RCSs for Low-Energy Injectors

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- **Basic Spec's and Requirements**
  - **???**
- **PSB Injectors:**
  - **Possible and Impossible Scenarios**
- **PS Replacement and SPS Injector :**
  - **ν-Factory Proton Driver Results**
- **Some Details of ν-Factory Booster**
- **2001 Cost Estimate of ν-Factory Booster**
- **Conclusions**

Basic Spec's and Requirements

BEAM	N_b	ε_h µm	ε_v µm	
LHC Nominal Beam	1.625 E12	2.5	2.5	
LHC Ultimate Beam	2.55 E12	2.5	2.5	
CNGS Beam for SPS	7.225 E12	11.5 20.7	4.6 7.6	1% loss 5% in PS
(HIE) ISOLDE	~1.2 E13	~21	~7	Required: 10 kW Beam

Limits to Intensity and Brilliance $\frac{N_b}{\varepsilon_n}$

Laslett Tune Shift:

$$\Delta Q_{s.c.} = -\frac{N_b}{\varepsilon_n} \frac{r_p}{\pi \; \beta\gamma^2} \frac{F\,G\,H}{B_b}$$

N_b…p/bunch
F …Image Factor ~1
G …Distribution Factor (transverse)
Gaussian =2, uniform =1 (for $\varepsilon(2\sigma)$)

H …Aspect Ratio Factor
LHC = 0.5, CNGS h,v ~ 0.4, 0.6
B_b…Bunching Factor,
aver./peak line density of single bunch
β, γ …Lorentz Factors

PSB Laslett Tune Shifts at 50 MeV
(calculated)

BEAM	Δ_h	Δ_v	H_h	H_v	G optimistic!
LHC Nominal Beam	- 0.28	0.28	0.5	0.5	1.5
LHC Ultimate Beam	- 0.43	- 0.44	0.5	0.5	1.5
CNGS Beam 1% loss	- 0.28	- 0.44	0.4	0.6	1.25
5% loss	- 0.16	- 0.26	0.38	0.42	
(HIE) ISOLDE	-0.27	-0.51			1.25

PSB Tune Shift Limits ~:

-0.28, -0.53

<-0.5 @ 160 MeV?

G…Distribution Factor
Gaussian =2, uniform =1

H…Aspect Ratio Factor
LHC = 0.5, CNGS Hh,Hv ~ 0.4, 0.6

B_b…Bunching Factor **~0.6 at dB/dt~0.4 T/s**

Injectors for the PSB :

Alternatives to Linac4 to double Intensity and brilliance of the PSB beam?

Wanted Factor 2: $$\frac{\beta\gamma^2(160MeV)}{\beta\gamma^2(50MeV)} = 2.04$$

- **Using Linac2**
  1. RCS 50 - 160 MeV (synchrotrons less expensive than linacs ?)
  2. FFAG 50 - 160 MeV
  3. Increasing Linac2 and PSB rep rate → ~2 Hz

- **Using Linac4 DTL (40 MeV)**
  4. Synchrotron
  5. FFAG

All Scenarios but #3 fill one PSB ring with 2 bunches !

Requires merging 2 b → 1 b later in the cycle!

Limits due to RF Voltage Requirements

$$\hat{V}_{RF}\sin(\varphi_s) = C\,\dot{B}\,\rho$$

C …Machine circumference
φ_s …stable phase angle

Assume:
f_{rep} =50 Hz for an RCS 50 - 160 MeV;
T_{rise}/T_{fall} = 3/1; R = 4m; ρ =1 .9m, B = 0.54 – 1 T,

Obtain for RCS:
for frep =50 Hz, Trise = 15 ms (lin.),
$V_{RF,p}\sin\varphi_s$ = 1.67 kV, for φ_s =45 deg, $V_{RF,p}$ = 2.4 kV

Obtain for FFAG - limited by total (low-Q-)RFC Voltage, e.g. for $V_{RF,p}$ = 30 kV, φ_s =45 deg: T_{rise} = 1.2ms

For 8 PSB Bunches (4 Rings , one needs

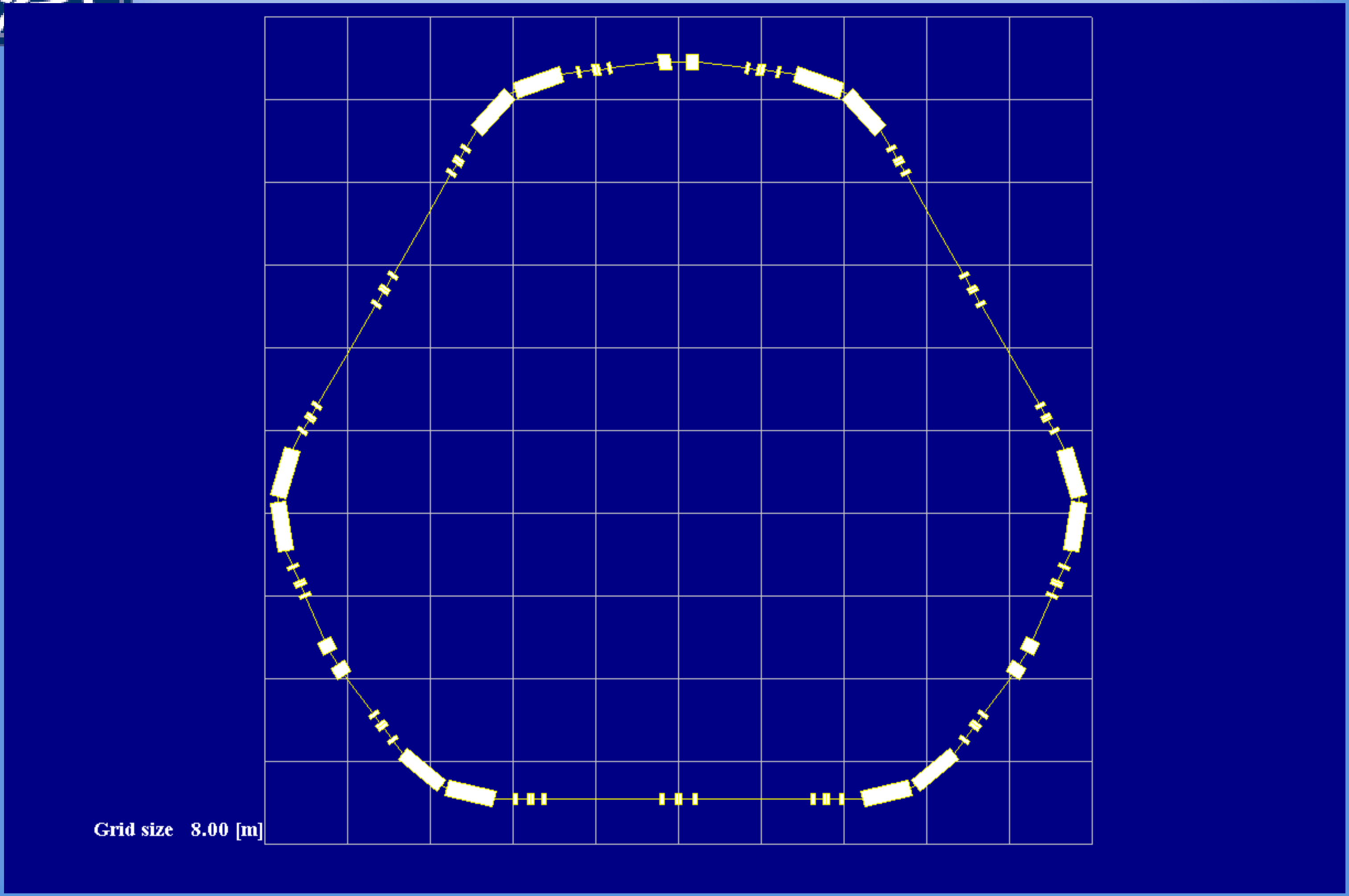
- **RCS: a 50 Hz Linac or a pulse of length: 7 × T_{rep} = 140 ms…**
- **FFAG: a pulse of length: 7 × T_{rise} = 8.4 ms (+ 8 × 50 µs injection)**

Injector for SPS > γt , replacing CPS
and
2.2 GeV/50 Hz / 0.44 MW Booster

- **Injector for SPS > γ_t , replacing CPS :**
  2.2 GeV/50 Hz / 0.44 MW Booster from CERN RCS
  ν-Factory Scenario

- **3 GeV/25 Hz Boosters from RAL 15 GeV ν-Factory Scenario**

2.2 GeV Booster Lattice
(Stretched Austron RCS Lattice)



2.2 GeV Booster for the SPS

Parameter	Unit	Injection	Extraction
Kinetic Energy	GeV	0.16	2.2
β		0.52	0.95
γ		1.17	3.34
Pulse frequency	Hz	50	
Pulse duration	μ s		0.64
Beam			
Number of bunches		2	
Bunch intensity	p/bunch	1.25E+13	
Number of injected turns		100	
Ring physical emittance (σ)	π mm mrad	35 x 13	16
Ring normalised emittance (σ)	π mm mrad	21 x 7.5	
Longitudinal Emittance	eV s		
Space Charge detuning	-ΔQy	0.3	
Machine			
Mean radius	m	34.375	
Main dipole bending radius	m	16.88	
Main dipole magnetic field	T	0.16	0.89
γ-transition		4.1	
Qx, Qy		4.27, 5.3	
RF			
RF peak voltage	MV	0.07	0.3
Harmonic number		2	
RF frequency	MHz	1.32	2.43
Synchrotron Frequency	Hz	4130	680

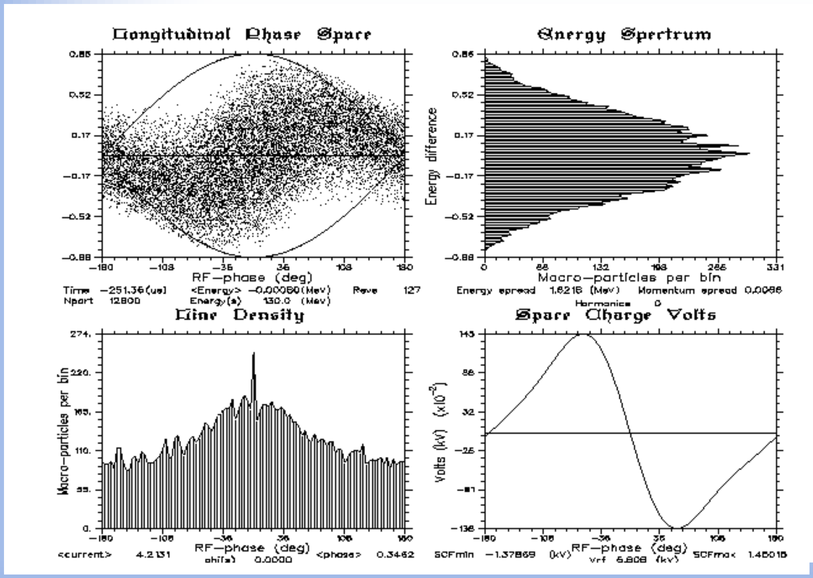
2.2 GeV Booster for a CERN ν-Factory

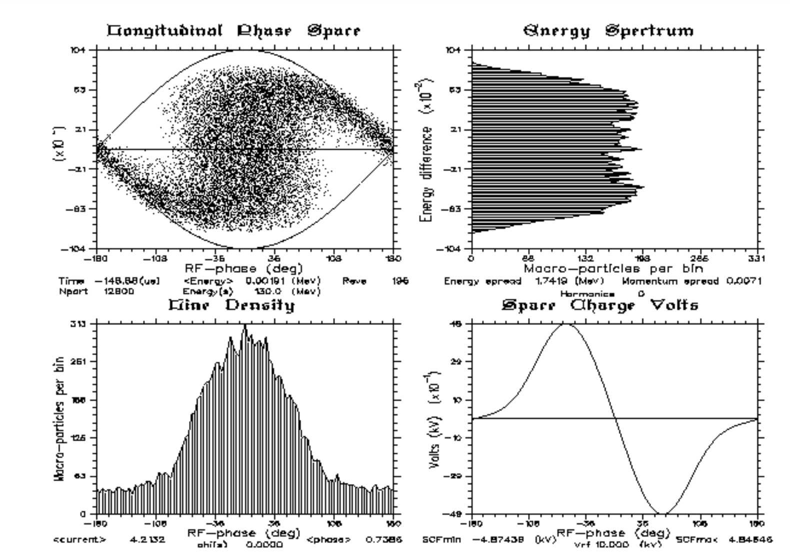
Parameter	Unit	Injection	Extraction
Kinetic Energy	GeV	0.18	2.2
β		0.51	0.95
γ		1.16	3.34
Pulse frequency	Hz	50	
Pulse duration	μ s		0.64
Beam			
Number of bunches		2	
Bunch intensity	p/bunch	1.25E+13	
Number of injected turns		100	
Ring physical emittance (2σ)	π mm mrad	230	47
Ring normalised emittance (2σ)	π mm mrad	150	
Longitudinal Emittance	eV s		2
Space Charge detuning	-ΔQy	0.18	
Machine			
Mean radius	m	37.5	
Main dipole bending radius	m	16.88	
Main dipole magnetic field	T	0.16	0.89
γ-transition		4.1	
Qx, Qy		4.27, 5.3	
RF			
RF peak voltage	MV	0.07	0.3
Harmonic number		2	
RF frequency	MHz	1.29	2.43
Synchrotron Frequency	Hz	4130	680

Specific Challenges of the RCS’s

- RF capture during injection into booster accelerating bucket: no time for truly adiabatic capture $\rightarrow$ critical voltage program, cf. Slide “Quasi-adiabatic capture in RCS”
- Some capture loss may be inevitable $\rightarrow$higher injection energies unfavorable
- Very large RF voltages required; Limited SS space for RFC’s in dispersion-free regions

Quasi-Adiabatic Trapping into a Rapidly Cycling Synchrotron at 150 MeV (0.5 MW/50 Hz AUSTRON III)





Early Trapping: RF Voltage limited to preserve capture efficiency

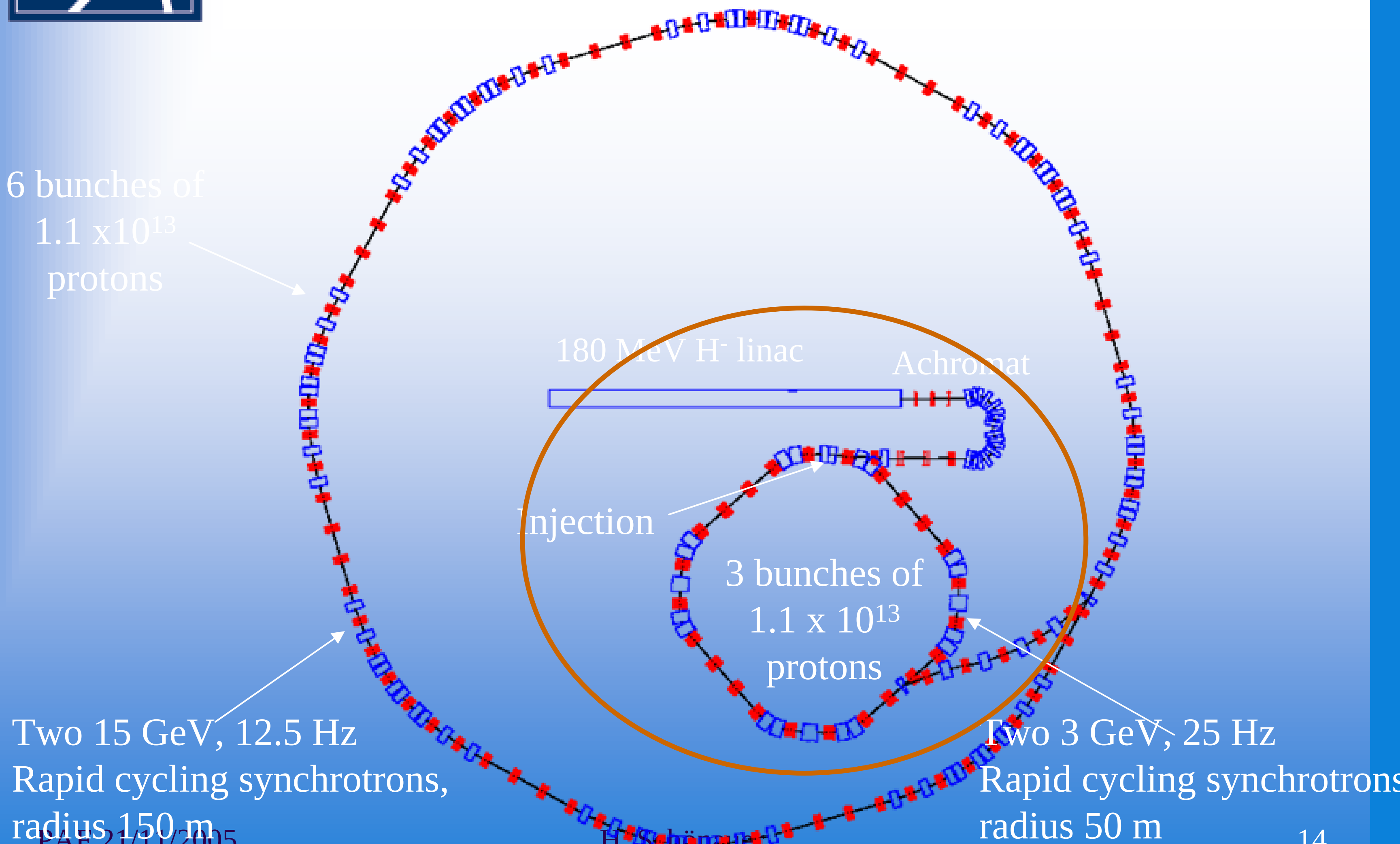
RF Voltage increase can begin only after 1/4 rotation !

A careful tracking study is always necessary to achieve loss-less capture at least in simulation !

Cost Estimate of 2.2 GeV / 50 Hz Booster for the CERN RCS scenarios

RCS 1: Booster		TRIUMF Estimates incl. Manpower		Source
		Sassowsky	Rees	
Magnets	Dipoles	10677	8571	
	Quadrupoles	15068	8153	
	Correctors			
Vacuum Syst	Magnet Ch.	2,402		P.Strubin
	Drift Ch.	499		
	Ion pumps	100		
	Bellows	95		1.33 = fall(B Ring)/fall(NFB)
Power Supplies	Dipoles	5,228		1.33*TRIUMF*Wstored/Wstored(TRIUMF) +15%
	Quadrupoles	2,295		1.33*TRIUMF +15%
	Filters	1,984		1.33*TRIUMF*Wstored/Wstored(TRIUMF) +15%
180 MeV Line		7271		
Injection System		3000		
Kickers		4,174		TRIUMF + 15%
RF Systems		16,000		16 RFC Systems 22.5 kV 1 MCHF each
Beam Diagnostics		1,390		TRIUMF+15%
Engineering, Design		1,531		TRIUMF+20%
Septum Magnets		302		TRIUMF+20%
Collimation		289		ESS/4 +30%
880 J Beam Dump		20		TRIUMF+30%
Alignment & Survey		53		TRIUMF+15%
Civil Engineering		8,036		TRIUMF*circ.ratio +15%
Total So Far:		80,413	71,392	
Contingency 8.9%	(Same as SPL)	7,151	6,354	
TOTAL	kCHF	**87,570**	**77,746**	

RAL 15GeV, 25 Hz, 4MW Proton Driver

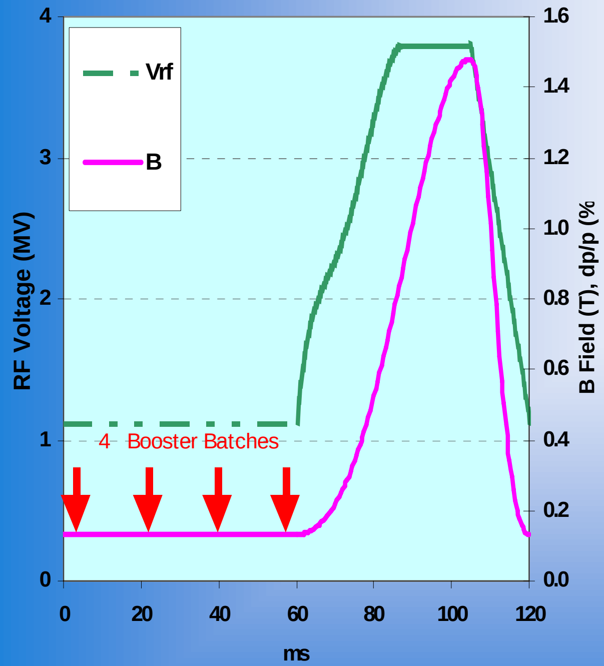


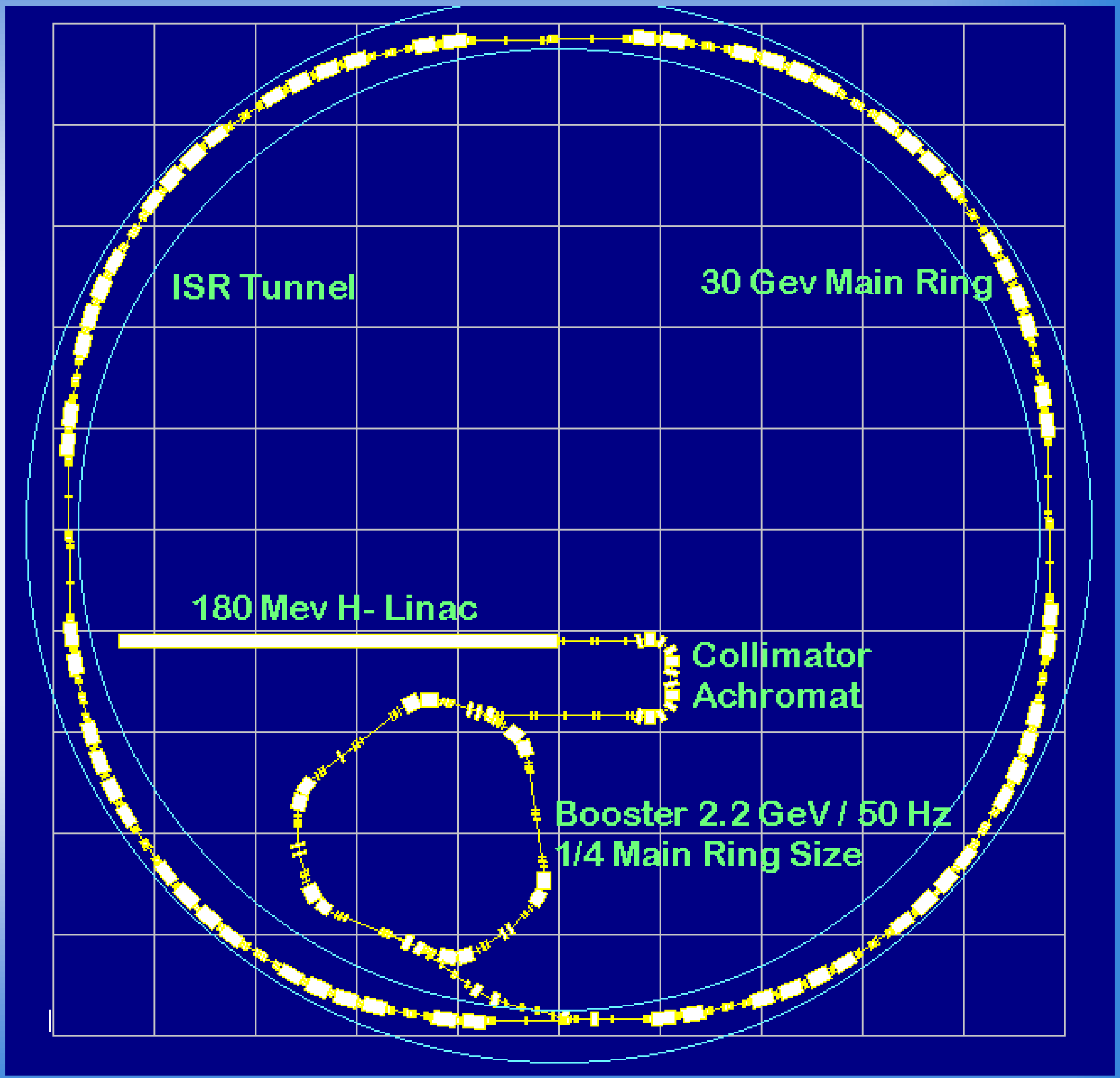
Conclusions :

- Doubling PSB Intensity/Brilliance by rising Injection Energy to 160 MeV:
  - RCS : Impossible with Linac2 @ <2Hz
  - FFAG: Appears possible at the expense of high RF Voltage, if Linac2 can stretch its pulse to ~ 8ms
- Linac2 + PSB @ ~ 2 Hz : Bunch merging 2 into 1 in CPS
- RCS + Linac4 DTL 40 MeV @ 50 Hz
- >2 GeV RCS to be studied in context of CPS replacement

RCS Driver Layout

Main Ring Cycle

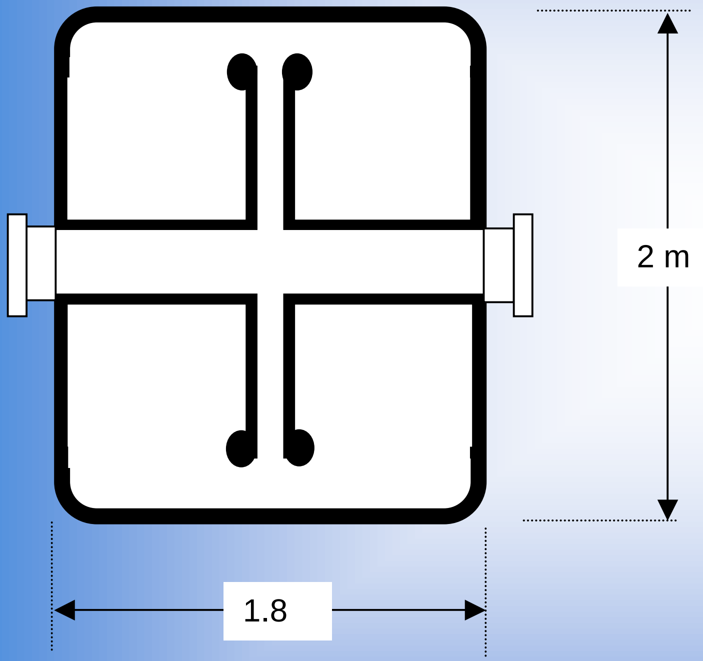




30 GeV / 8 Hz Main Ring

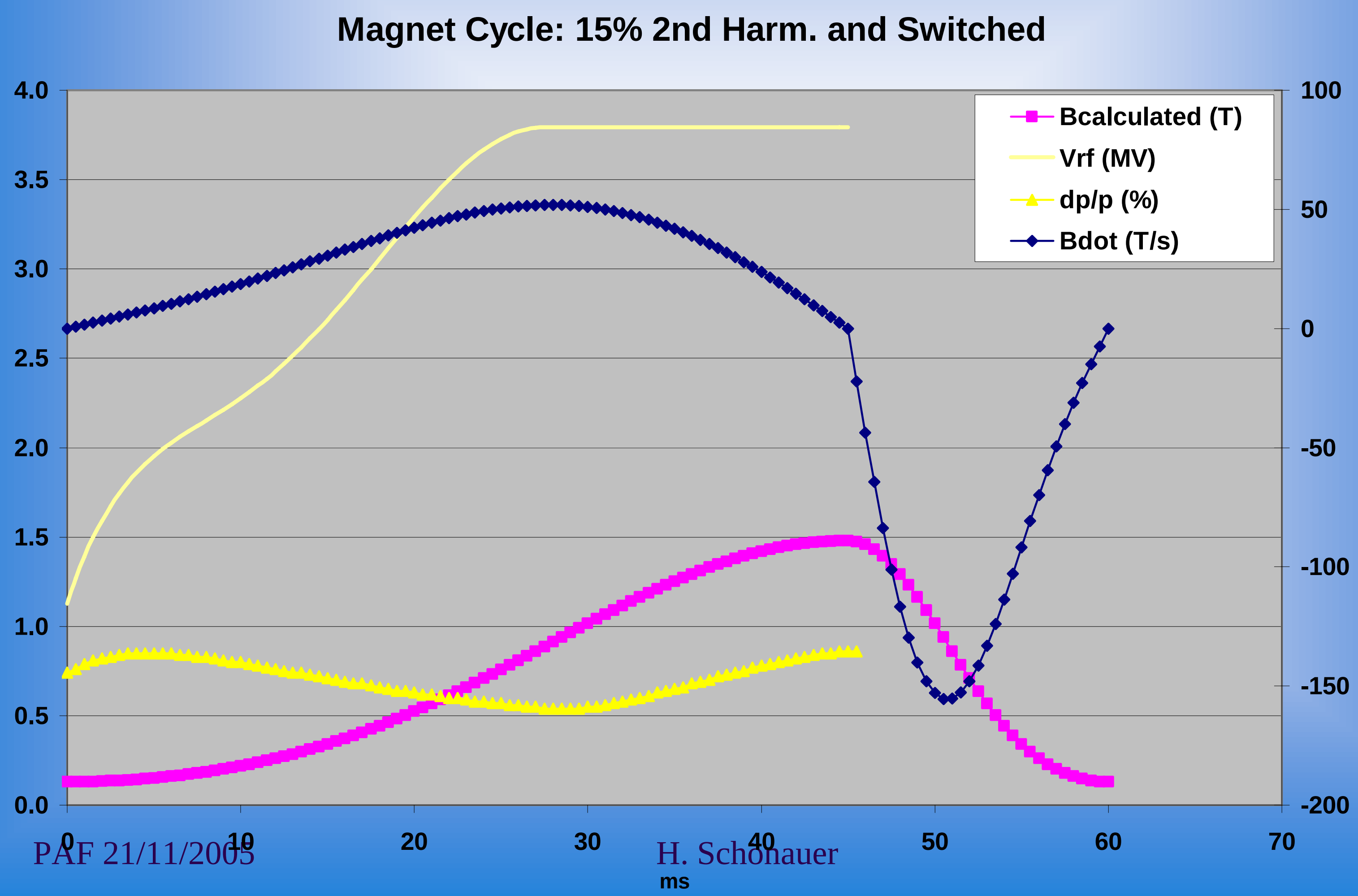
Parameter	Unit	Injection	Extraction
Kinetic Energy	GeV	2.2	30
β		0.95	1.00
γ		3.34	32.97
βγ		3.19	32.96
Pulse frequency	Hz	8.33	
Beam			
Number of bunches		8	
Bunch intensity	p/bunch	1.25E+13	
Ring physical emittance (2σ)	π mm mrad	47	4.6
Ring normalised emittance (2σ)	π mm mrad	150	
Space Charge detuning	-ΔQy	0.20	
Longitudinal Emittance	eV s	2	2.4
Bunch Length (rms)	n s		1.2
Bunch Length (full)	n s	67	5
Momentum spread		0.008	0.01
Machine			
Mean radius	m	150	
Main dipole bending radius	m	67.5	
Main dipole magnetic field	T	0.15	1.53
γ-transition		40 (45)	
Qx, Qy		14.2, 10.3 (19.3, 14.8)	
RF			
RF peak voltage	MV	1.5	3.5
Harmonic number		32	
RF frequency	MHz	9.71	10.17
Synchrotron Frequency	Hz	3039	141

W. PIRKL'S DESIGN for RF CAVITY 10 MHZ for the 30 Gev / 8 Hz RCS



Voltage > 100 kV
R/Q = 42 ohms
Q ~ 5000 - 10000
(depending on ferrite fine tuner)
Tuning range: 9.65 - 10.2 MHz
(external mechanical vibrators)
3" cables to tuner
(vibrator BW 13 kHz)

A 2nd harmonic has been added to the sinusoidal magnet cycle to smooth the motion and the forces on the tuning vibrator.



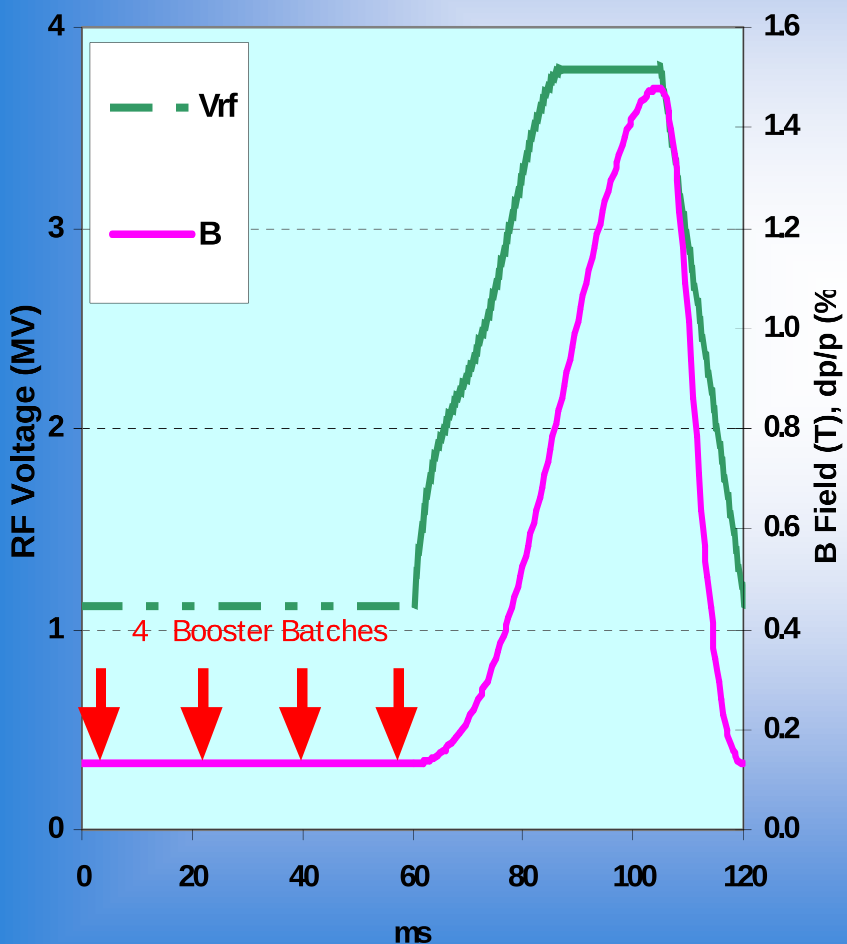
Availability of dispersion-free long straight sections in the 30 GeV Lattices

GHR30	Length (m)	# of WP RFC's	RF Voltage (kV)
O5 + O2 + O64	8	3	> 300
2*(O5 + O2 + O63)	2 * 6.5	2 * 3	> 600
Total per SP	23	9	> 900

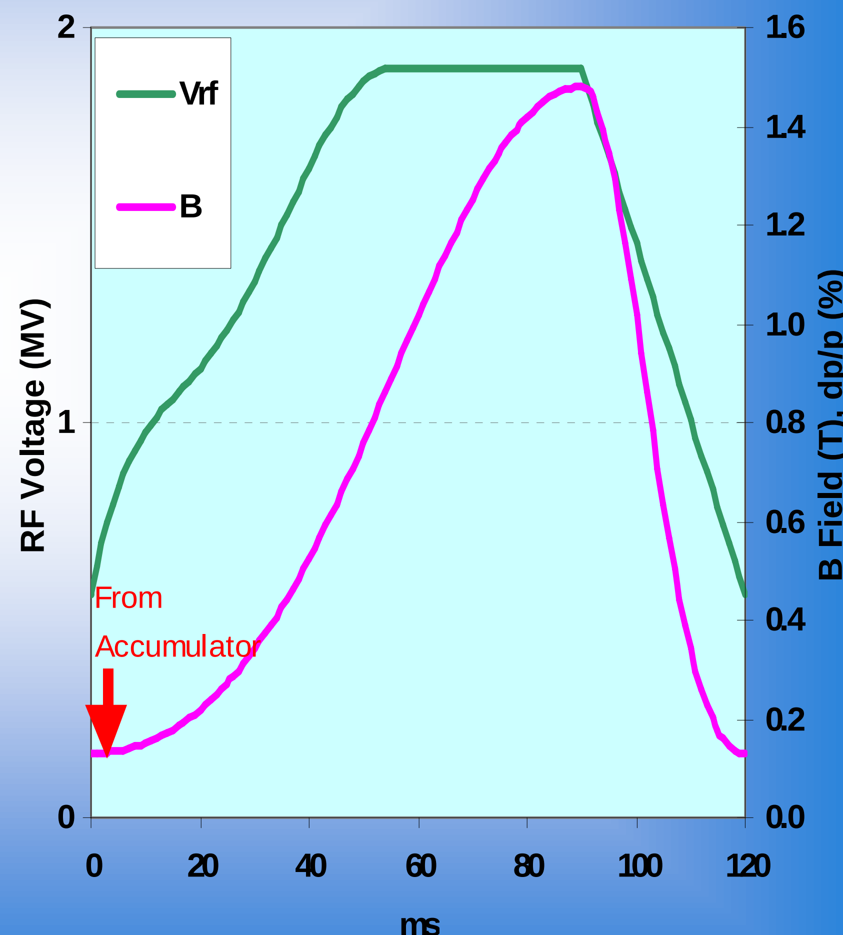
NF952	Length (m)	# of WP RFC's	RF Voltage (kV)
2*S2	2 * 9	2 * 4	> 800
2* S3	2 * 10	2 * 4	> 800
Total per SP	23	16	> 1600

The SPL + 30 GeV RCS Scenario

RCS Scenario



SPL + RCS Scenario



Specific Challenges and Problems of the 30 GeV RCS

- Enormous stored energy in the large magnets: 300 kJ in each of the 64 main dipoles of the NF952 lattice.
- Consequence: Very expensive resonant PS or even more expensive IGBT groups
- Long holding time on flat bottom of main synchr. $\rightarrow$ coupled bunch instabilities
- All resonators need to be damped; difficult for HOM in accelerating cavities;
- 30 GeV adiabatic compression: Low f_{sy} =140 Hz at end of cycle. Nevertheless natural bunch length of 1 ns rms is achieved.
- High Q resonators up to 200 MHz may cause loss.
- Tight Impedance budget: Z/jn <2 ohms critical
- Large shielded ceramic chambers or alternatives

Cost Estimate of 25-30 GeV / 8 Hz Drivers for the CERN RCS scenario

RCS 2: Driver	kCHF					
		NF952		GHR25		
		Sassowsky	GHR	Sassowsky	GHR	
Magnets	Dipoles	34942	62562	31501	48539	
	Quadrupoles	27330	11004	35892	31995	
Vacuum Syst	Magnet Ch.	9,540		11473		P.Strubin
	Drift Ch.	1,421		820		
	Ion pumps	400		400		
	Bellows	288		414		1.67 = fall(D Ring)/fall(RCS2)
Power Supplies	Dipoles	54,759				.67*TRIUMf*Wstored/Wstored(D Ring) +15%
	Quadrupoles	9,665				1.67*TRIUMF * 2 (4 types) +15%
	Filters	22,456				1.67*TRIUM*Wstored/Wstored(D Ring) +15%
Kickers		5,383				TRIUMF+15%
RF Systems		22,000				22 RFC Systems 1 MCHF each
Beam Diagmostics		4,970				TRIUMF+15%
Engineering, Design		3,808				TRIUMF+20%
Septum Magnets		508				TRIUMF+20%
Collimation		578				ESS/2 +30%
0.5 MJ Dump		4,619				ESS/2 +20%
Alignment & Survey		499				TRIUMF+15%
Tunnel Repair & Upgrade		10,000				
Total So Far:		213,165		219,744		
Contingency 8.9%	(Same as SPL)	18,972		19,557		
TOTAL	kCHF	**232,137**		**239,301**		

RCS Scenario

RCS Scenario	
	MCHF
Linac (RAL 180 MeV)	**110**
Booster RCS	**88**
Driver	**233**
TOTAL	**431**

Appendix: Cost Estimate and Power Requirements of RCS Main Magnets

25 GeV Lattice(G.Rees) γ_t=30			
Cost	kCHF	Power	MW
TOTAL Bendings	**31501**	TOTAL Bendings	**6.4**
TOTAL Quads	**35892**	TOTAL Quads	**0.68**
TOTAL Magnets	**67393**	**TOTAL Magnets**	**7.1**

30 GeV Lattice (Y. Senichev) γ_t=40			
Cost	kCHF	Power	MW
TOTAL Bendings	**34942**	TOTAL Bendings	**9.2**
TOTAL Quads	**27330**	TOTAL Quads	**0.4**
TOTAL Magnets	**62272**	**TOTAL Magnets**	**9.6**