Super-bunch Hadron Colliders

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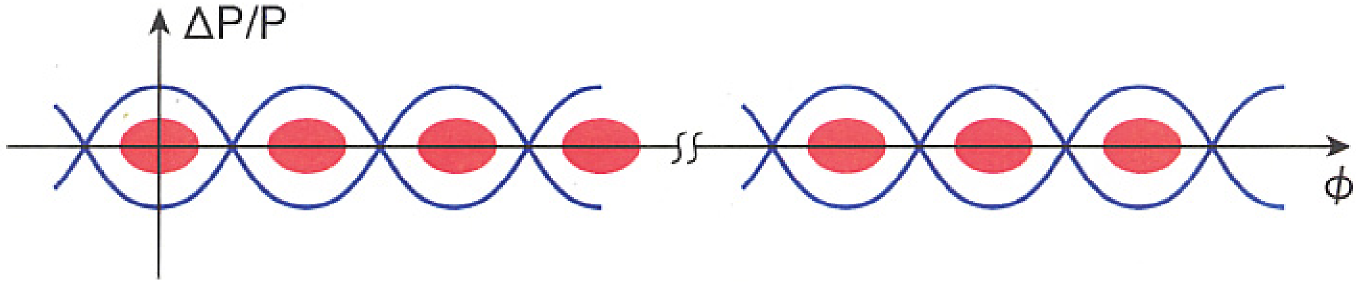
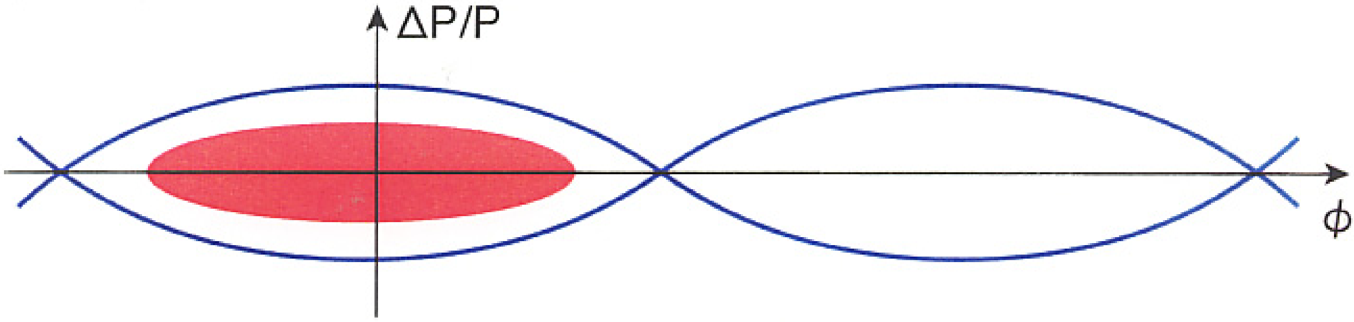
1. Introduction
2. What is a Super-bunch?
3. Milestone toward a Super-bunch Hadron Collider
4. Characteristics
   - Bunch formation
   - Collision scheme and beam-beam tune spreads
   - Luminosity
5. Possible parameters
6. Beam physics issues
   - Long range beam-beam effects
   - Coherent instability
7. Machine issues
   - Heat Load
   - IR design
8. R&D time table
9. Summary

RF bunch & Super-bunch

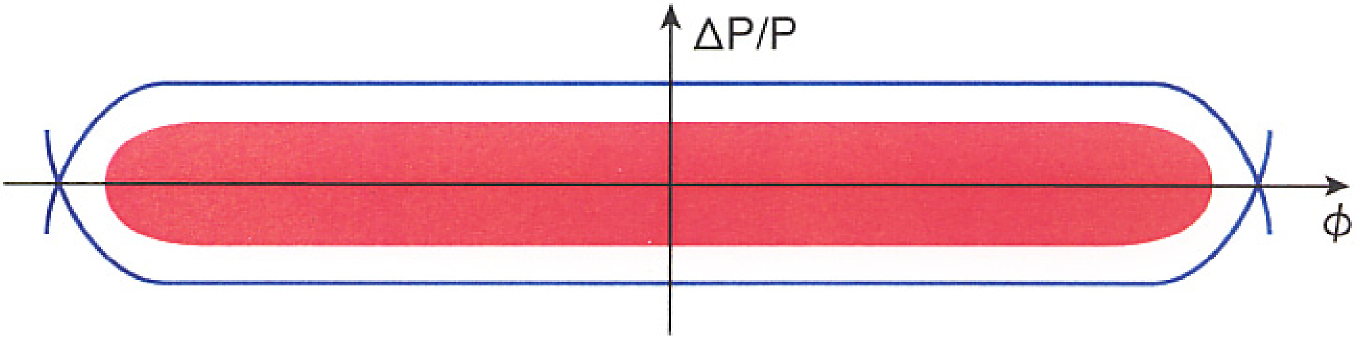
(1) Present higher harmonic RF bunch



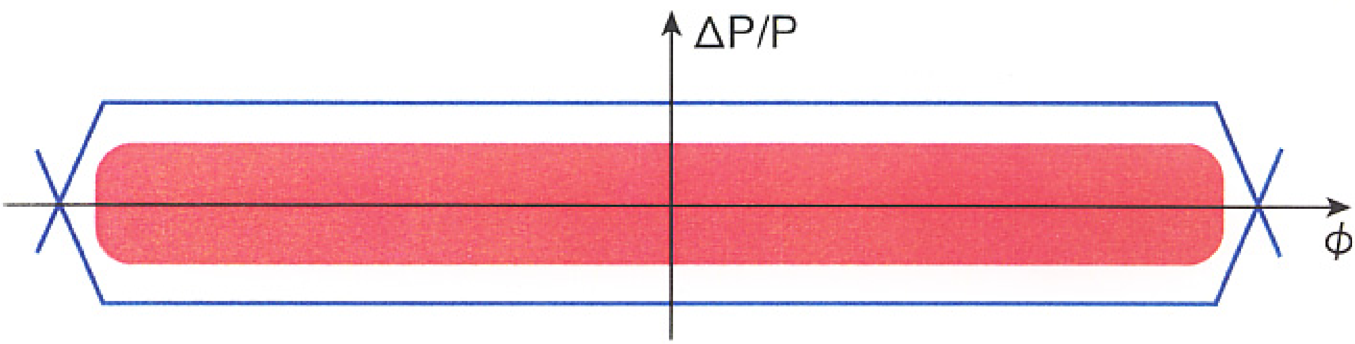
(2) Low harmonic RF Super-bunch



(3) Super-bunch in an RF barrier bucket



(4) Super-bunch in a Step-barrier bucket



Super-bunch

	Type of Super-bunch		
	Low harmonic RF bunch	Barrier bucket bunch	
		RF barrier	Step barrier
Required devices	low harmonic cavity and low freq. power source	• low Q cavity and multiple RFs or amplified pulse voltage	induction cavity
Characteristics			
Advantage	• well developed technology • small RF voltage bucket height $\approx \left[\frac{V}{h}\right]^{1/2}$	• already demonstrated • easy bunch formation	• easy bunch formation by only controlling a trigger timing • uniform line density
Disadvantage	• limited available space in the phase space • highest line density at the bunch center • slow synch. osci.	• no acceleration • slow synch. osci.	• not demonstarated yet • slow synch. osci.
Remarks	• may need minor changes for bunch formation in the upstream • merging process?	• good exercise for Step barrier beam handling	• needs modification for bunch-formation in the upstream accelerators

Milestone toward Super-bunch Hadron Colliders

Date	Authors or Institute	Pub. or Presentation	Remarks
Early 70's	CERN		Demonstration of the first continuous p-p beam collider (ISR)
1973	E.Keil	*Nucl. Inst. Meth.* 113, 333 (1973)	Luminosity, beam-beam tune-shift calculation for coasting beam collision
1983, March	J.Griffin et al.	PAC1983	Proposal of RF barrier bucket
1999, July	K.Takayama and J.Kishiro	νFACT'99 *Nucl. Inst. Meth.* 451, 304 (2000)	Concept of Induction Synchrotron
2001, March	K.Takayama et al.	KEK Preprint 2000-147 (2001)	First proposal of SHC concept
2001, June - July	R.Yamada, Super-bunch sub working-group	PAC2001 Snowmass 2001	Proposal of VLHC schemes with Super-bunch option Beam physics
2002, April	K.Takayama, J.Kishiro, M.Sakuda, Y.Shimosaki, and K.Wake	*Phys.Rev. Letts* 88, 144801 (2002)	Concept and Beam physics of SHC (Luminosity, tune-spread, inclined crossing)
2002, June	F.Zimmermann	EPAC2002, in Proc., 25 (2002)	e-p Instability in Super-bunch option
2002, October	F.Ruggiero,R.Garoby, F.Zimmermann et al.	LHC Project Report	Feasibility study of Super-bunch option in LHC upgrade

ISR

ISR Parameter List

Max. total energy	E_{max}	28 GeV
Average radius	R	150 m
Intersection angle	α	15^{o}
No of magnet periods	N	48
No of superperiods	S	4
No of intersections		8
Long s.s. length		16.8 m
Q value	Q	8.75
Max. horizontal β value	β_H max	41 m
Max. vertical β value	β_V max	51 m
Max. momentum compaction	α_p max	2.3 m
No of magnets per ring		132
Max. field	B_o	1.2 T
Bending radius	ρ	78.5 m
Profile parameter	n/ρ	3 m^{-1}
Gap height		0.1 m
Harmonic number	h	30
R.F. volts per turn	50 V to	20 kV
Design pressure		10^{-9} torr
Vac. chamber dimensions		16 × 5.2 cm^2

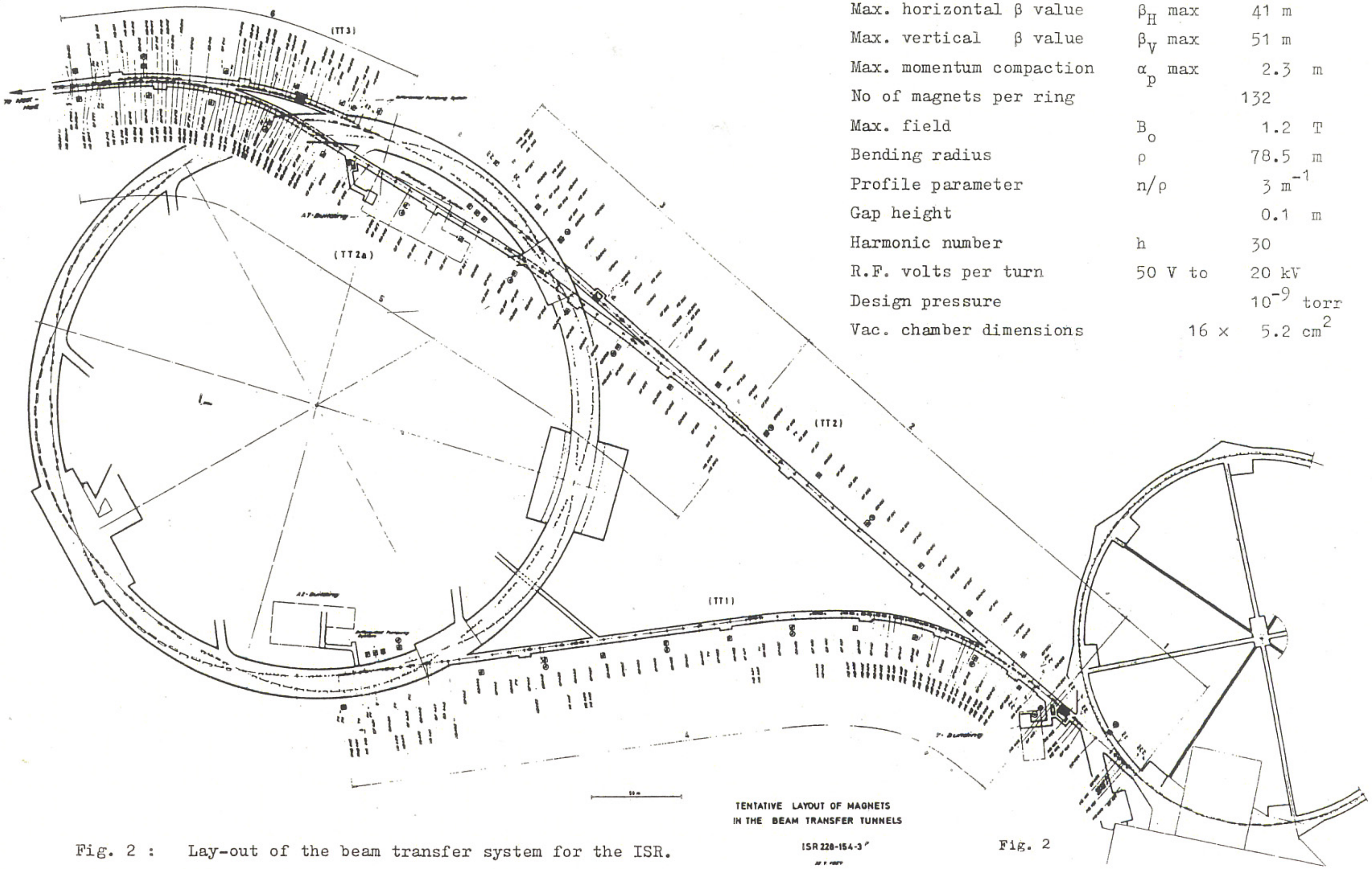
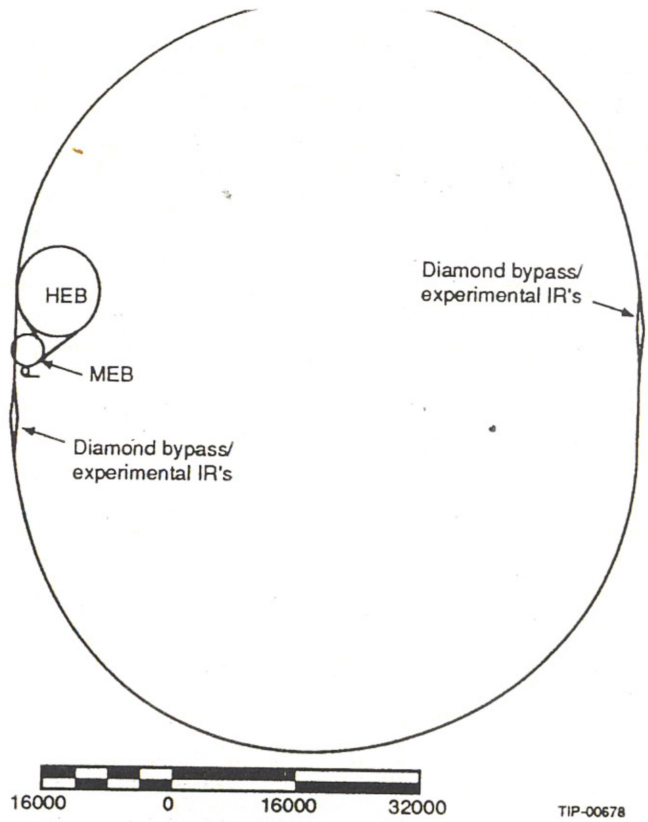


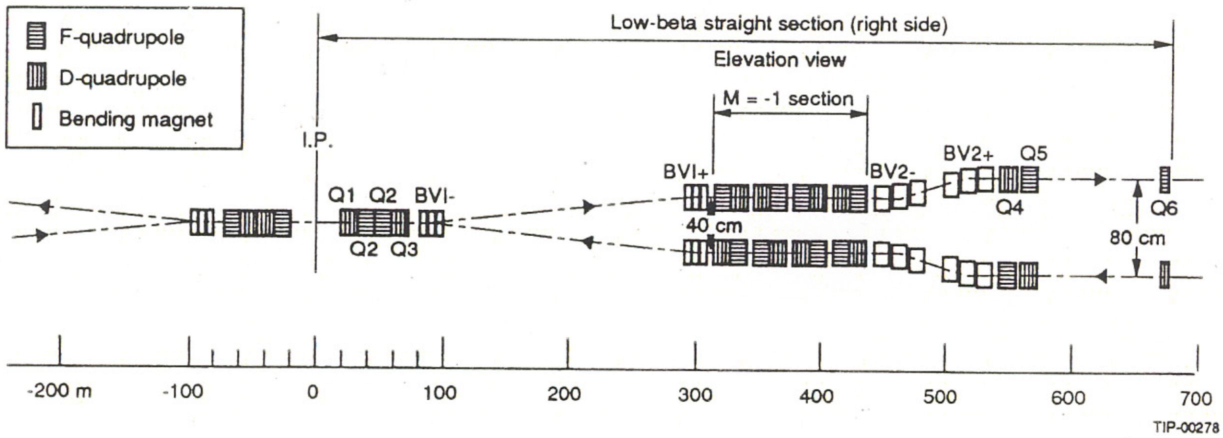
Fig. 2 : Lay-out of the beam transfer system for the ISR.

Fig. 2

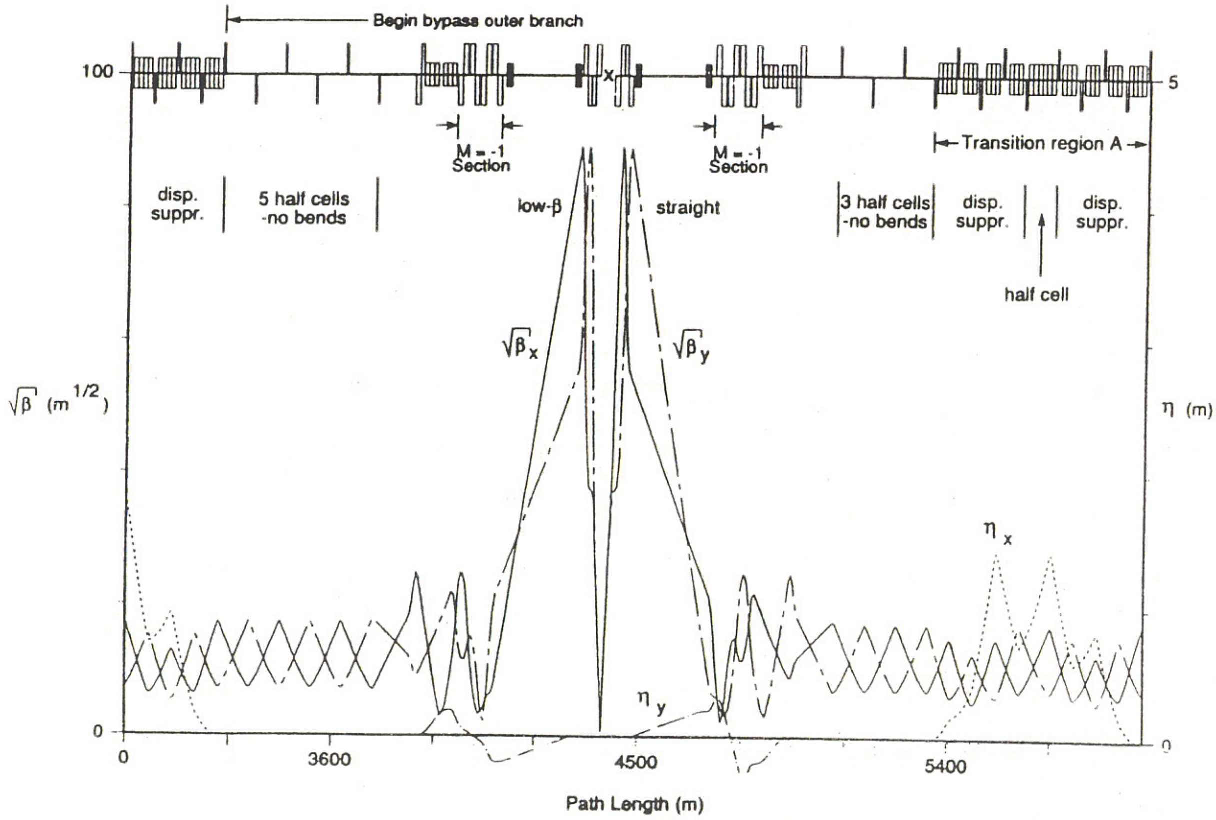
SSC



HEB
MEB
Diamond bypass/ experimental IR's
Diamond bypass/ experimental IR's
16000
0
16000
32000
TIP-00678



F-quadrupole
D-quadrupole
Bending magnet
Low-beta straight section (right side)
Elevation view
M = -1 section
I.P.
Q1 Q2 BVI-
Q2 Q3
BVI+
BV2-
BV2+ Q5
Q4
Q6
40 cm
80 cm
-200 m
-100
0
100
200
300
400
500
600
700
TIP-00278



Begin bypass outer branch
100
5
M = -1 Section
M = -1 Section
Transition region A
disp. suppr.
5 half cells -no bends
low-β
straight
3 half cells -no bends
disp. suppr.
disp. suppr.
half cell
√β x
√β y
√β (m 1/2)
η (m)
η x
η y
0
0
3600
4500
5400
Path Length (m)

Limit or Overview of Conventional Hadron Colliders

Luminosity

$$L = F\frac{k_b N_b^2 f_{rev}\gamma}{4\pi\varepsilon_n\beta^*}$$

k_b: number of bunches

N_b: number of protons / bunch

f_{rev}: revolution frequency

ε_n: normalized emittance

β^*: betafunction at the IP

F: reduction factor with crossing Φ

Beam physics limit

Space-charge limit in upstream accelerators:

$$\Delta\nu \propto N_b/\varepsilon_n \le 0.25$$

Beam-beam limit:

$$\xi = \frac{N_b r_0}{4\pi\varepsilon_n} \le 0.004 \text{ / IP (empirical)}$$

Cryogenetic limit

Synchrotron radiation limit:

$$P_{rad} \propto k_b N_b \le \text{a few watts / m}$$

Time resolution requirement from a detector

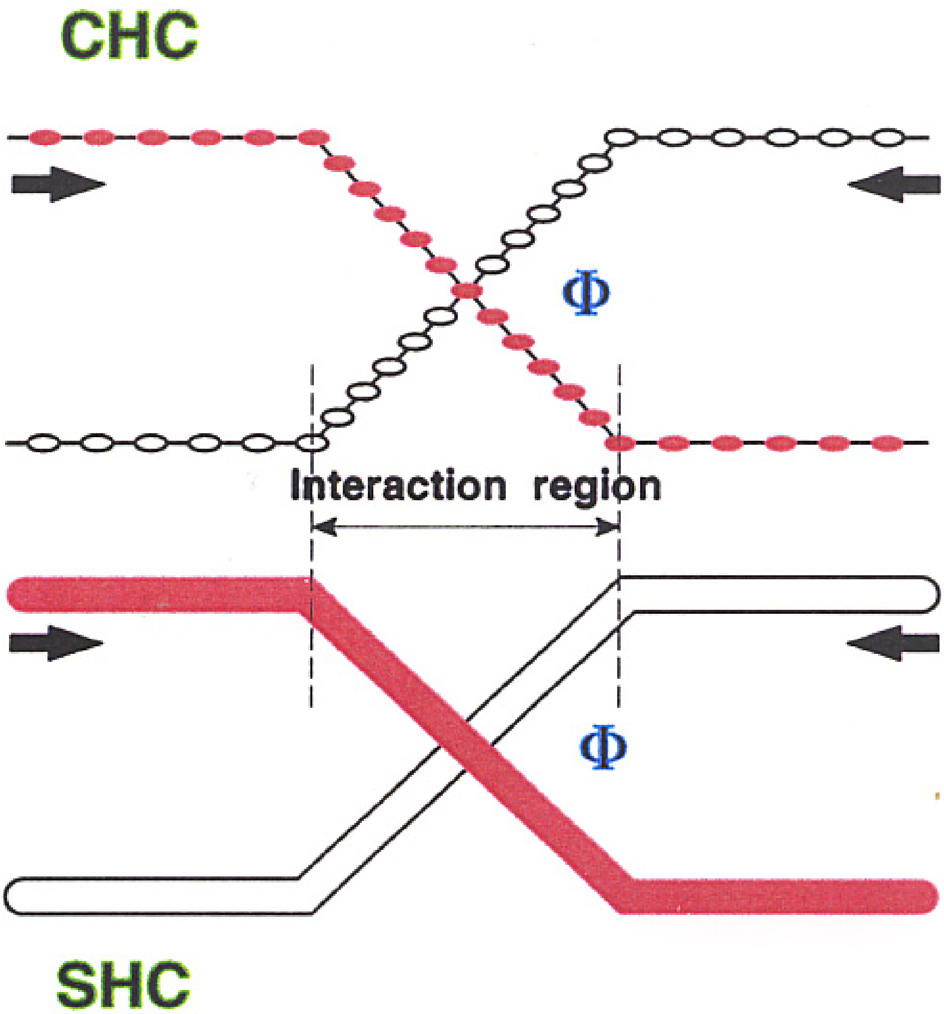
Bunch spacing limit: $d \ge 5m$

Beam occupation ratio

$$\kappa = \frac{\sqrt{2\pi}\sigma_s k_b}{C_0} \quad (\sigma_s\text{: rms bunch size})$$

$$= 2\% \text{ for LHC, } 1-3\% \text{ for VLHC}$$

Crossing with Angle

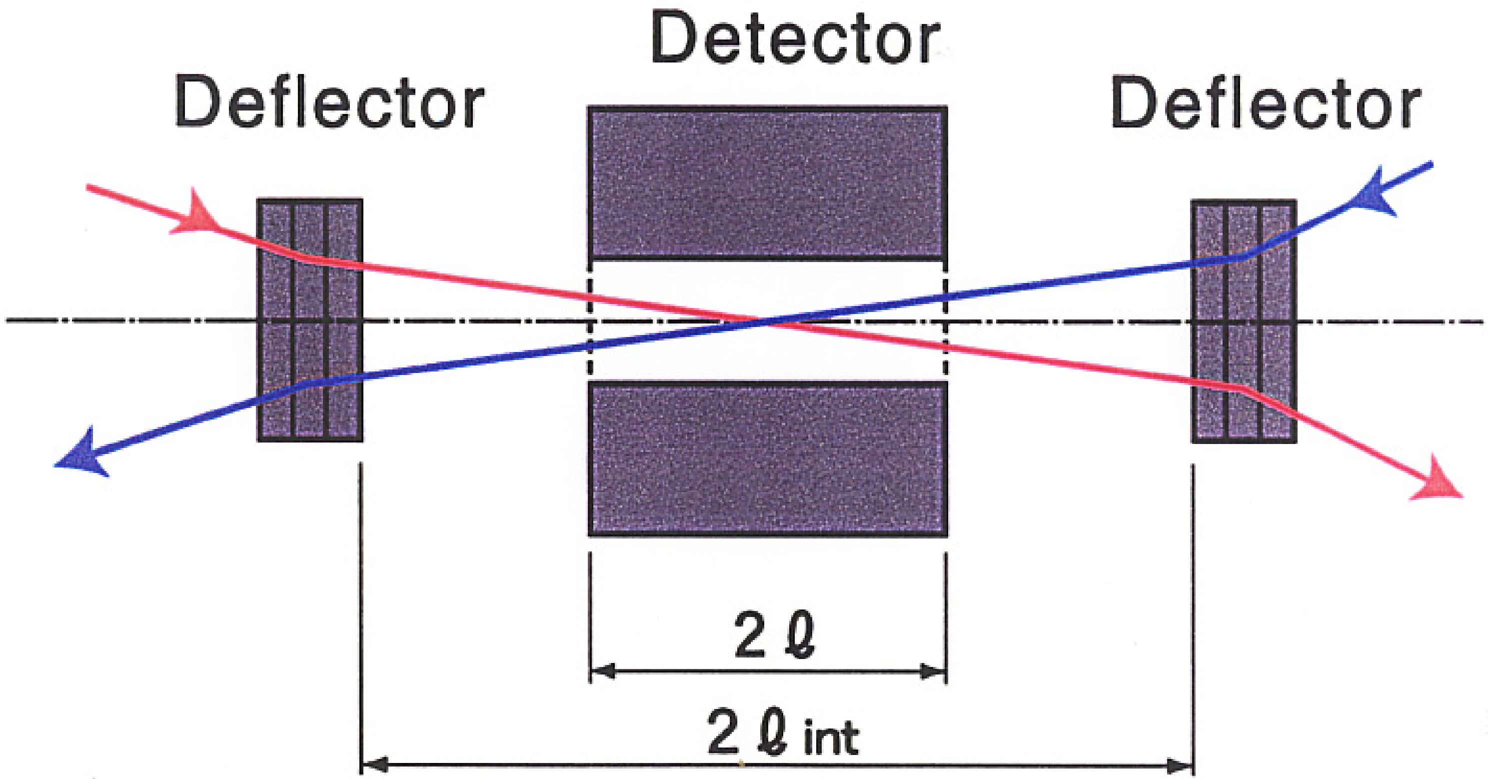


Big Questions

- How a long bunch (super-bunch) with the same local intensity as that of conventional hadron colliders (CHC) is generated?
- What happens in collision between such super-bunches?
- Which collision scheme is possible with super-bunches?
- What machine parameters are assumed?
- Obstacles can be overcome or not?

Preliminary results for case study at KEK and FNAL have been published in *Phy. Rev. Lett.* 88, 144801 (2002) and presented at Snowmass 2001 and at PAC2001. In addition, CERN has started their feasibility study as an upgrade plan of LHC in this early spring, where a low harmonic RF super-bunch is assumed. F.Zimmermann will describe about its details at this workshop.

INTERACTION REGION



Beam-beam tune shift in the SHC scheme

- **Beam-beam tune-shift can be analytically evaluated by manipulating the 0-th harmonics of the Fourier components in the beam-beam perturbation term.**
- **The tune-shift normalized by the tune-shift ξ in the head-on collision of the CHC scheme is given in the form,**

$$\frac{(\Delta\nu_x)_\Phi^{SHC}}{\xi} = \frac{8\beta^*\varepsilon_n}{\sigma_s'\gamma}\int_0^{l_{int}} \frac{1+s^2/(\beta^*)^2}{\Phi^2 s^2}\left[1-\exp\left(-\frac{\gamma\Phi^2 s^2}{2\varepsilon_n\beta^*\left(1+s^2/(\beta^*)^2\right)}\right)\right]ds \tag{1}$$

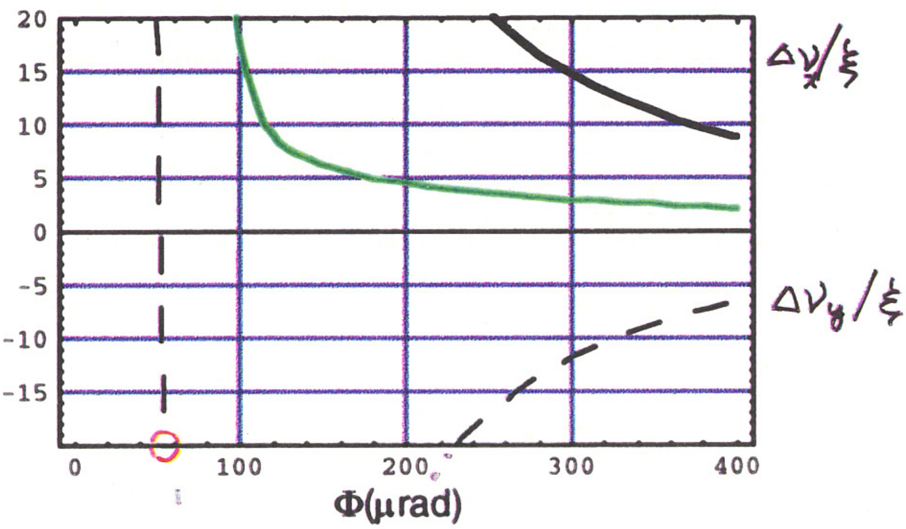
$$\frac{(\Delta\nu_y)_\Phi^{SHC}}{\xi} = \frac{8}{\sigma_s'}\int_0^{l_{int}} \exp\left(-\frac{\gamma\Phi^2 s^2}{2\varepsilon_n\beta^*\left(1+s^2/(\beta^*)^2\right)}\right)ds - \frac{(\Delta\nu_x)_\Phi^{SHC}}{\xi} \tag{2}$$

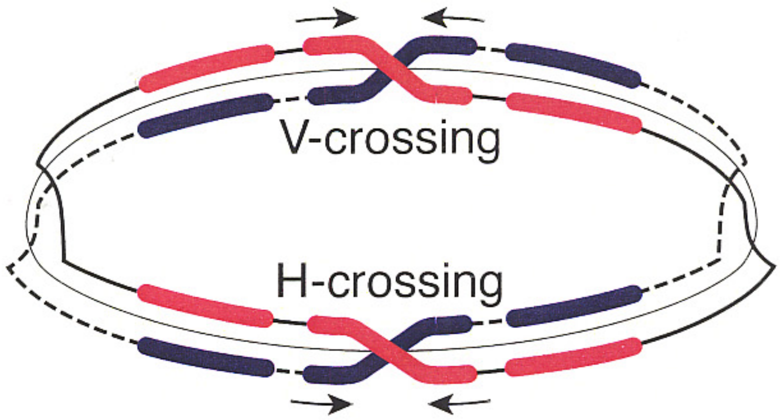
where crossing in the vertical direction is assumed and $2\ell_{int}$ is a size of the interaction region, $2l \langle\langle 2l_{int} \langle\langle \sigma_{sb}$.

- **In the limit of $\Phi = 0$, $2l_{int} = \sigma_s'/2$, Eqs. (1), (2) become unity.**

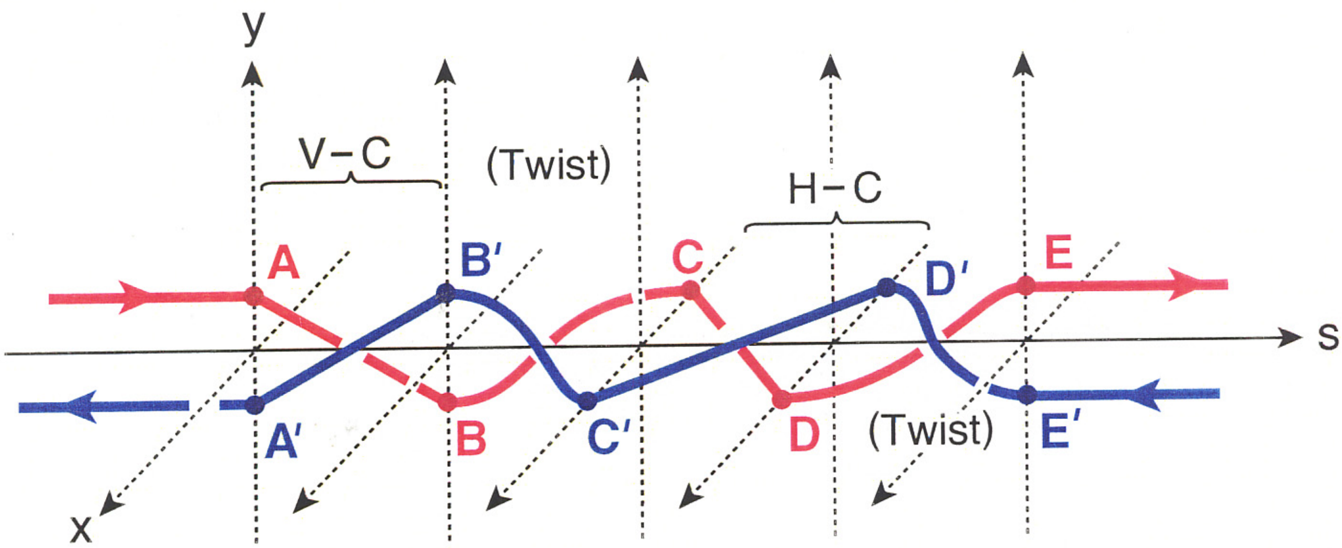
The numerical values for both directions are shown as functions of the crossing angle Φ below.

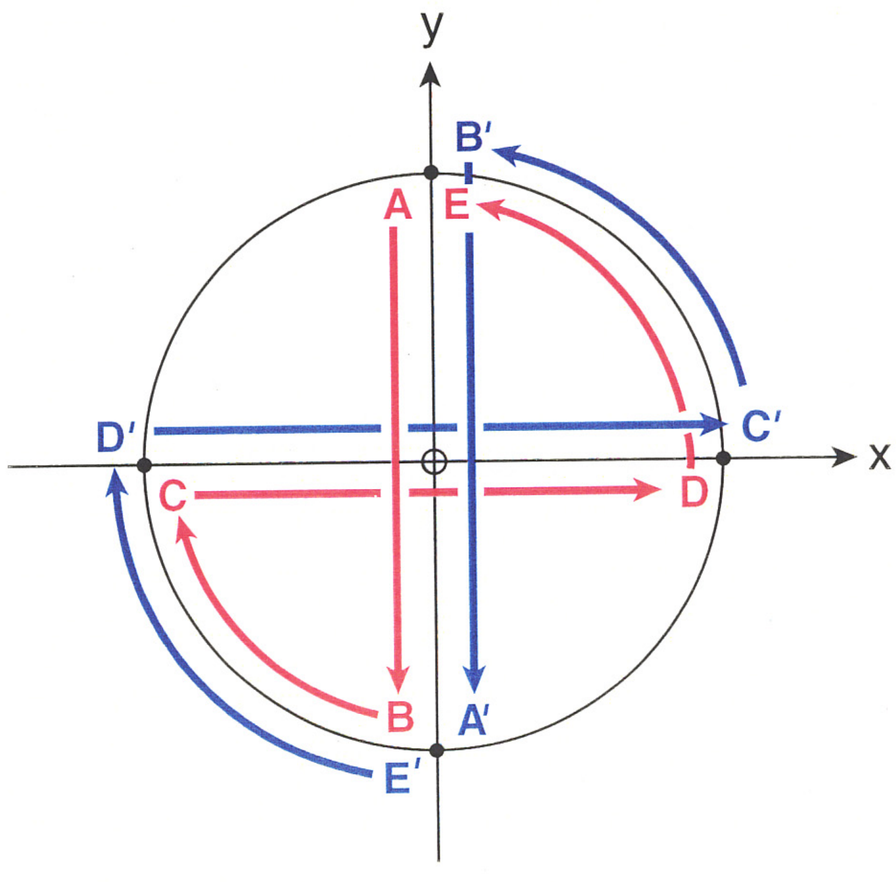
Black: horizontal, dash: vertical, green: sum



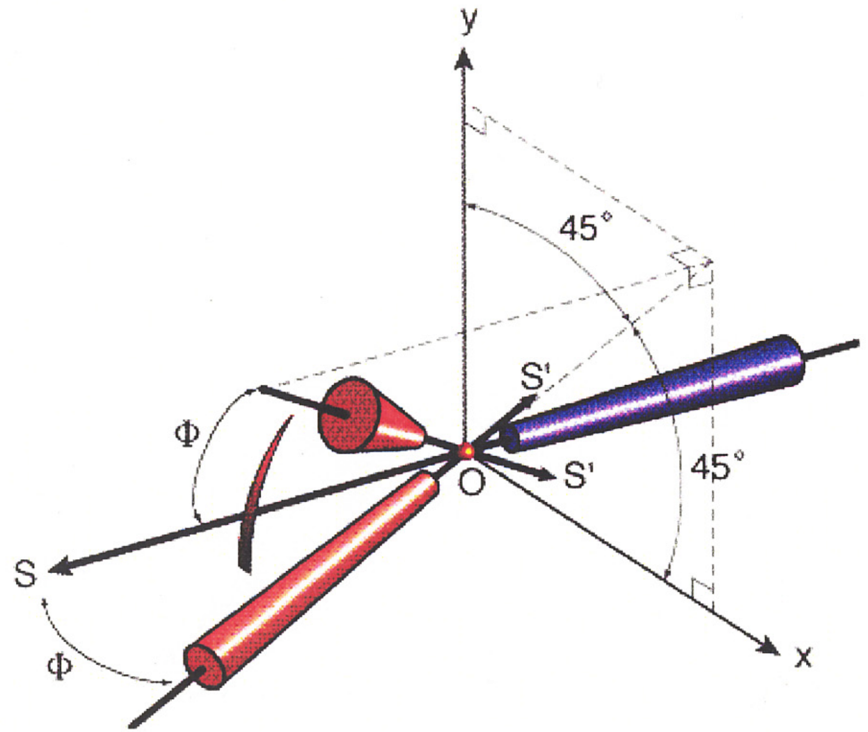

V-crossing
H-crossing

Hybrid Crossing (Mixed X−Y Crossing) in the same S.S.

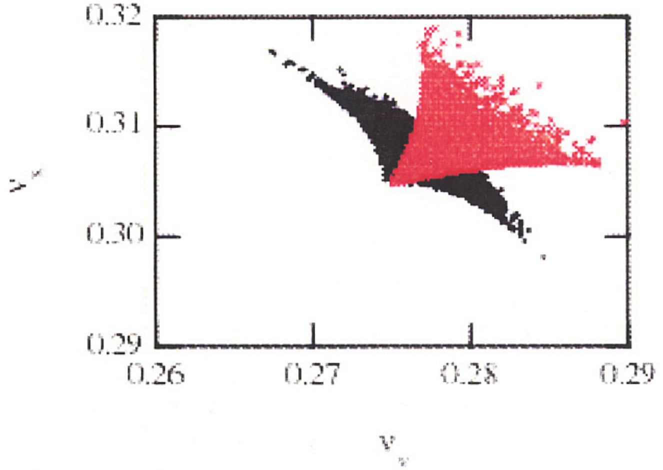




Inclined Crossing & Beam-beam Tune Spread



For a case of LHC



Black: Hybrid crossing
(Vertical cross at North IR and horizontal cross at South IR)
Red: Inclined hybrid crossing

Luminosity in the SHC

$$L_{SHC}(\Phi,\ell)=4\frac{(k_{sb}\sigma_{sb})}{(k_b\sigma_s^{'})}\frac{F_{SHC}(\Phi,\ell)}{\sigma_s^{'}F_{CHC}(\Phi^{'})}L_{CHC}(\Phi^{'})$$

where k_{sb}, k_b: number of superbunches, RF bunches per beam

σ_{sb}: superbunch length (full)

$\sigma_s^{'}=\sqrt{2\pi}\sigma_s$ (σ_s: rms RF bunch length)

$\Phi,\Phi^{'}$: collision angle for SHC and CHC

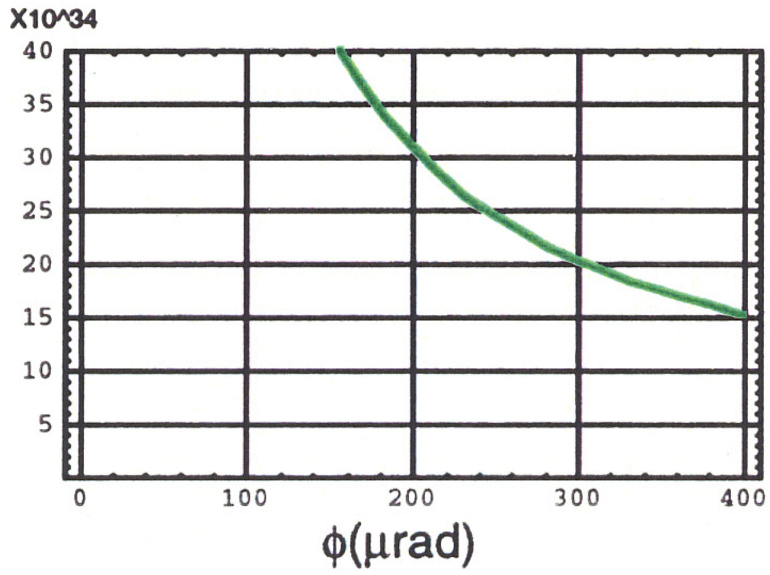
2ℓ: size of detector region

form factor:

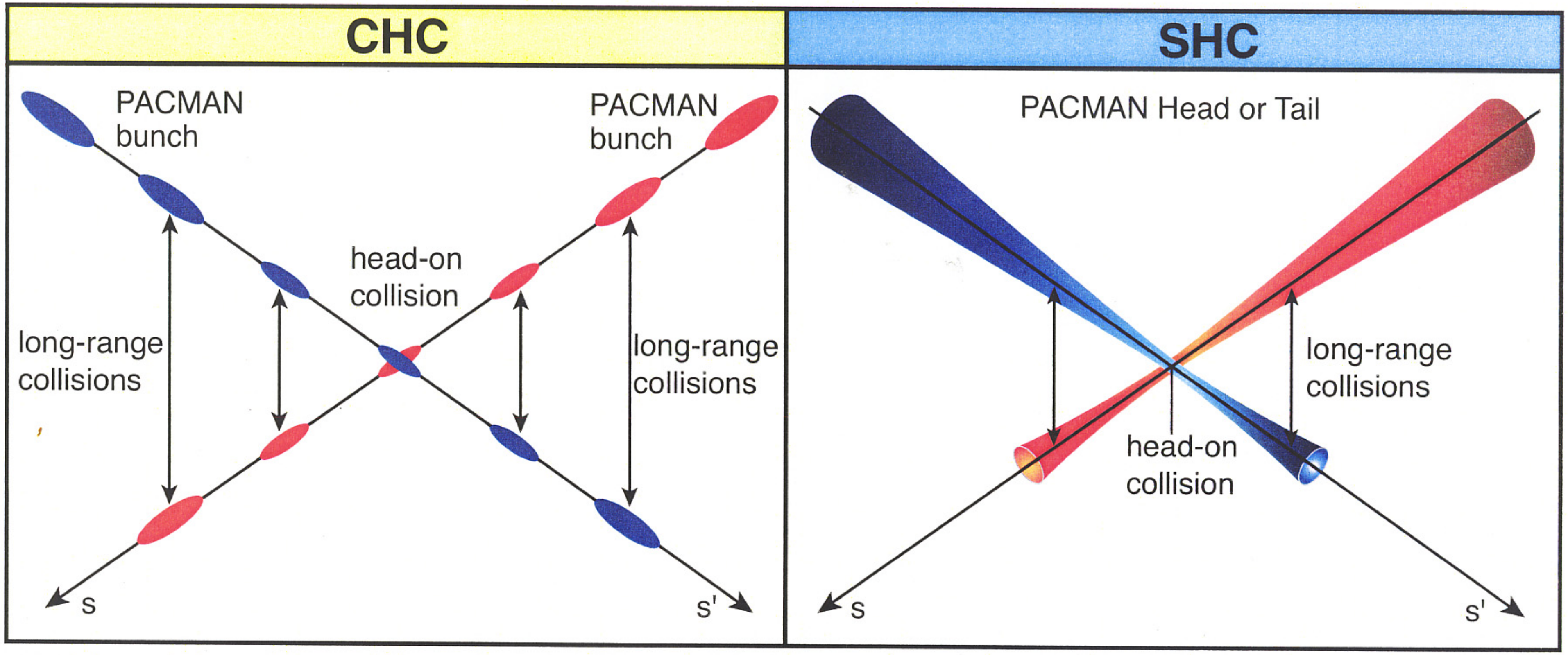
$$F_{CHC}(\Phi^{'})=1/\sqrt{1+(\Phi^{'}\sigma_s/2\sigma^{*})^2}$$

$$F_{SHC}(\Phi,\ell)=\int_0^{\ell}\frac{\exp\left(-\frac{\gamma\Phi^2 s^2}{2\beta^{*}\varepsilon_n\left[1+(s/\beta^{*})^2\right]}\right)}{\left[1+(s/\beta^{*})^2\right]}ds$$

LHC-size SHC ($2\ell=5m$)



PACMAN EFFECTS



Effect	CHC	SHC
Abnormal COD Abnormal Q_x, Q_y Abnormal β_x, β_y	yes	yes
Fraction of PACMAN bunches/particles	15/72 for LHC	mixed in the entire superbunch
Simulation work	done	not yet

Heat Load

Cooling capacity of a vacuum chamber embedded in the super-conducting magnet is limited. A few W/m. Heat load originated from circulating beams is serious problem.

Item	remarks	CHC	SHC
Synchrotron radiation	$P = 7.36 \times 10^{-21} \dfrac{N}{R(m)\rho^2(m)} \left(\dfrac{E}{mc^2}\right)^4$ simply proportional to *N*	200mW/m/ring for LHC	Significant for high luminosity operation
Joule-loss due to wall current	Heat power averaged over τ $\overline{P} = \dfrac{1}{\tau}\int_0^{\tau} dt \int_V \dfrac{\|i\|^2}{\sigma} dx^3$ τ: revolution time i: wall current σ: electric conductivity	70mW/m for LHC	Relatively small because of small magnitude of high frequency components in wall current
Electron cloud * pointed out and esimated by F.Zimmermann	Electrons accelerated in beam-charge potential or induced electric fields proportional to the fall-off in line density hit vacuum chamber	Serious because many short bunches place in the entire ring	much reduced quite few fall-off in line density

Summary

- The SHC scheme seems to be attractive as a possible candidate for LHC upgrade and the future VLHC with an extremely high luminosity.

- In order to convince the high-energy accelerator society of its capability, barrier bucket acceleration must be demonstrated in any existing accelerators as soon as possible.

- How to create a super-bunch by conventional RF and induction devices should be carefully exmined.

- Remained beam physics issues such as coherent beam-beam effects and collective instability of a super-bunch must be systematically studied.

- Advantageous and disadvantageous features of the inclined crossing scheme must be evaluated from a more technical point of view and experimental demonstration in a small e^-- e^- test-collider is remarkably desired.