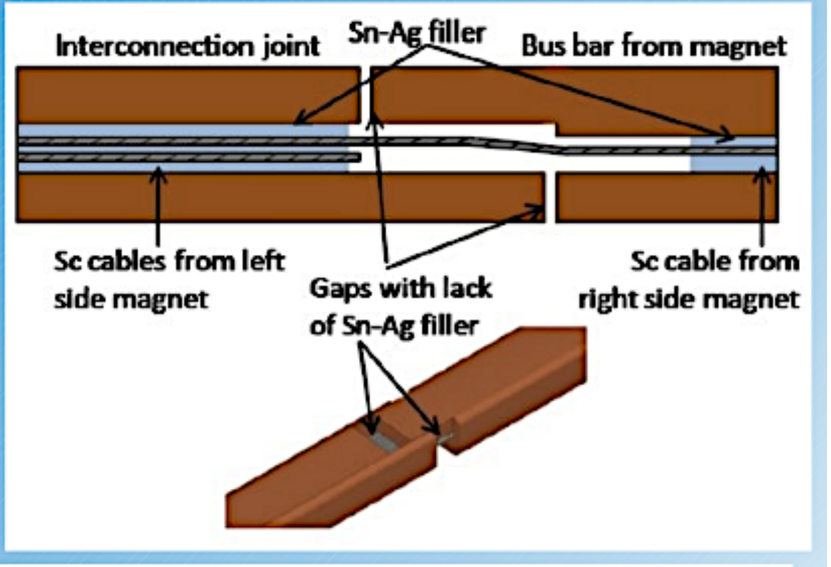
And then…

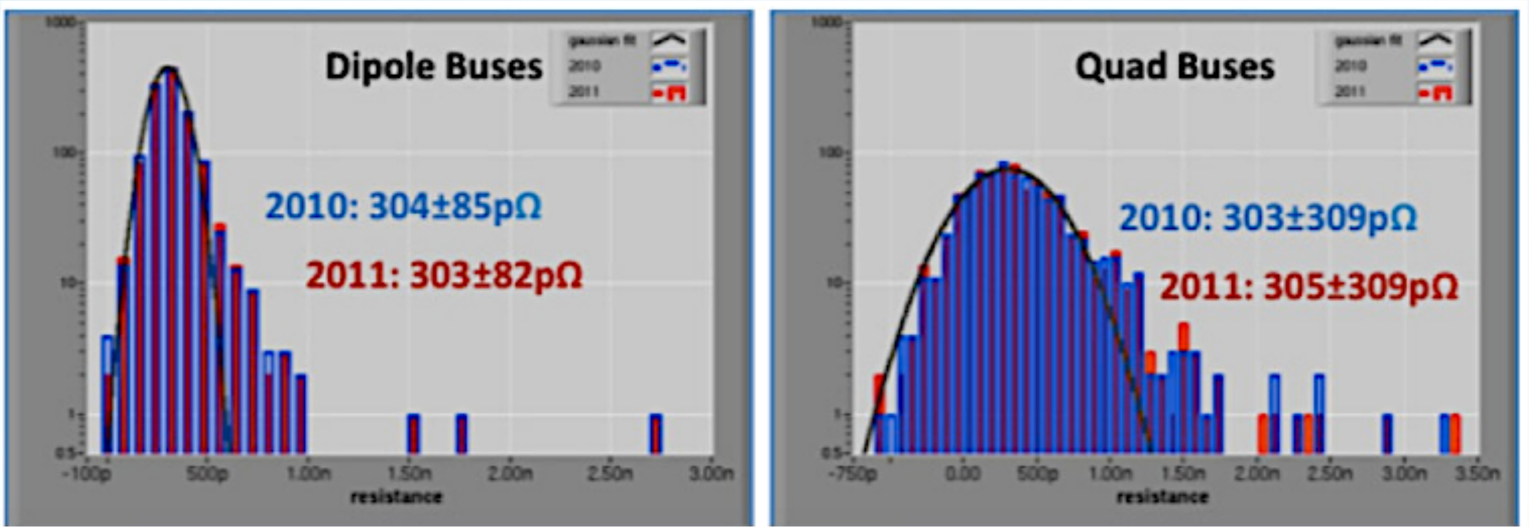


All superconducting magnets in LHC connect their supply and return currents through current bus cables, located in conduits within the magnet cryostats. Each bus in each magnet must be spliced to the same bus in the neighboring magnets. Those splice joints must be stable against quench. The provisions for stabilizing copper, and the provisions for soldering, were inadequate in the original installation.

Interconnection Joints

Splice Resistance Measurements (A.Siemko et al)





LHC Repair

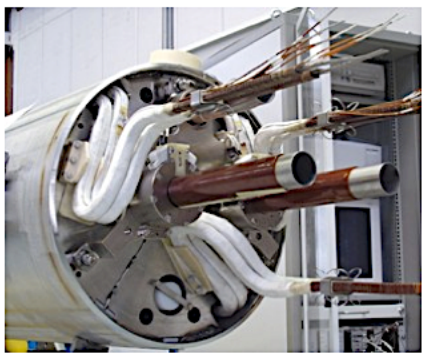
Quench protection of the superconducting magnets

LHC dipole protection: practical implementation

It's difficult! - the main challenges are:

1) Series connection of many magnets

- In each octant, 154 dipoles are connected in series. If one magnet quenches, the combined energy of the others will be dumped in that magnet ⇒ vaporization!
- **Solution 1**: cold diodes across the terminals of each magnet. Diodes normally block ⇒ magnets track accurately. If a magnet quenches, it's diodes conduct ⇒ octant current by-passes.
- **Solution 2:** open a circuit breaker onto a resistor (several tonnes) so that octant energy is dumped in ~ 100 secs.

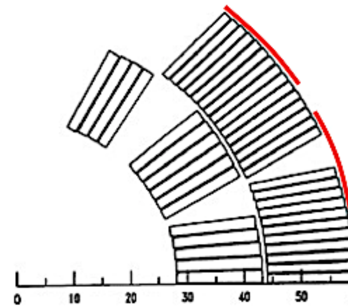


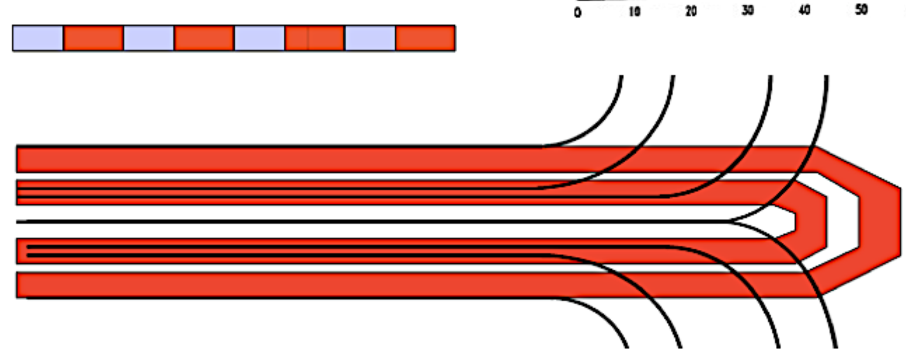
2) High current density, high stored energy and long length

- Individual magnets may burn out even when quenching alone.
- **Solution 3:** Quench heaters on top and bottom halves of every magnet.

LHC quench-back heaters

- stainless steel foil 15mm x 25 μm glued to outer surface of winding
- insulated by Kapton
- pulsed by capacitor 2 x 3.3 mF at 400 V = 500 J
- quench delay - at rated current = 30msec
  - at 60% of rated current = 50msec
- copper plated 'stripes' to reduce resistance



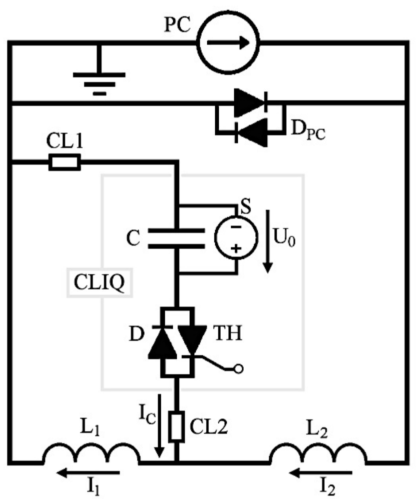


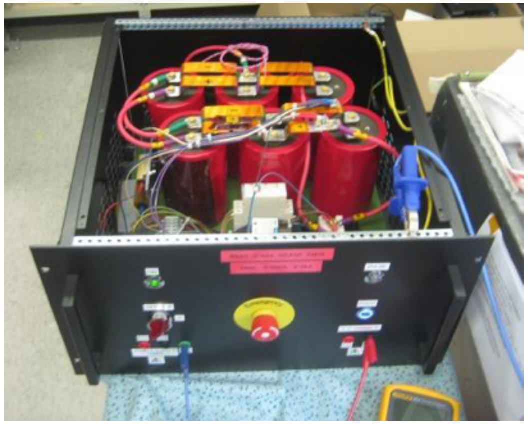
But the quench heater leads are beginning to fail open.

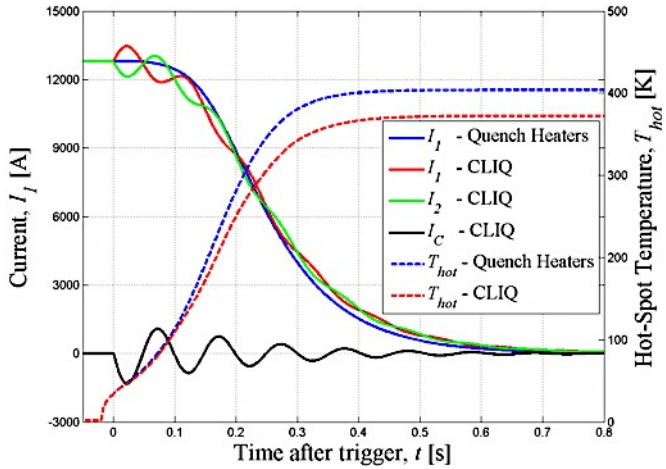
It is suspected that warmup-cooldown stresses weaken the connections.

CERN is evaluating a new quench protection method: CLIQ

Datskov, GSI



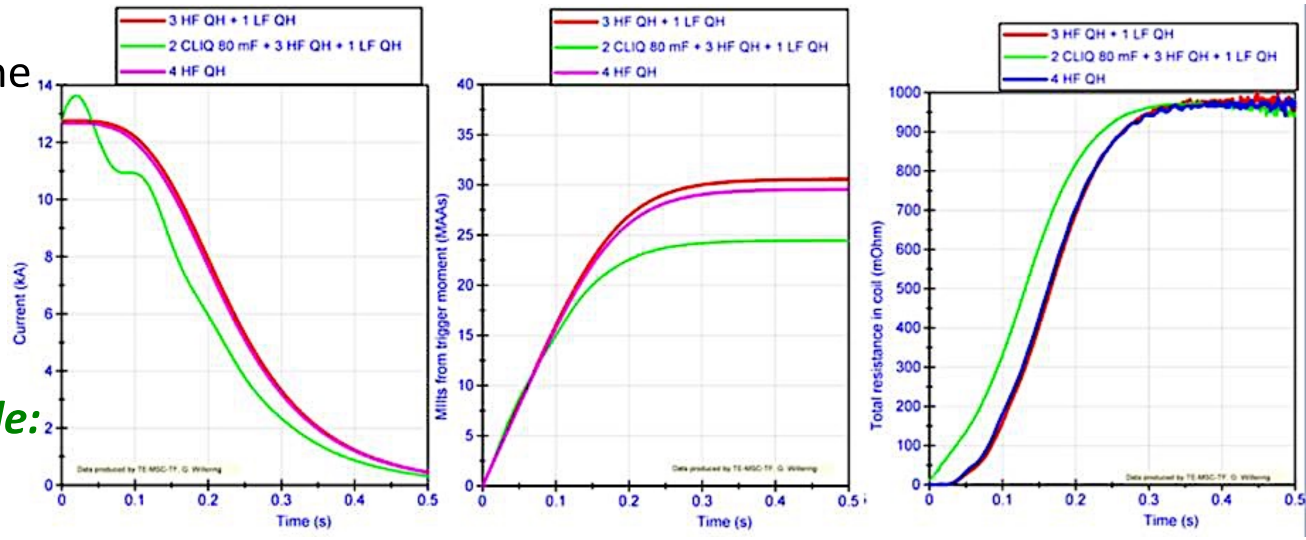




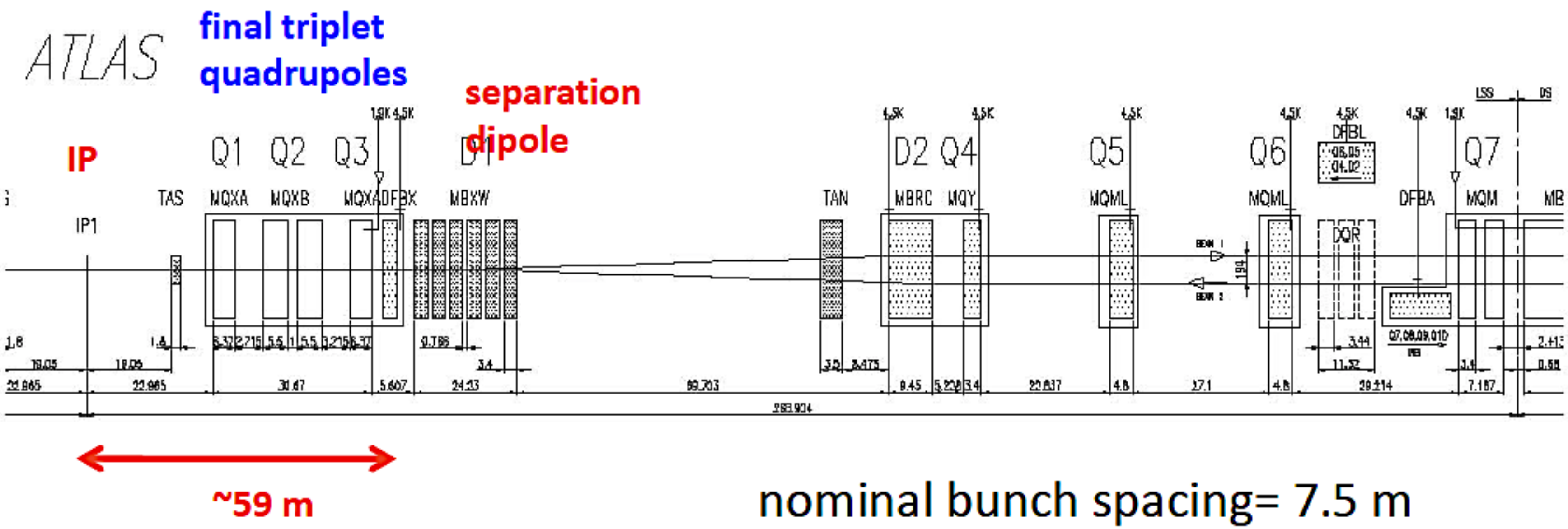
Discharge a capacitor across the inductive circuit of the dipole winding.

It induces distributed AC loss spike that drives quench everywhere in winding.

It works great on an LHC dipole:



LHC interaction-region layout



nominal bunch spacing= 7.5 m

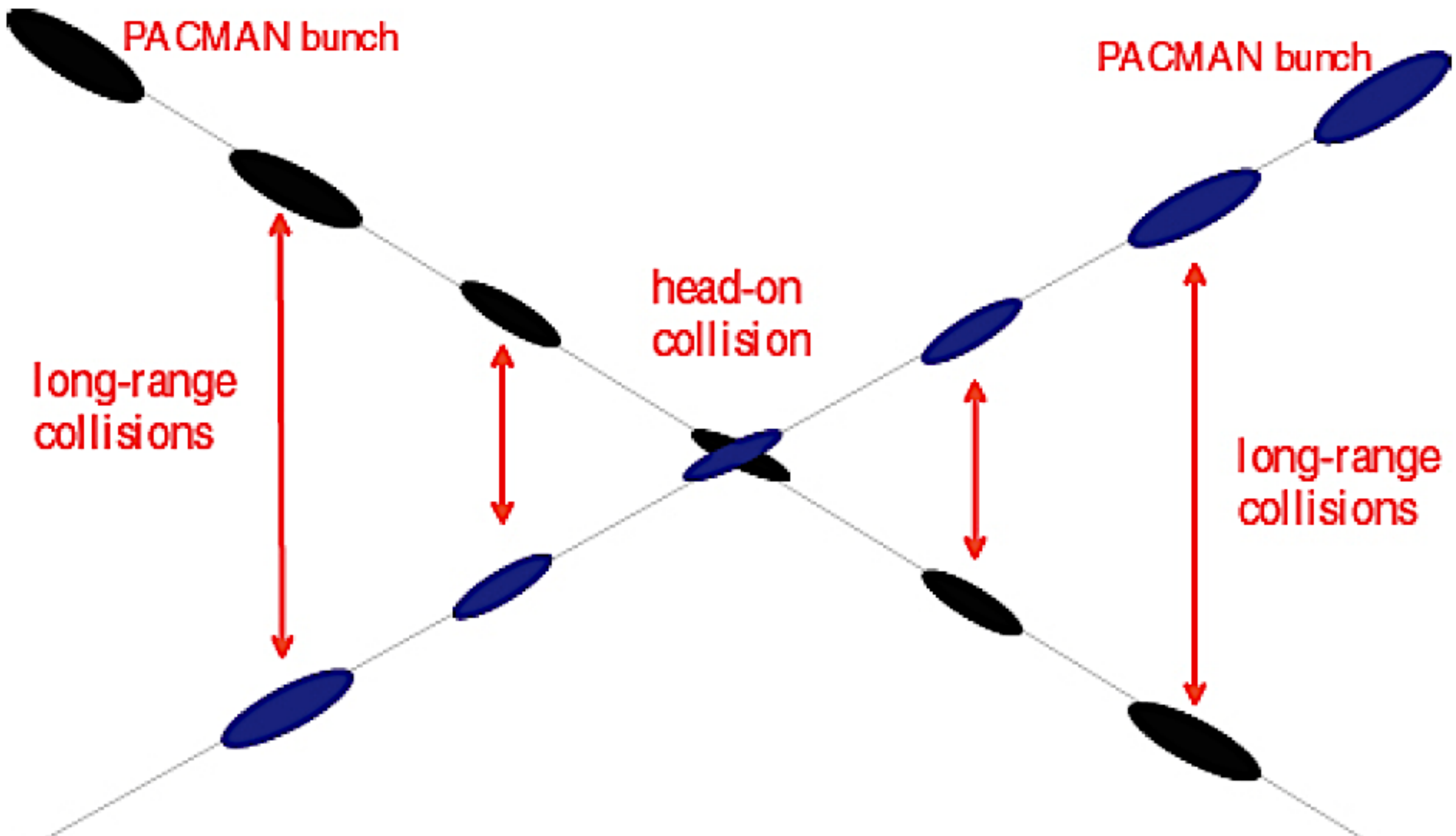
nominal collision spacing = 3.75 m

→ *about 2x15 collisions between IP and separation dipole!*

tune shift would increase 30 times!

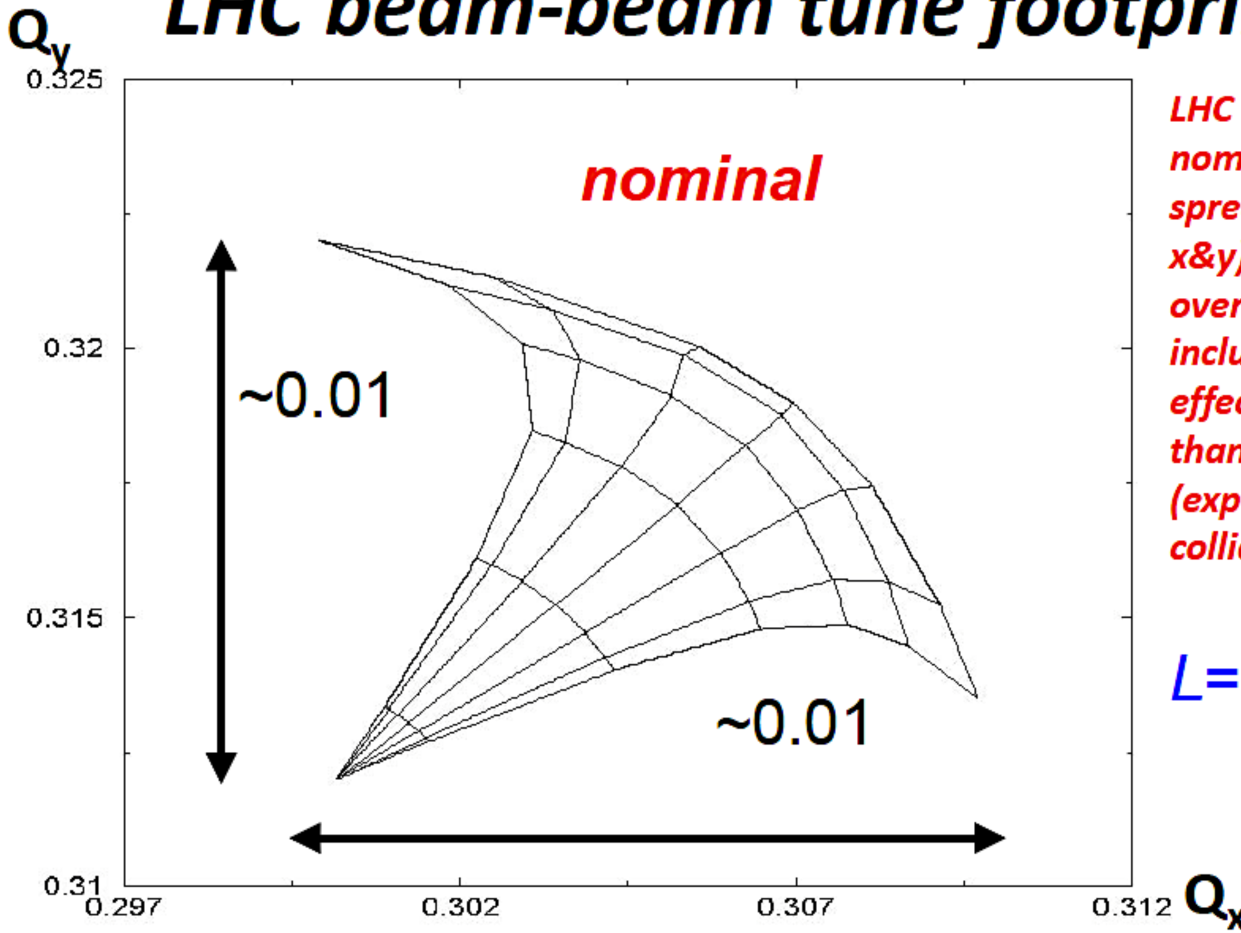
solution: crossing angle

LHC: long-range beam-beam



30 long-range collisions per IP, 120 in total

LHC beam-beam tune footprint



LHC design criterion: nominal total tune spread (up to 6σ in x&y) from all IPs and over all bunches, including long-range effects, should be less than 0.01 (experience at SPS collider)

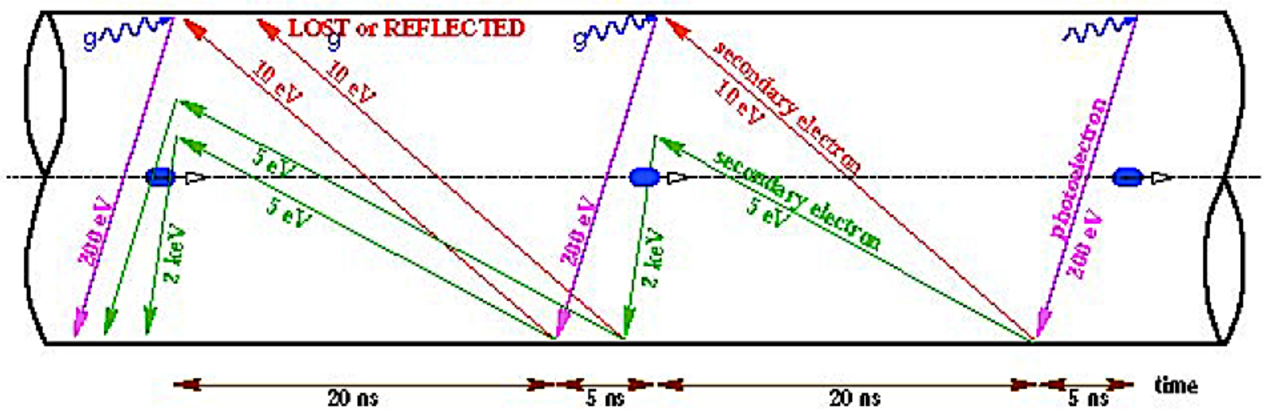
L=10^{34} cm^{-2}s^{-1}

nominal tune footprint up to 6σ with

4 IPs & nom. intensity N_b=1.15x10^{11}

electron cloud

[F. Ruggiero]



schematic of e- cloud build up in LHC beam pipe, due to **photoemission** and **secondary emission**

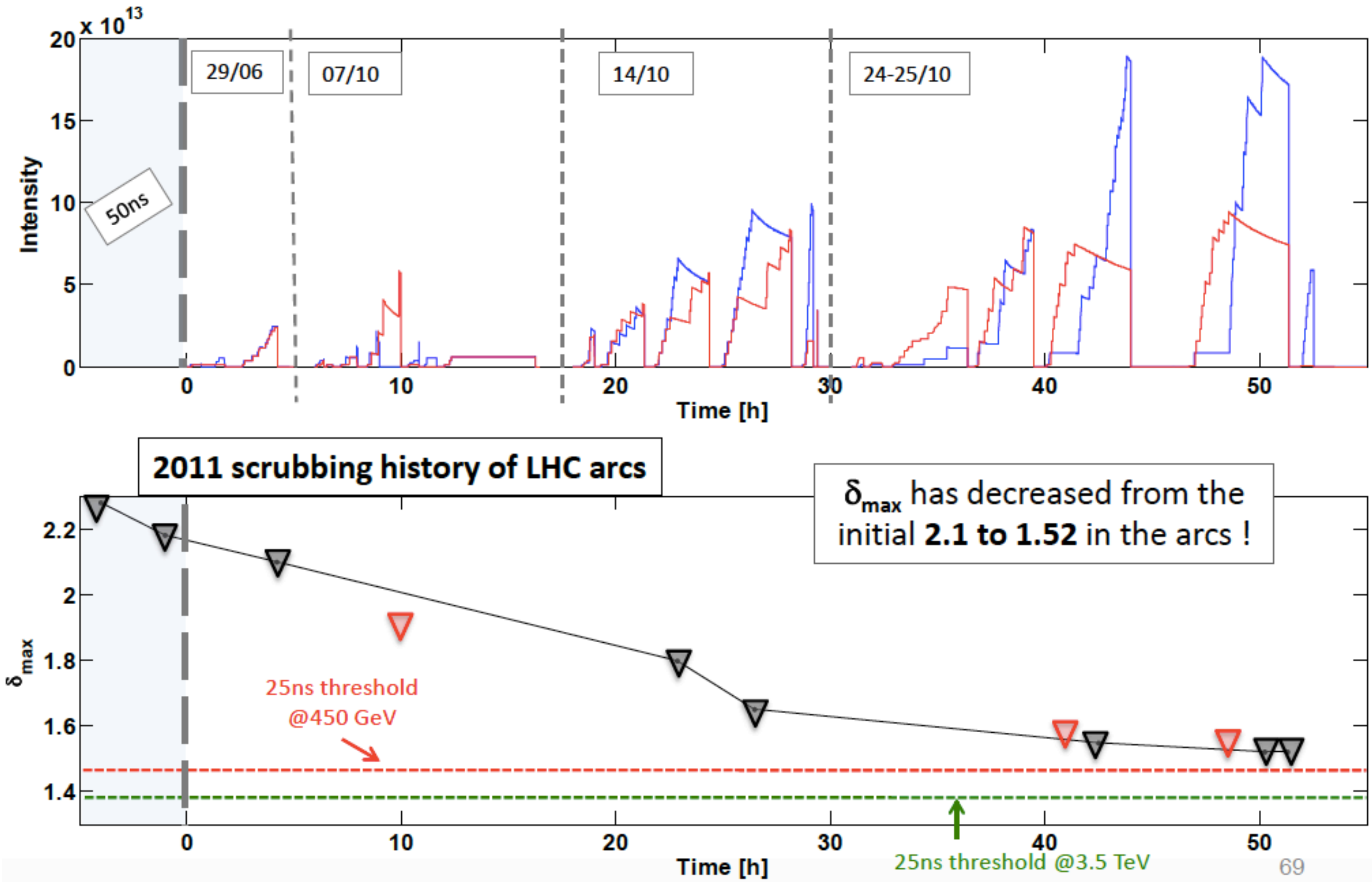
→ ***heat load (→ quenches), instabilities, emittance growth, poor beam lifetime***

also synchrotron radiation & beam image currents add to heat load

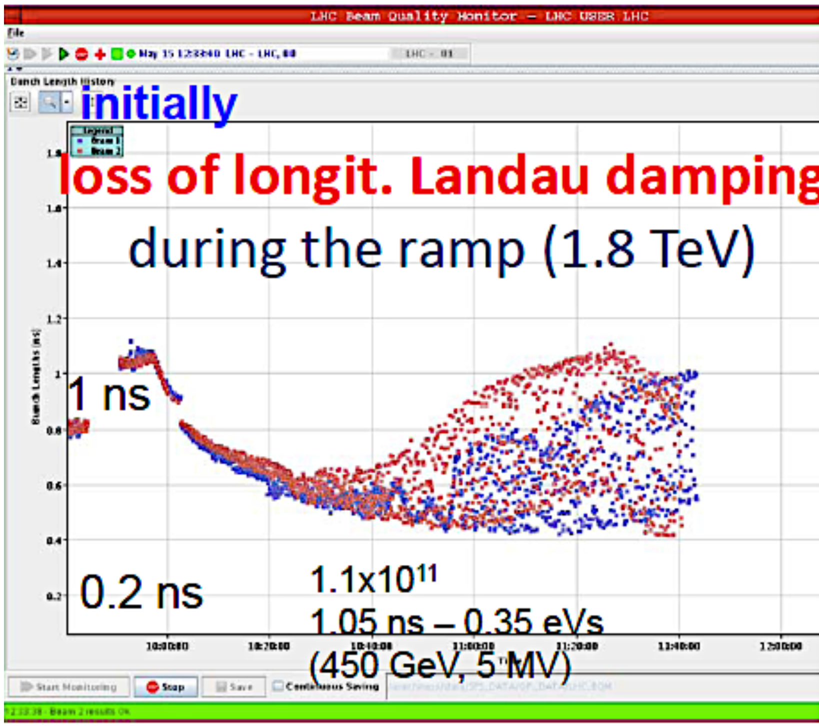
Beam scrubbing gradually reduces the secondary electron yield.

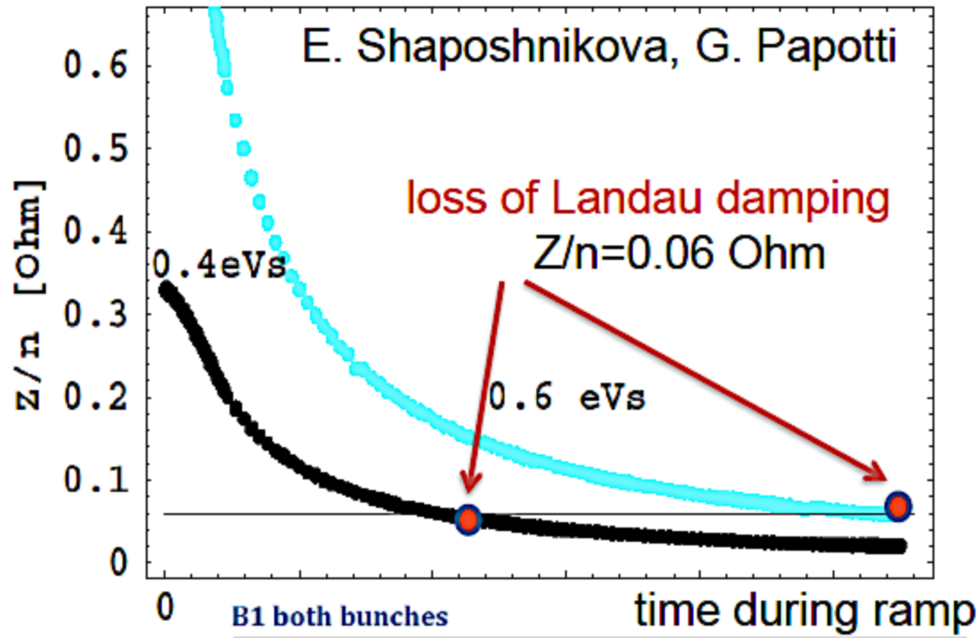
G. Rumolo

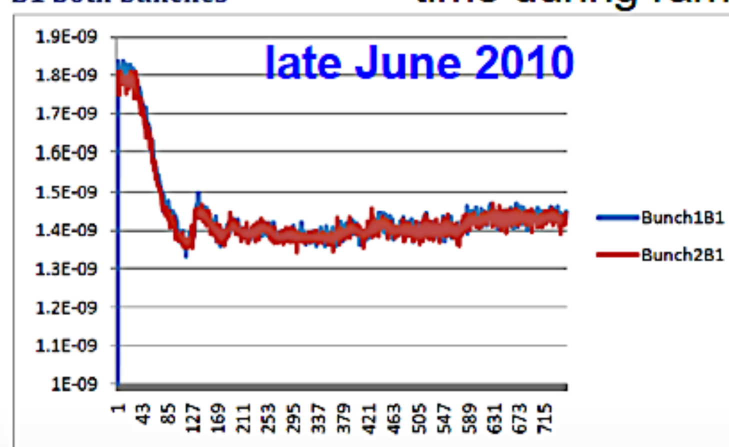
Electron cloud: δ_{max} in the arcs: results



LHC – longitudinal instability







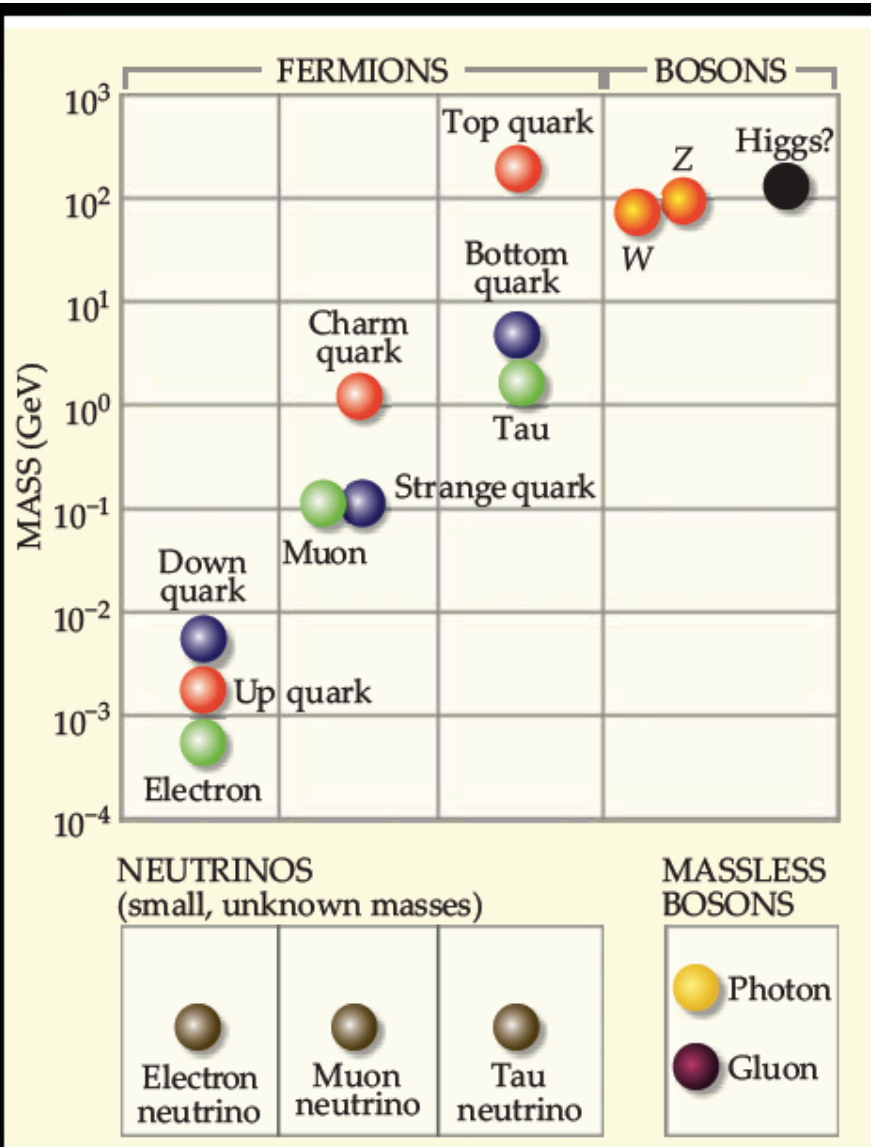
main cure: controlled longitudinal blow up on LHC ramp

feedback on bunch length measurement modulates noise amplitude to control blow-up rate;
bunch lengths converge correctly to target 1.5 ns
(now ~1.25 ns)

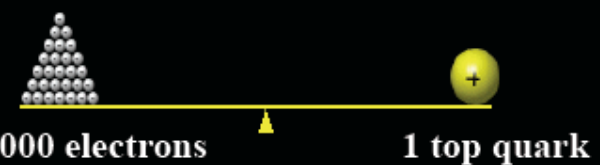
Back in business…
Discover the Higgs…
Then what?

- Supersymmetry
  - Naturalness bound…

The Standard Model



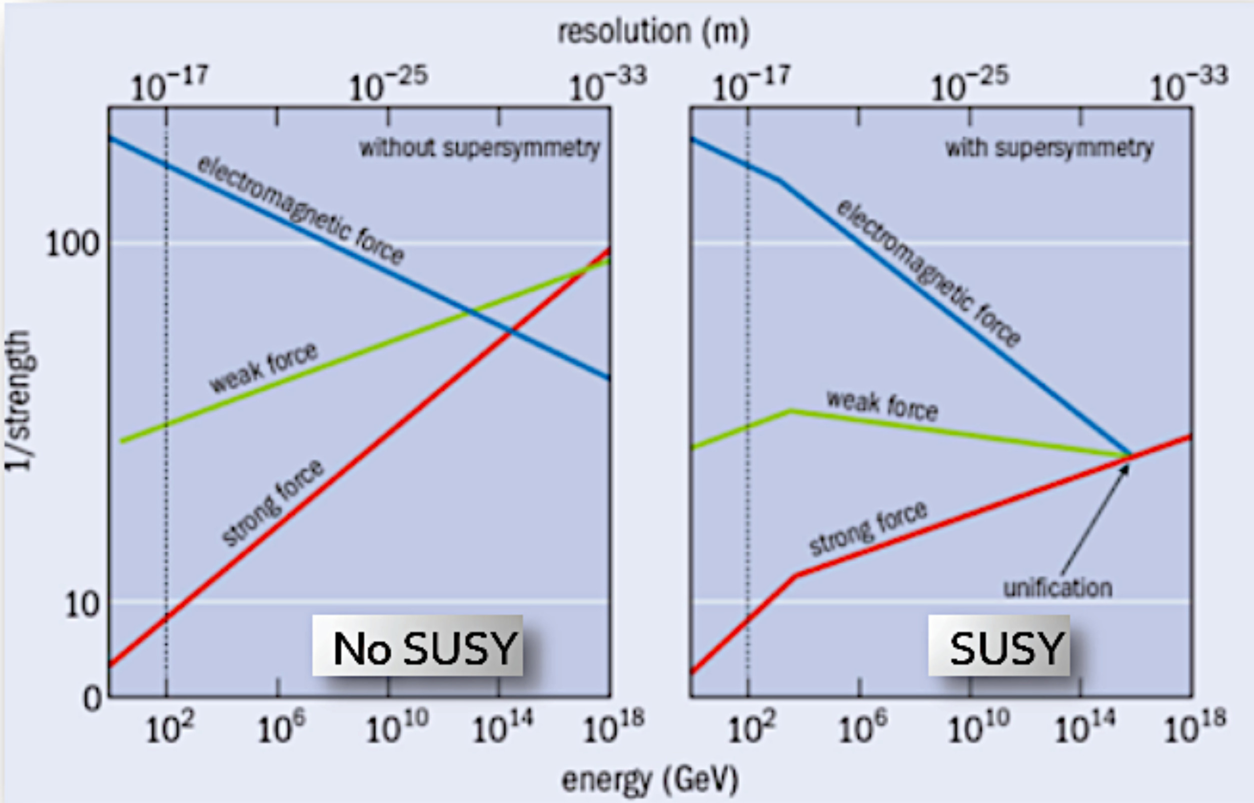
- It's an effective theory with many unanswered questions



- What determines the masses?
  - particularly the 3rd generation?
- Why this energy scale?
  - Electroweak scale ~0.1-1.0 TeV
  - The only 'natural' scale is the Planck scale (~10^{19} GeV)
    - m_H = 125 GeV requires extraordinary fine tuning of SM parameters

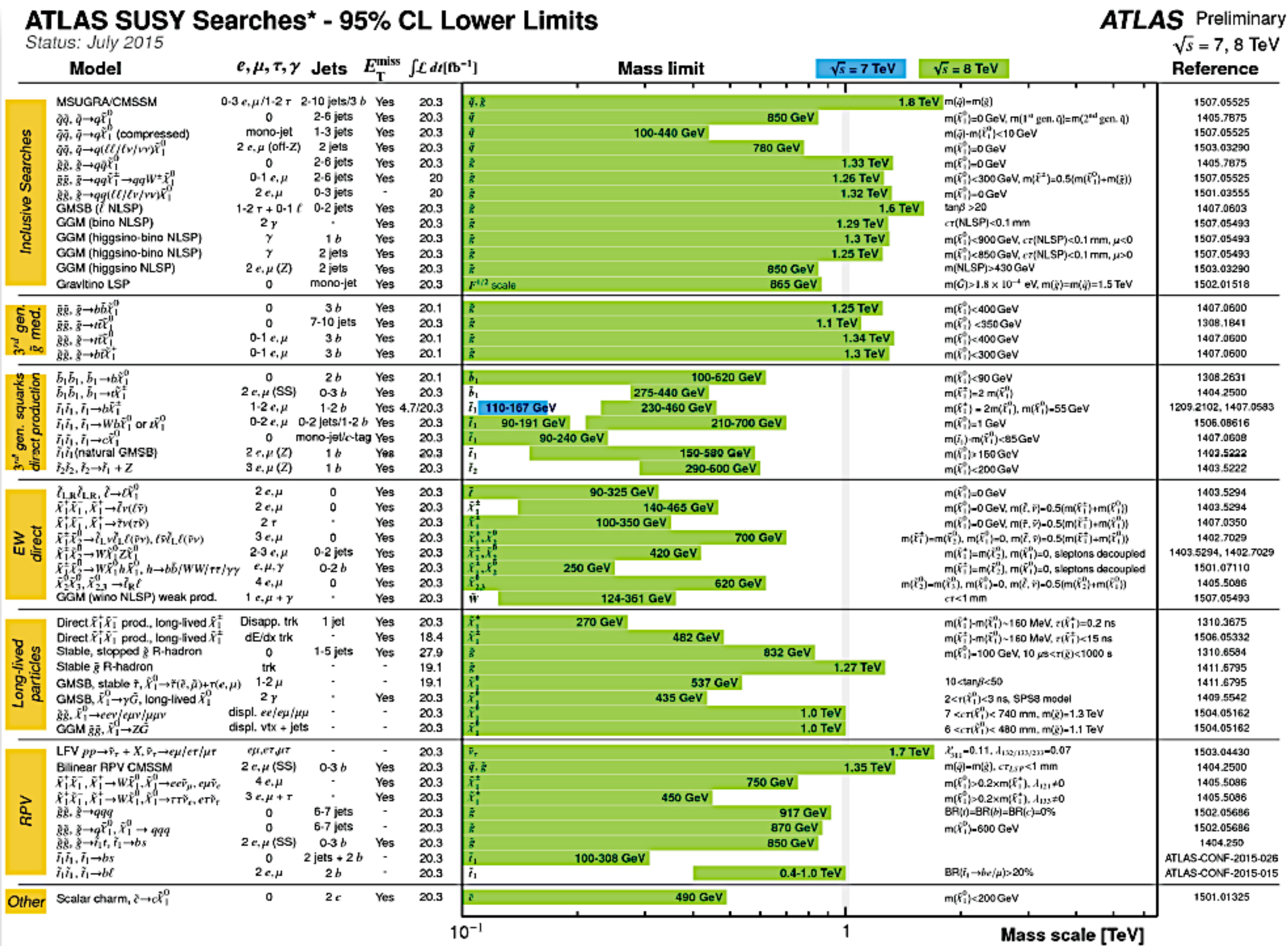
Prime candidate (is still) Supersymmetry

- SUSY provides appealing Dark Matter candidates
  - Light Supersymmetric Particles – e.g. Neutralino (or Gravitino…)
- Provides remarkable unification of forces
  - At the grand unification scale ~ 10^{16} GeV

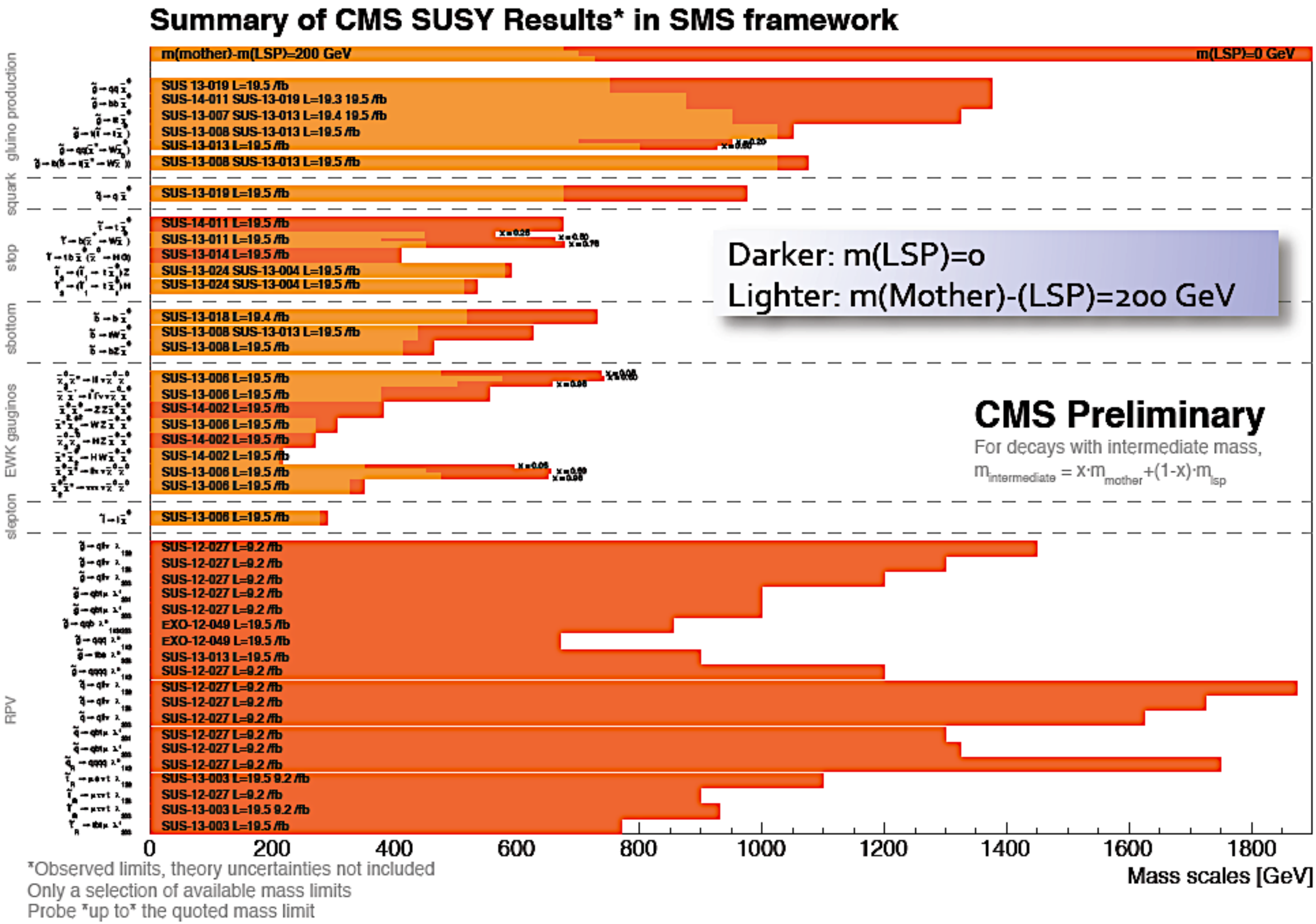


- Predicts a standard-model-like Higgs with m_h < 130 GeV!

Report card from ATLAS



Report card from CMS



The pileup challenge

Events taken at random (filled) bunch crossings

2010

O(2) Pile-up events

150 ns bunch spacing

2011

O(5-10) Pile-up events

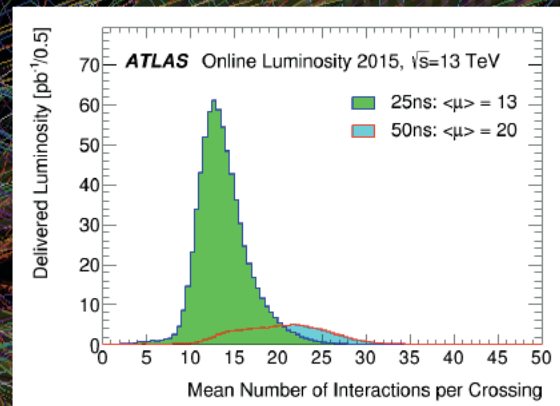
50-75 ns bunch spacing

2012

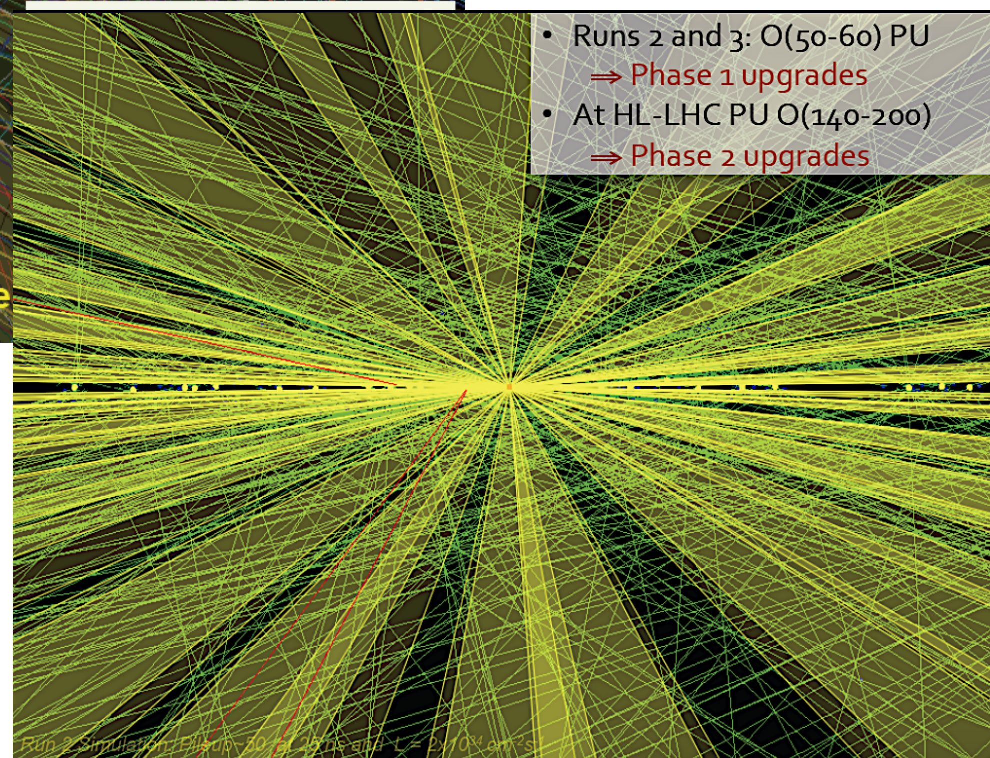
O(20-30) Pile-up events

50 ns bunch spacing

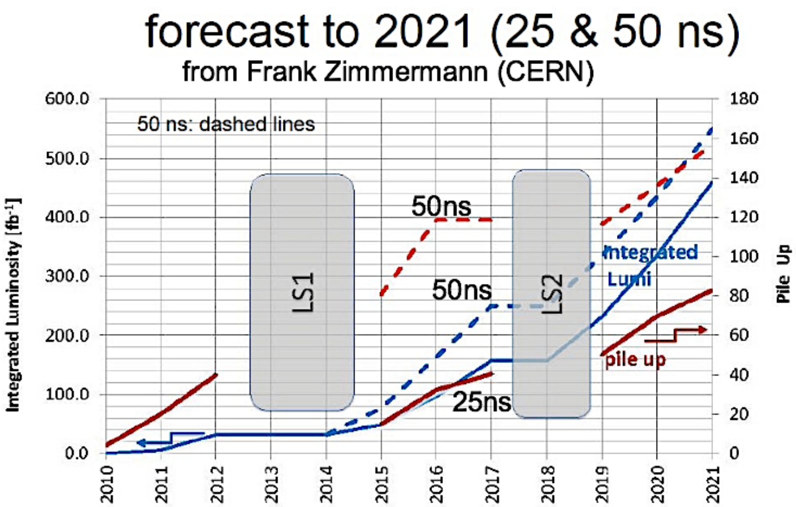
Pileup beyond design value



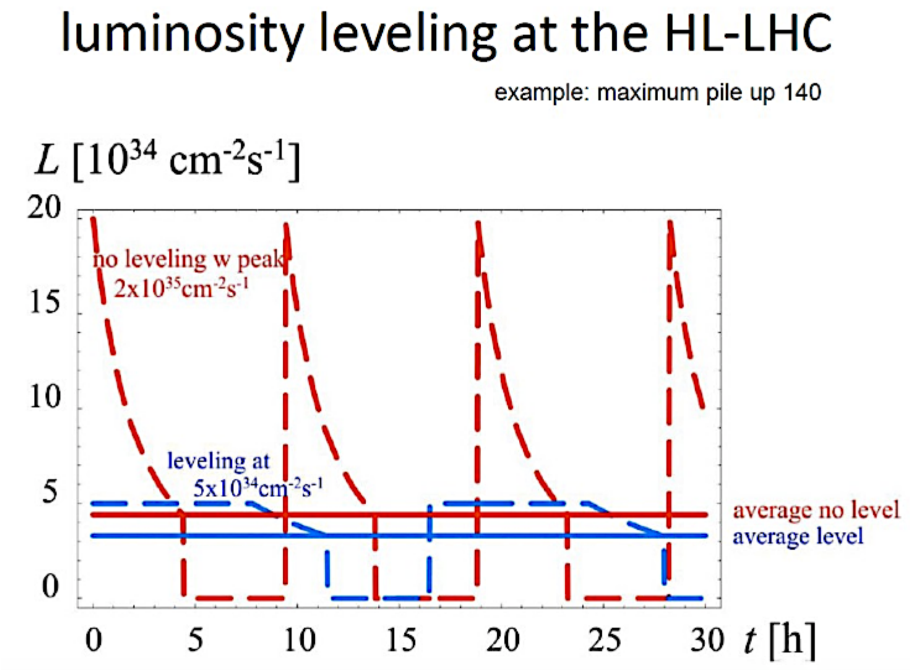
- Runs 2 and 3: O(50-60) PU
  ⇒ Phase 1 upgrades
- At HL-LHC PU O(140-200)
  ⇒ Phase 2 upgrades



Luminosity upgrades



- pile up high (80-120) in 2015-2017 with 50 ns spacing
  (50-ns pile up >2x more than for 25 ns spacing)



Nb_3Sn Superconducting Magnets for the Luminosity Upgrade

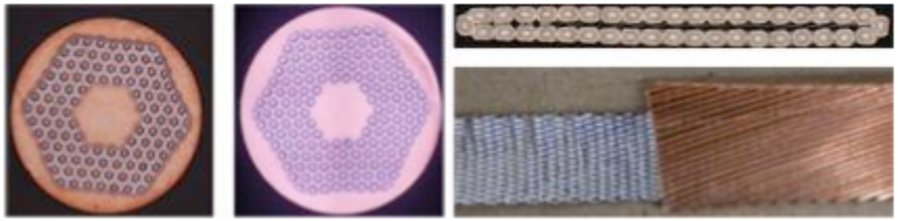


Fig. 2. RRP108/127 and RRP150/169 strands and 40-strand cored cable.

11 T dipoles to free space for dispersion suppressors in the arc lattice.

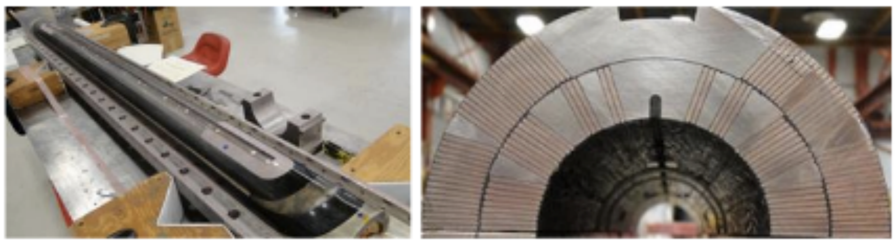


Fig. 3. Impregnated coil (left) and coil cross-section (right).

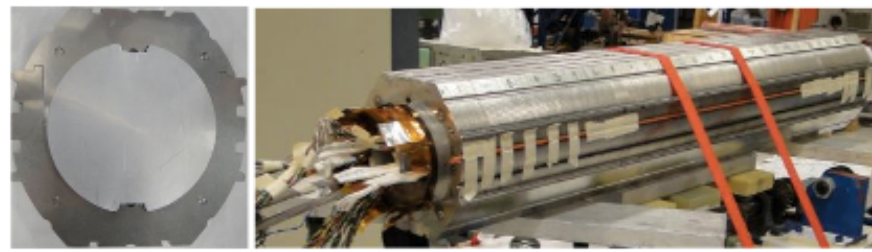


Fig. 4. Stainless steel collars (left) and collared coil assembly (right).

200 T/m quadrupoles with 120 mm aperture for the low-beta triplets flanking each IP.