Mandate for the Neutrino Factory Working Group for Accelerator Aspects

1. This Working Group (WG) is supposed to study the accelerator aspects of a possible Neutrino Factory at CERN. Guided by the results of the recent prospective ECFA Study on muon colliders, the means to reach the most important physics goals should be examined together with the Research Sector and, possibly, in collaboration with interested Laboratories and Institutes in Europe. The WG keeps in appropriate contact with our colleagues in the US working in the same topic.

2. The options to be examined comprise -- direct neutrino production from pi, K decay -- neutrino production from muons circulating in a storage ring (Koshkarev 1974, Geer 1998) -- appropriate proton drivers (fast-cycling synchrotrons, linac using copper or superconducting cavities) -- targetry, collection and, possibly, acceleration of secondary particles

3. A few scenarii should be established ranging from simpler, less costly ones to the more complex ones with wider reach in physics. The feasibility of these options should be studied and the most relevant R&D should be defined including the required resources. Particular attention should be given to the possible use and upgrade of existing facilities/hardware, provided the performance is not unduly compromised. Simple upgrades of the NGS Facility will be treated in the CERN-INFN Technical Committee.

4. A clear orientation of the study should be established in a few months guided by the findings of the Neutrino Factory Workshop in July so that a brief intermediate internal progress report could be prepared for September 1999. A more detailed progress report is expected for March 2000.

5. The Working Group is lead by H.Haseroth/PS. The presently known Members of the Working Group are listed in the Annex I. It is expected that further members will be coopted especially when the present projects of the PS Division (Upgrade of the proton injector chain for LHC and AD) have made significant progress.

6. The mandate is valid until March 2000 when a new or modified mandate will be discussed with the new PS management.

K.Hubner and D.J.Simon

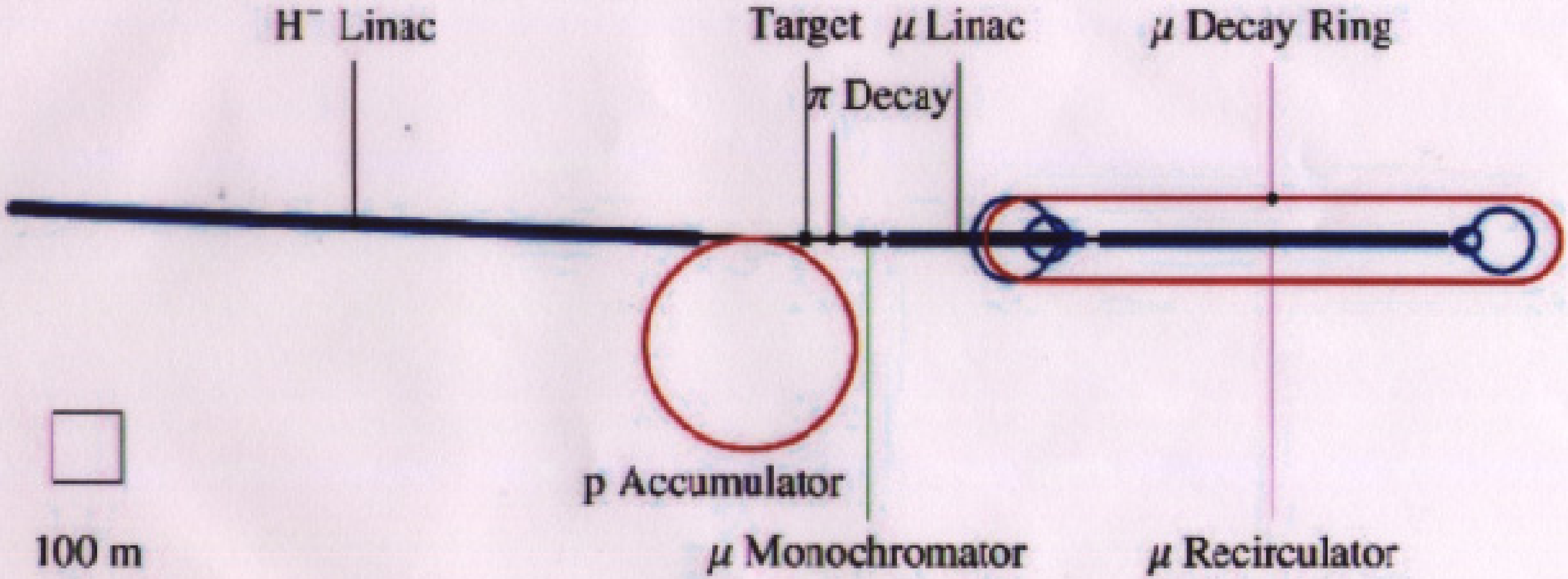
Annex I

Members of the Accelerator Working Group (Draft list)
Status 25.4.1999

PS H.Haseroth (Study leader)
R.Garoby (convenor linac)
H.Schonauer (convenor synchrotrons)
A.Lombardi (secretary) *
B.Autin
C.Johnson

SL O.Bruening*
J.Gareyte
M.Lamont
E.Keil
AC E.J.N.Wilson
ST to be announced, coopted when necessary
TIS M.Silari

ν Factory


H⁻ Linac
Target
μ Linac
π Decay
μ Decay Ring
p Accumulator
100 m
μ Monochromator
μ Recirculator

1. Why and how ?

1.1 High intensity beams at CERN

- **Planned uses of high intensity proton beams**

  and interesting directions of improvement :

  - LHC: increased beam brightness at injection
  - CERN Neutrinos to Gran Sasso (CNGS): higher proton flux*
  - Anti-proton Decelerator: idem*
  - Neutrons Time Of Flight (TOF) experiments: idem*
  - ISOLDE: idem*

- **Potential uses of high intensity proton beams:**
  - Fixed target Physics with low to medium energy muons and neutrinos
  - “Neutrinos Factory” based on a muon storage ring
  - “Muons Collider”

2. Present ideas for an SPL

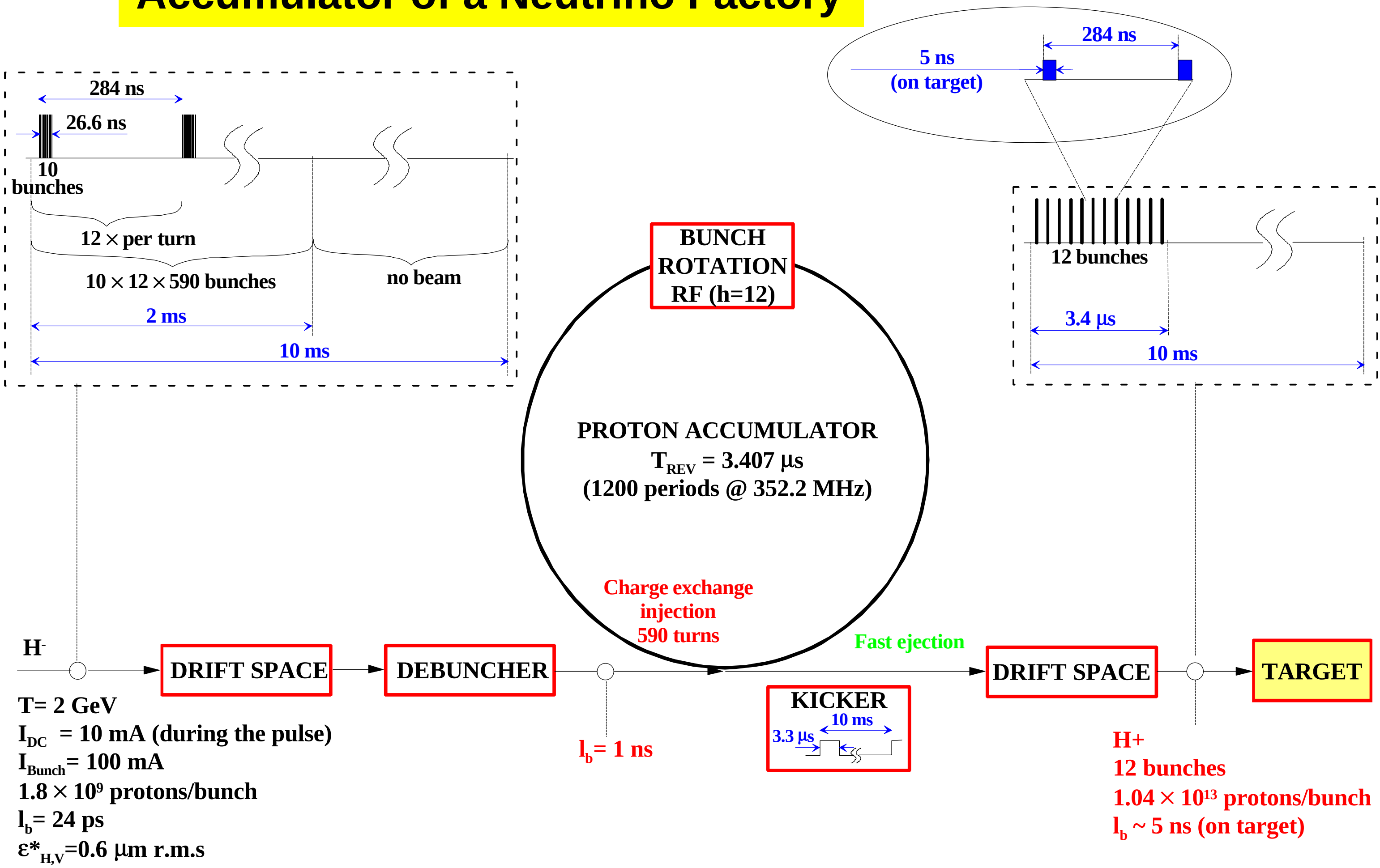
2.1 Beam specifications

[After NuFact'99]

Particle type	**H^-**	
Energy (kinetic)	**2**	**GeV**
Mean Current	**10**	**mA**
Duty Cycle (2ms pulse / 10 ms)	**20**	**%**
Beam Power	**4**	**MW**
Transverse Emittance (rms norm.)	**0.6**	**μm**
Longitudinal Emittance (total)	**80**	**μeVs**
Bunch Length (total)	**24**	**ps**
Bunch Current	**100**	**mA**
Beam time structure (within pulse)	**Flexible**	**!**

2.1 Beam specifications

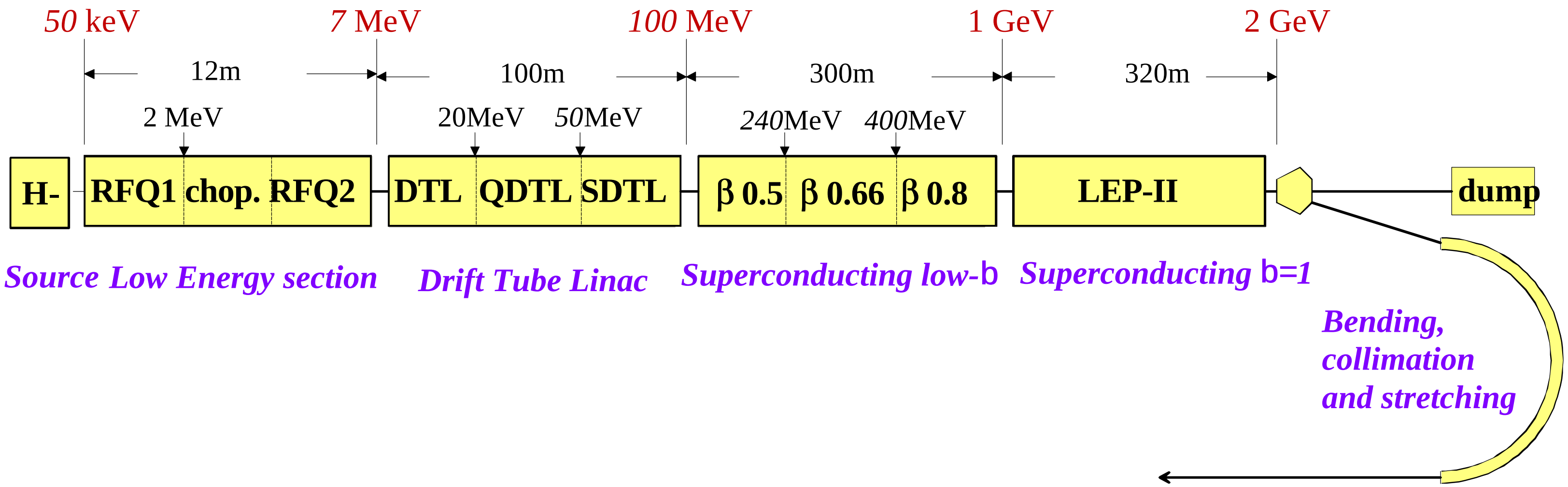
Filling scheme for the Accumulator of a Neutrino Factory



2. Present ideas for an SPL

2.2 Outline of the Accelerator

Preliminary SPL layout



2.2 Outline of the Accelerator

Basic Sections Parameters

Section	Out. Energy [MeV]	Frequency [MHz]	No. Cavities	RF Power [MW]	No. Klystrons	Length [m]
RFQ1	2	*352.2*	1	0.5	1	2.5
RFQ2	*7*	352.2	1	0.5	1	4
DTL	*100*	352.2	29	5.8	6	99
SC β=0.5	*235*	352.2	40	1.4	5	89
SC β=0.66	*360*	352.2	24	1.2	3	60
SC β=0.8	1010	352.2	48	6.5	12	148
SC - LEP II	2000	352.2	104	9.9	13	320
TOTAL			303	25.8	41	~723

2.2 Outline of the Accelerator

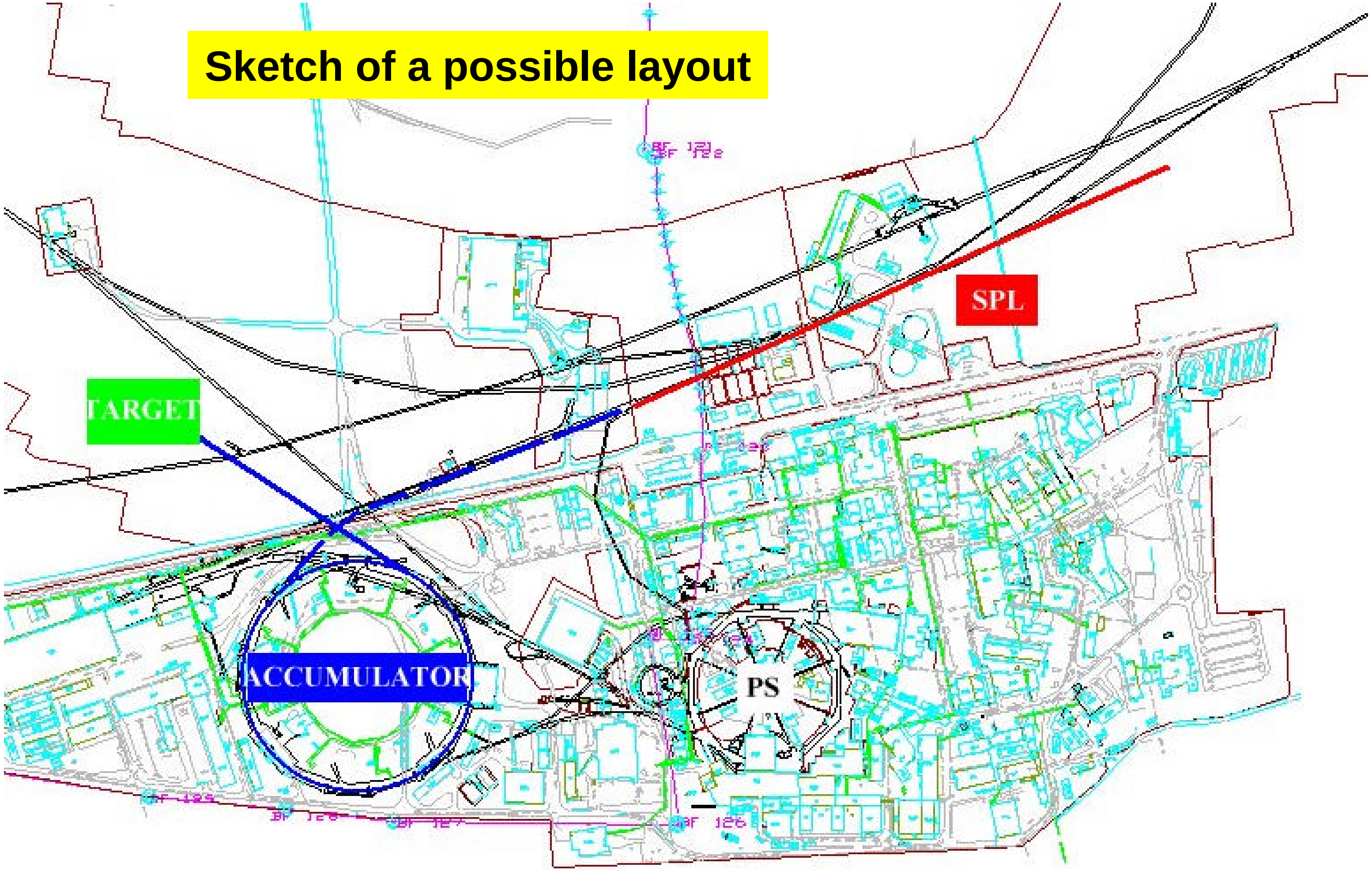
RF and Superconducting cavities Parameters

Section	design beta	Gradient [MeV/m]	N. of cells/cavity	Cryostat length [m]	Input Energy [MeV]	Output Energy [MeV]	N.of cavities	N.of cryostats	N.of klystrons	RF Power [MW]	Length [m]
1	0.5	5	4	7.88	100	235	40	10	5	1.4	88.8
2	0.66	5	4	8.97	235	360	24	6	3	1.2	59.8
3	0.8	9	5	11.29	360	1012	48	12	12	6.5	147.5
4	1	6.7	4	11.29	1012	2000	104	26	13	9.9	319.5
TOTAL							272	68	33	19	615.6

NOTES:

distance between cryostats (for focusing doublets) is 1 m all along the linac
8 cavities/klystron sections 1,2,4
4 cavities/klystron section 3 (beta 0.8)
gradient in section 4 adjusted for maximum klystron power <800 kW
RF power per klystron: minimum 220 kW maximum 780 kW
RF power per cavity: minimum 25 kW maximum 145 kW

2.2 Outline of the Accelerator



2. Present ideas for an SPL

2.3 Studies: status and plans

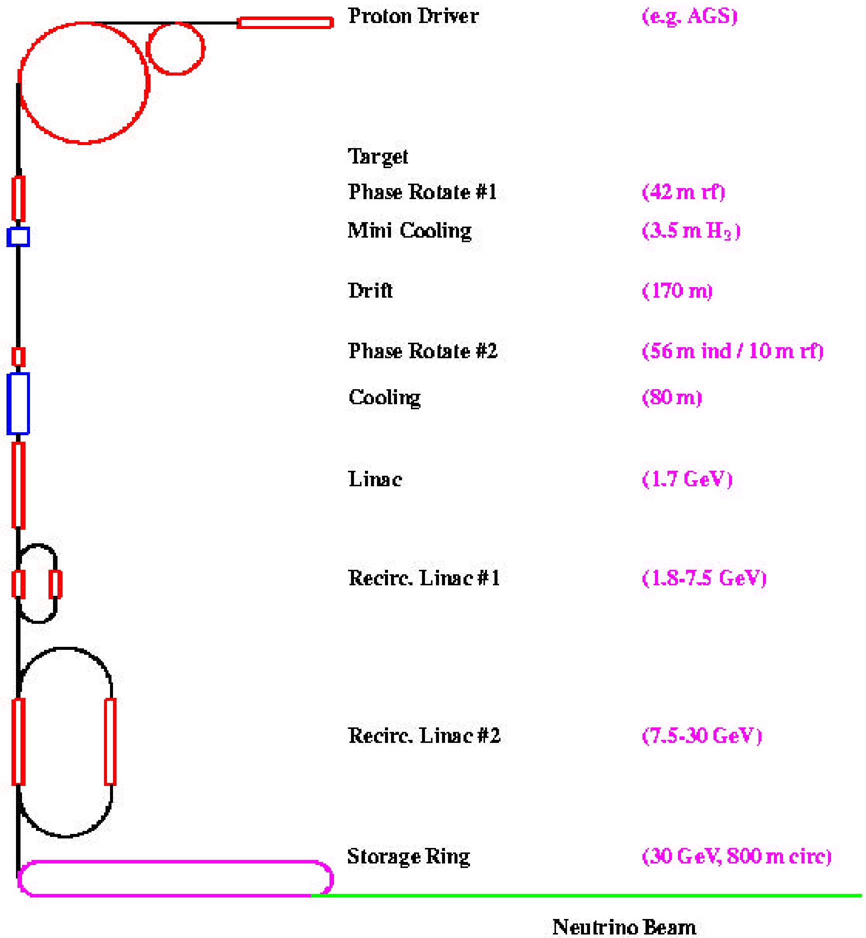
ITEM	MAIN THEME	STATUS
H- source (100 mA pulsed)	20 % duty cycle & low emittances	Collecting information
Chopper	Rise time ~ 1 ns	
RFQ(s)	20 % duty cycle & emittances preservation	Active
DTL	20 % duty cycle & emittances preservation	Active
SC – reduced b	Maximum gradient	Active
SC – LEP 2	Maximum gradient	Active
Servo-systems for pulsed operation of SC cavities	Microphonics	Study started in stage 1. To be continued…
Debunching	Minimise energy spread & maximize bunch length	
Beam dynamics	Optics design, particle tracking Halo and distributed losses	Study started in stage 1. To be continued…
Cryogenics		Pending
Services (electricity, cooling water etc.)		Pending
Radio-protection		Recommendations available
Lay-out & civil engineering		Pending
Coordination with users – Refinement of specs.		Active

A Cost-Effective Design for a Neutrino Factory

R.B. Palmer, BNL
C. Johnson and E. Keil, CERN

`~keil/MuMu/Recirculator/lyon.ps`

Neutrino Factory Layout



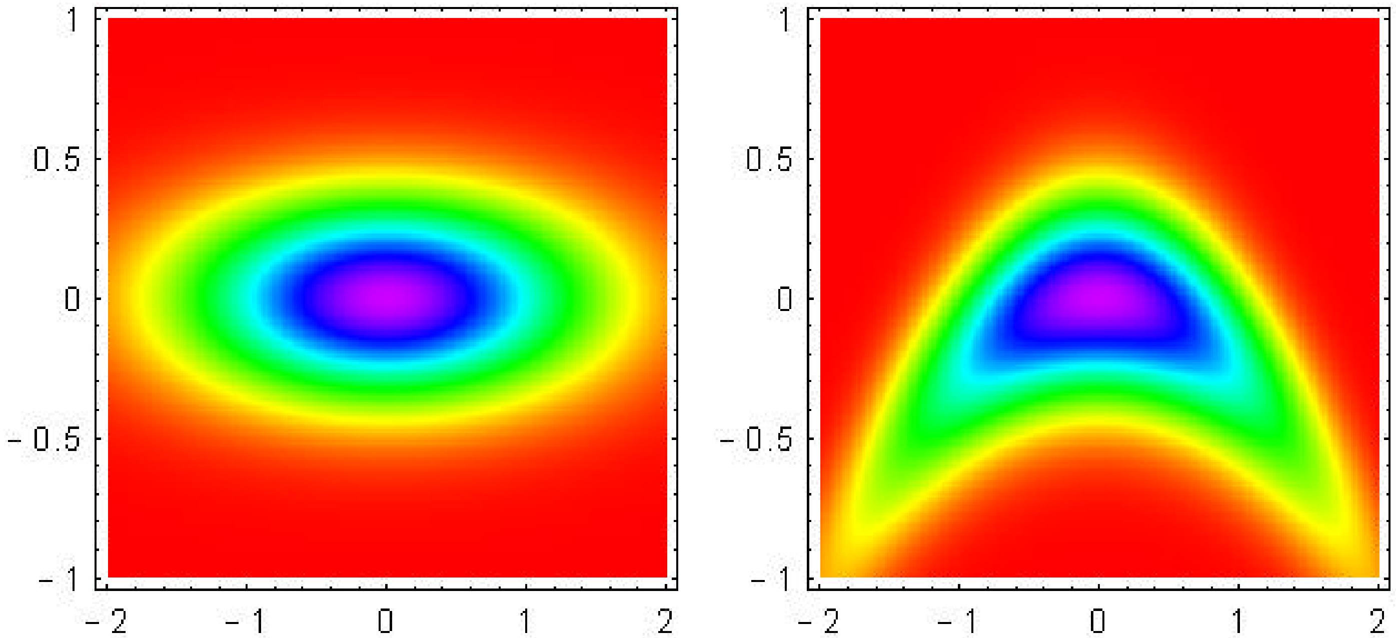
Beam Parameters at Input of Modules

	μSR	μRLA2	μRLA1	
Injection energy injE	30	8	2	GeV
Normalized RMS emittance ϵ_{xn}	1667	1667	1667	μm
RMS energy spread σ_e	0.01			
RMS bunch length σ_s	16	16	16	mm
Bunch spacing s	1.7	1.7	1.7	m
Bunch train length L	$<$0.8	$<$0.8	$<$0.8	km
Bunch population N	?			
Beam current beamI	0.1			A

Linac Parameters of μRLA1 and μRLA2

	μRLA1	μRLA2	
*Injection energy injE	2	8	GeV
*Number of passes passN	4	4	
*Ejection energy ejE	8	30	GeV
*Frequency of RF system freqRF	352.209	352.209	MHz
*Radius of beam ports cavity A	0.09925	0.09925	m
*Number of RF modules moduleN	64	112	
Total accelerating voltage totalV	1.5	5.5	MV
*Length of half cell/λ_{RF} halfCellL	11.5	17.5	
Total length of linac totLinL	626.467	1668.31	m
*Phase advance in first pass linAdv	0.212071	0.212071	
Maximum β-function in linac linβ_{max}	32.5977	49.6052	m
Normalized acceptance A_{xn}	6.02224	15.2341	mm

Bunch Length and Energy Spread II



Magnetic Horn Study for the NuFact

By:

Alan Ball

Alain Blondel

Simone Gilardoni

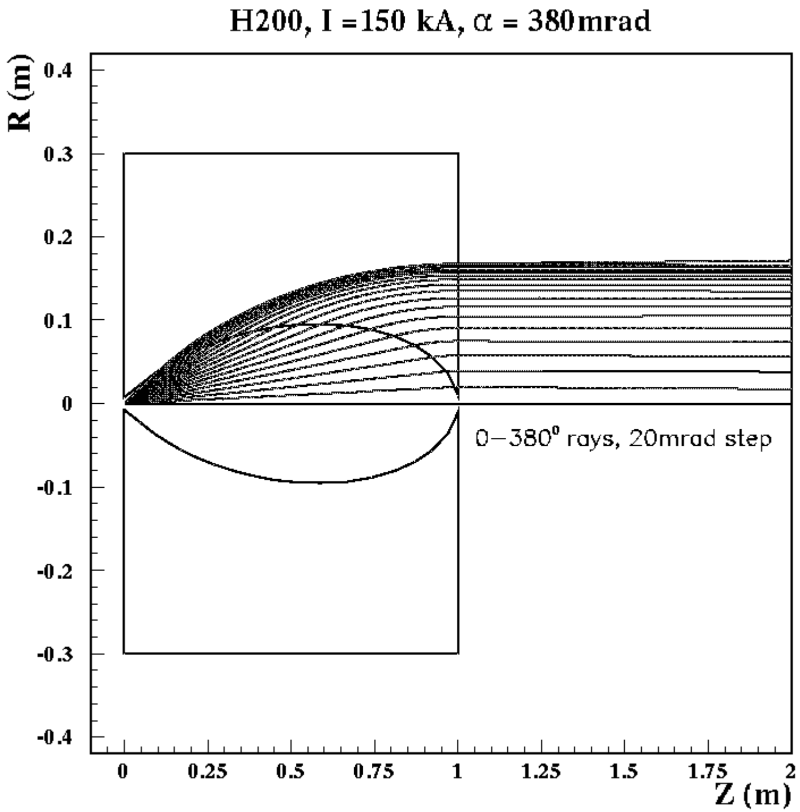
Nikolaos Vassilopoulos

Meeting 1/9/1999

Nufact Collection scheme:
why a horn?

- change of π's $p_t \Rightarrow p_l$
- π's focus point to parallel
- compact system ($\approx$ 1 m)
- possibly better efficiency for thin targets
- horn can be made “radiation hard”
- the removable part is very cheap

The Horn: vote for it!!!



@ 2 GeV Study

Simulation using GEANT transportation and
FLUKA particle production tables

Target: Hg cylinder r = 4 mm L = 2.6 cm (2% λ_I)

λ_I = 13.3 cm

X_0 = 0.3 cm

(only available file from FLUKA authors)

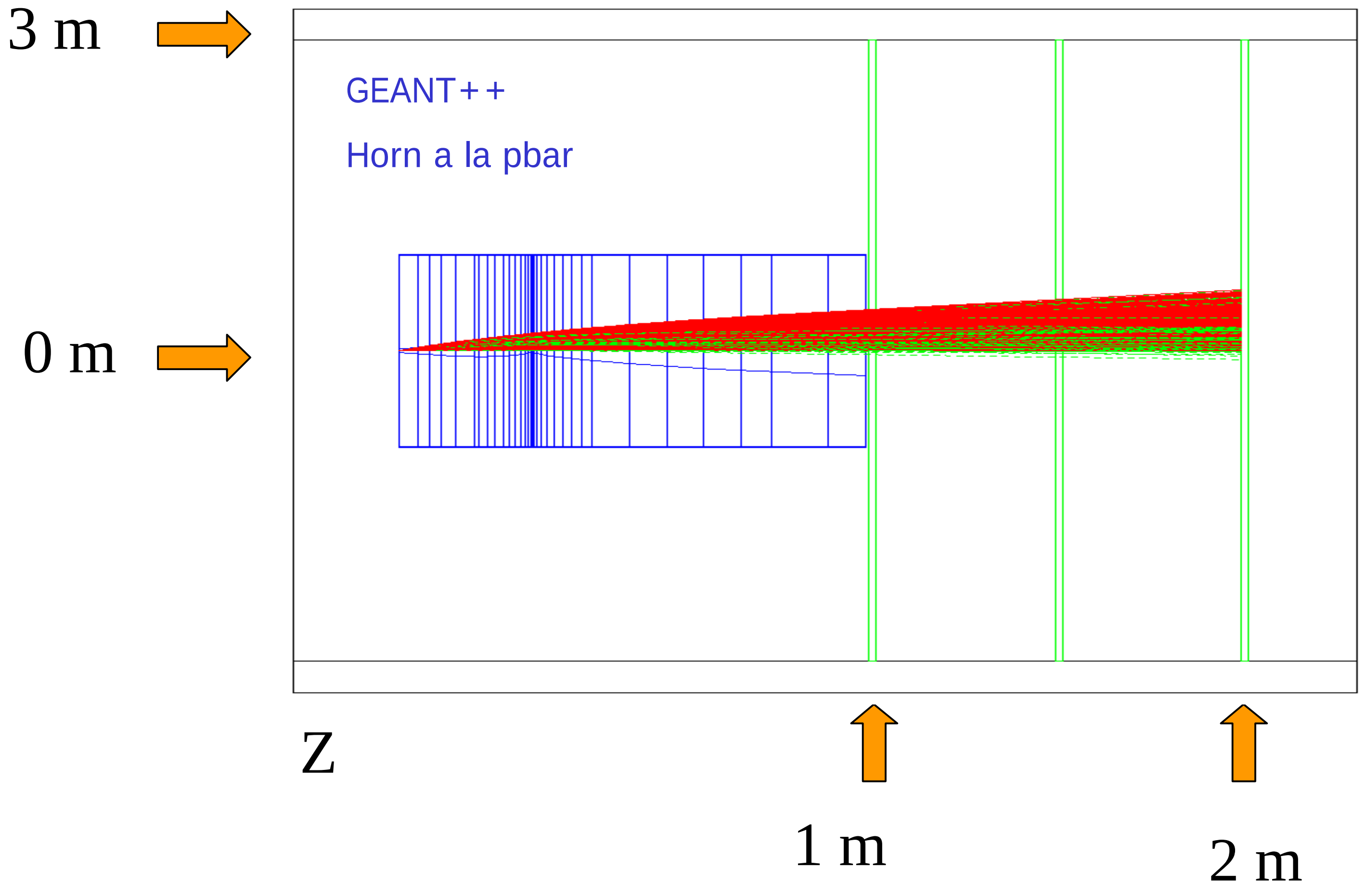
Horn simulation:

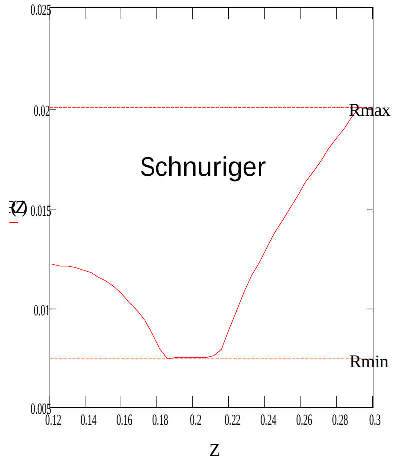
no material (Al) is simulated yet

minimum thickness 1.8 mm (CNGS construction)

@ 2 GeV Study

300 MeV π^+ 400 kA



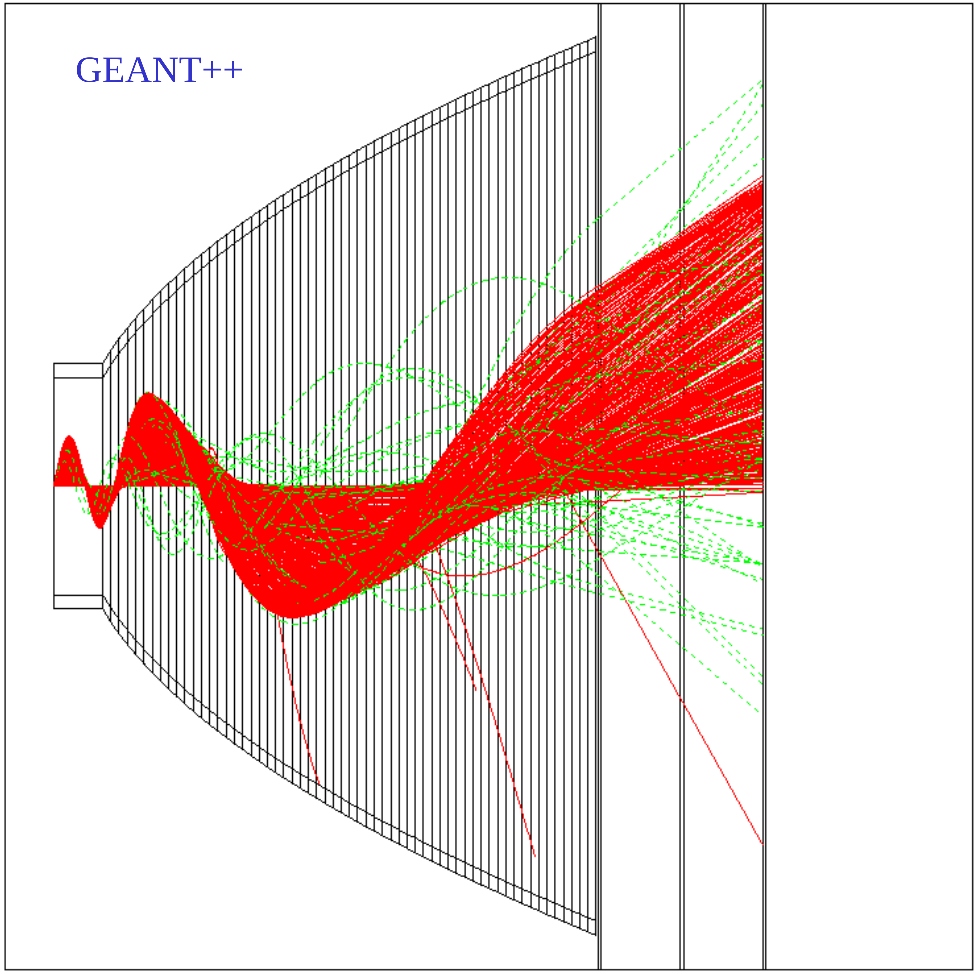


Solenoid (USA scheme)

30 cm

7.5 cm

0



0

3 m

Field map

$$B(z) = \frac{B_0}{1+15\frac{z}{L}}$$

Some points mentioned by Bob Palmer for possible collaboration:

1) Studies of proton driver

compare → Linac and accumulator
compare → synchrotron

2) Study higher gradients for SC cavities
   - in pulsed mode
   - after cleaning
   - after recoating

3) Study high gradient low frequency cavities
   - RF source
   - design (Werner Pirkl)
   - building cavity (GSI?)
     - (could be used for experiment at BNL)

4) Target
   - Design (Colin Johnson) (test at BNL?)
   - Test with jet in B-field (CERN, Grenoble)

5) "Global collaboration"
   - CERN builds recirculator #2
     - (including LEP cavities)

Muon Collider Collaboration / CERN Neutrino Factory Working Group Information Meeting

on

simulation codes and analytic tools for design of muon capture and cooling channels

CERN 1st September 1999

PS Auditorium 6 - 2-024

AGENDA

The purpose of this meeting is to introduce NFWG members to ICOOL and DPGeant and the considerable expertise already acquired by the MCC. We shall make a comparison of the tools available for the design and performance appraisal of the muon capture and cooling section for a Neutrino Factory. We shall not go so far as to evaluate capture and cooling scenarios, although we do expect a range of scenarios to be discussed within the context of applying the various tools. Nor shall we get into discussions of the relative merits of FLUKA, MARS, ARC etc. **cdj & nv.**

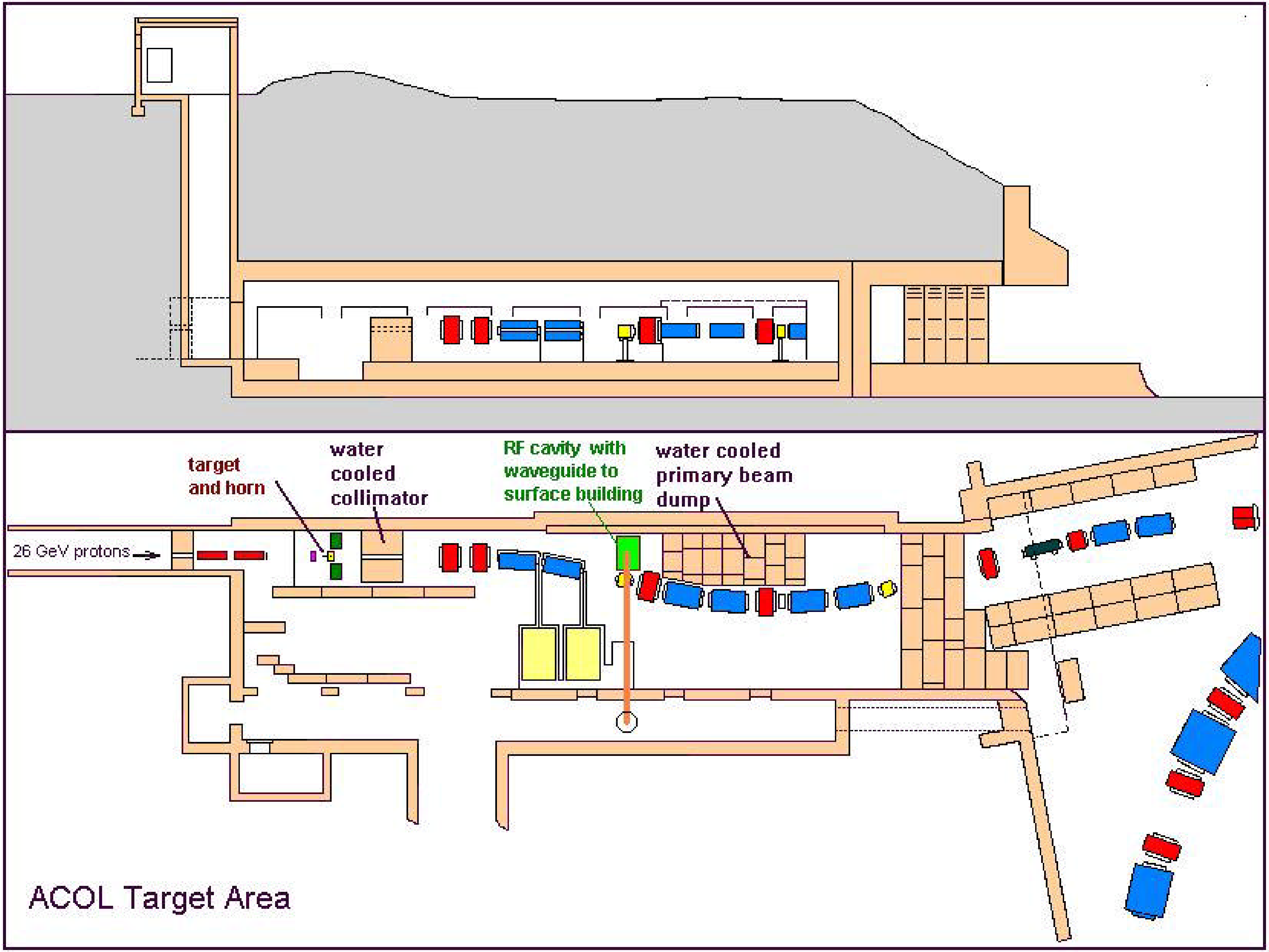
Introduction	Colin Johnson	09:00
FLUKA + GEANT321 for nu-beams simulation	Nikos Vassilopoulos	09:15
Preliminary magnetic horn simulations for nu-factory	Simone Gilardoni	09:40
GEANT4 for Nu-factory simulations	to be annonced	10:00
Coffee		10:30
MCC work with Geant3, DPGeant		
and Geant4:methodologies and results	Paul Lebrun, Fermilab	11:00
Introduction to ICOOL	Rick Fernow, BNL	12:00
Discussion		
Lunch		13:00
On-line demo of DPGeant	Paul Lebrun	14:30
Codes used for muon capture studies at CERN	Alessandra Lombardi	15:00
Cooling lattice design using ICOOL	Rick Fernow, BNL	15:15
Optics functions developed by P. Royer (on vacation)	Peter Gruber	15:45
Special relativity functions for various decays and spin	Peter Gruber	16:00

Proposal

(Colin Johnson)

To study the behaviour of a high-power RF Cavity in a high-intensity pulsed radiation field

The PS beam can be up to 5 bunches spaced by 110 ns each in the region of 10 to 15ns FWHH and 5x1012 p/bunch. The target is Iridium of 1 interaction length, but it can be removed if desired. The collimator downstream of the target has a large aperture (10 to 15 cm diameter, from memory) so the secondary radiation from the target would illuminate a disc of ~1m diameter at the dump, which is just about right. An option would be to move the primary target and to place a temporary target, of say 3 interaction lengths, 1 to 2 m upstream of the cavity (at the same position). The proton beam could be re-focused to a spot size of ~ 1cm diameter at this target. The advantage of the first scenario is that we could run parasitically during AD fills. But the second option could probably be accommodated in the AD program without much difficulty.


target
and horn
water
cooled
collimator
RF cavity with
waveguide to
surface building
water cooled
primary beam
dump
26 GeV protons
ACOL Target Area


CERN Antiproton Decelerator
Target Area
Schematic of RF cavity
installed upstream of
the AD proton dump

Appendix: Output from Spreadsheet Accu_2gev.XLS

2 GeV - Accumulator 17/9/99

Parameter	Unit	Value
Power on Target	W	4.00E+06
Nr. of Rings		3
Extraction Kinetic Energy	eV	2.00E+09
Injection Kinetic Energy	eV	2.00E+09
frep	Hz	100
Radius of Storage Rings	m	50
rho/R		0.3
B Injection	T	0.62
Revolution Period at Injection	s	1.11E-06
Phys. Emittance (x) (injection)	mm mrad	70.0
Phys. Emittance (y) (injection)	mm mrad	70.0
Nr of Protons / Ring		4.17E+13
Sp.Ch. Tune Shift at Injection		0.07
Macro Bunching Factor (Injection)		0.10
Transition gamma		3.25
RF Harmonic Number		4
Nr of Bunches in Ring		4
RF frequency	Hz	3.62E+06
Long. Emittance (per macro bunch)	eVs	0.03
Average Linac Current	A p	0.01
Duration of Linac Pulse	s	2.0E-03
Linac Bunch Frequency	Hz	3.52E+08
Linac RF Frequency	Hz	3.52E+08
Linac Beam Emittance (x)	mm mrad	1.2
dp/p of Linac Beam [at injection point]		2.00E-04
Microbunch half length [injection point]	rf deg	18
Microbunch half length [injection point]	m	0.040
Microbunch half length [injection point]	ns	0.142
Linac 1/2 Energy W.	eV	5.28E+05
Microbunch long. Emittance	eV	0.00024
Local Duty Factor		0.1
Peak Linac Current	A	0.1
Local Sp.Ch. Tune Shift of Injected Beam		0.14
Max. long. Sp.Ch. E-Field (bunch edge)	V/m	1080
Nr. of Injected Turns (transverse)		603

Parameter	Unit	Value		
Energy on Target/Pulse	J	4.00E+04		
Charge State		1		
gamma		3.13		
beta		0.95		
gamma_ex		3.13		
beta_ex		0.948		
Atomic mass	H-	1		
Brho	T m	9.29		
Normalized Emittance (x)	mm mrad	208		
Normalized Emittance (y)	mm mrad	208		
Qx		3.25	Rm/Qx	15.4
Qy		4.45	Rm/Qy	11.2
FormFactors F*G		1.35		
Bufac of injected linac bunches		0.000171		
RF Period	s	2.76E-07		
1/2 Energy of rotated bunch for this E:	eV	4.22E+06		
1/2 dp/p of rotated bunch		0.0016		
Length of Linac Pulse	m	5.68E+05		
Nr of Linac Bunches		70400		
Nr. of Ions / Linac Bunch		1.78E+09		
Linac Beam Emittance (y)	mm mrad	1.2		
Nr. of linac emittances in final Em.		3403		
Drift Length requ'd to obtain this lengt	m	330		
Microbunch long. Emittance	deg MeV/pi	9.50		
Energy gain/turn of bunch edge (th	**MeV/turn**	0.34		

Blue Fields: Input Parameters
Yellow: Dependent Values
Orange: Critical Values

Spreadsheet Display for CERN Specific Scenario 30 GeV / 4MW

RCS1 (BOOSTER) Parameter	Unit	Value			
RCS1 Peak Power per Ring	W	4.89E+05	Ion	H-	1
Nr. of Rings		1	Charge State		1
Extraction Kinetic Energy	eV	2.00E+09	gamma		1.16
Injection Kinetic Energy	eV	1.50E+08	beta		0.51
frep	Hz	50	gamma_ex		3.13
Machine Radius	m	25	beta_ex		0.948
Normalized Emittance (x)	mm mrad	150			
Normalized Emittance (y)	mm mrad	150			
Phys. Emittance (x) (injection)	mm mrad	255			
Phys. Emittance (y) (injection)	mm mrad	255			
Revolution Period at Injection	s	1.03E-06			
rho/R		0.3			
B Injection	T	0.37	Brho	T m	1.84
B Ex	T	1.86	Brho_ex	T m	9.29
Max. Bdot (sinusoidal rise)	T/s	234.0			
for Rise Fraction		0.5			
Nr of Protons / Ring		3.06E+13			
Nr of Protons / Bunch		1.52778E+13			
Sp.Ch. Tune Shift at Injection		0.208	FormFactors F*G		1.35
Bunching Factor (injection)		0.45			
RF1 Harmonic Number		2			
Nr of Bunches in Ring		2			
RF1 frequency	Hz	1.93E+06			
Long. Emittance (per bunch)	eVs	1.39			
Min. RF Voltage for	V	3.13E+05			
max. phi_s of	deg	30			
Transition gamma		5			
Revolution Period at Extraction	s	5.53E-07			
Acceptance(x)		511			
Acceptance(y)		511			
Linac Current (particle amp)	A p	0.035			
Nr. of Injected Turns (transverse)		225			
Duration of Linac Pulse	s	2.33E-04	Length of Linac Pulse	m	3.54E+04
Local Sp.Ch. Tune Shift of Injected Beam		0.003			
Linac Bunch Frequency	Hz	2.00E+08			
Linac RF Frequency		2.00E+08			
Linac Beam Emittance (x)	mm mrad	6			
dp/p of Linac Beam(at injection point)		1.00E-03			

RCS2 (DRIVER) Parameter	Unit	Value			
Total Power on Target	W	4.00E+06	Ion	p	1
Nr. of Rings		1	Charge State		1
Extraction (Target) Beam Energy	eV	3.00E+10	gamma		3.13
Injection Kinetic Energy	eV	2.00E+09	beta		0.95
Rep. Freq. for full circumference	Hz	4.55	s		0.22
Repetition Frequency	Hz	4.55	gamma_ex		32.973
Machine Radius	m	150	beta_ex		1.000
1					
rho/R		0.3			
B Injection	T	0.21	Brho	T m	9.29
B Ex	T	2.29	Brho_ex	T m	103.16
Phys. Emittance (x) (injection)	mm mrad	50.5	Norm. Emittance (x	mm mrad	150
Phys. Emittance (y) (injection)	mm mrad	50.5	Norm. Emittance (y	mm mrad	150
Revolution Period at Injection	s	3.32E-06			
Nr of Protons / Ring		1.83E+14	p per Ring/sec		8.33E+14
Sp.Ch. Tune Shift at Injection		0.240	FormFactors F*G		1.5
Bunching Factor (injection)		0.40			
Max. Bdot (linear Rise)	T/s	34.8			
for Accel. cycle in # of RCS1 Cycles (>=1)		6	Trise		0.060
Transition gamma		50			
RF1 Harmonic Number		24			
Nr of Bunches in Ring		12			
RF1 frequency	Hz	7.23E+06			
Long. Emittance (per bunch)	eVs	1.39			
Min. RF Voltage	V	2.57E+06			
for max. phi_s of	deg	35			
Revolution Period at Extraction	s	3.15E-06			
Acceptance (x)	mm mrad	150	Qx		51.1
Acceptance (y)	mm mrad	150	Qy		52.2
RF System 2 (Bunch Rotation)					
Harmonic Number 2		72			
RF2 Frequency	Hz	2.29E+07			
Computed RF Voltage (RAMA Code)	kV				
Post-Rotation Parameters:					
DErot(1ns)	eV	2.0E+08	for 1 ns rms		
Dp/p rot(1ns)		6.4E-03	Parabolic Bunch		
		Inverse:			
Free Drift per m	ns/m	51104			
Free Drift per s	m/s	5.69E-04			
Ring Drift	m/s	1.01E-03			
Ring Drift	m/turn				
delt/turn in Ring	ns/turn	95.9			

Spreadsheet Display for 5 GeV / 4MW Scenario

RCS1 (BOOSTER) Parameter	Unit	Value			
RCS1 Peak Power per Ring	W	4.80E+05	Ion	H-	1
Nr. of Rings		2	Charge State		1
Extraction Kinetic Energy	eV	1.20E+09	gamma		1.16
Injection Kinetic Energy	eV	1.50E+08	beta		0.51
frep	Hz	50	gamma_ex		2.28
Machine Radius	m	32.5	beta_ex		0.899
Normalized Emittance (x)	mm mrad	150			
Normalized Emittance (y)	mm mrad	150			
Phys. Emittance (x) (injection)	mm mrad	255			
Phys. Emittance (y) (injection)	mm mrad	255			
Revolution Period at Injection	s	1.34E-06			
rho/R		0.2			
B Injection	T	0.28	Brho	T m	1.84
B Ex	T	0.99	Brho_ex	T m	6.41
Max. Bdot (sinuscidal rise)	T/s	119.4			
for Rise Fraction		0.5			
Nr of Protons / Ring		5.00E+13			
Sp.Ch. Tune Shift at Injection		0.340	FormFactors F*G		1.35
Bunching Factor (Injection)		0.45			
Nr of Protons / Bunch		2.5E+13			
RF1 Harmonic Number		2			
Nr of Bunches in Ring		2			
RF1 frequency	Hz	1.49E+06			
Long. Emittance (per bunch)	eVs	0.90			
Min. RF Voltage for	V	2.49E+05			
max. phi_s of	deg	35			
Transition gamma		5			
Revolution Period at Extraction	s	7.58E-07			
Acceptance(x)		511			
Acceptance(y)		511			
Linac Current (particle amp)	A p	0.035			
Nr. of Injected Turns (transverse)		283			
Duration of Linac Pulse	s	7.62E-04	Length of Linac Pulse	m	1.16E+05
Local Sp.Ch. Tune Shift of Injected Beam		0.003			
Linac Bunch Frequency	Hz	2.00E+08			
Linac RF Frequency		2.00E+08			
Linac Beam Emittance (x)	mm mrad	8			
dp/p of Linac Beam(at injection point)		1.00E-03			

RCS2 (DRIVER) Parameter	Unit	Value			
Total Power on Target	W	4.00E+06	Ion	p	1
Nr. of Rings		2	Charge State		1
Extraction (Target) Beam Energy	eV	5.00E+09	gamma		2.28
Injection Kinetic Energy	eV	1.20E+09	beta		0.90
Rep. Freq. for full circumference	Hz	25.00	Trep/2	s	0.04
Repetition Frequency	Hz	25.00	gamma_ex		6.329
Machine Radius	m	65	beta_ex		0.987
	1				
rho/R		0.3			
B Injection	T	0.33	Brho	T m	6.41
B Ex	T	1.00	Brho_ex	T m	19.56
Phys. Emittance (x) (injection)	mm mrad	73.2	Norm. Emittance (x)	mm mrad	150
Phys. Emittance (y) (injection)	mm mrad	73.2	Norm. Emittance (y)	mm mrad	150
Revolution Period at Injection	s	1.52E-06			
Nr of Protons / Ring		1.00E+14	p per Ring/sec		2.50E+15
Sp.Ch. Tune Shift at Injection		0.378	FormFactors F*G		1.5
Bunching Factor (Injection)		0.40			
Max. Bdot (linear Rise)	T/s	33.7			
for Accel. cycle in # of RCS1_GR Cycles (>=1)		1	Trise	s	0.02
Transition gamma		6.4			
RF1 Harmonic Number		12			
Nr of Bunches in Ring		4			
RF1 frequency	Hz	7.92E+06			
Long. Emittance (per bunch)	eVs	0.90			
Min. RF Voltage	V	4.68E+05			
for max. phi_s of	deg	35			
Revolution Period at Extraction	s	1.38E-06			
Acceptance (x)	mm mrad	150		Qx	6.3
Acceptance (y)	mm mrad	150		Qy	7.4
RF System 2 (Bunch Rotation)					
Harmonic Number 2		36			
RF2 Frequency	Hz	2.61E+07			
Computed RF Voltage (RAMA Code)	kV	2100			
Post-Rotation Parameters:					
DErot(1ns)	eV	1.3E+08	for 1 ns rms		
Dp/p rot(1ns)		2.2E-02	Parabolic Bunch		
			Inverses:		
Free Drift per m	ns/m	0.00187		536	
Free Drift per s	m/s	1.63E+05		6.12E-06	
Ring Drift	m/s	3.62E+03		2.76E-04	
Ring Drift	m/turn	0.005			
delt/dt in Ring		1.22E-05			
delt/turn in Ring	ns/turn	0.017		59.3	

DRAFT

Problems of an Accumulator Ring for a Neutrino Factory Scenario based on a 2 GeV Superconducting Linac

H. Schönauer

Introduction

A 2 GeV linac [1], that makes use of LHC superconducting rf cavities, named SPL, has been suggested as an injector for the CERN PS. This function being far from exhausting the potential of such a machine, more ambitious applications would be possible and desirable. Since the idea of studying concepts for a future neutrino factory at CERN has materialised and a working group is set up, the use of such a linac was one possible scenario, perhaps even the most natural one. A very rough outline was presented at the NuFact'99 Workshop in Lyon [2].

For a while the concept was that of a c.w. machine delivering up to 20 MW beam power, of which the time structure was converted to a pulsed beam by a proton accumulator. Initially the cycling rate was matched to the decay time of the muons in their accumulator. The scenario was abandoned when it turned out that kHz pulse rates appear not feasible. One attractive feature of cycling fast is that only a limited number of protons need to be accumulated and the number of turns is of the order 200 for 1 km accumulator circumference. Moreover, preservation of the linac's microbunch structure (bunch lengths of 30 - 300 ps) seemed to be equally attractive since it should allow a microbunch rotation of the pion beam emerging from the target. However, these pions, while decaying, induce an inevitable broadening to the order of a nanosecond of the muon beam, jeopardising all the potential gain from the ultra-short linac bunches.

Parameters of the 2 GeV Linac

R. Garoby [3] proposed an operating mode with a duty cycle of 10%, featuring bursts of 10 consecutive linac bunches separated by gaps of 90 empty buckets. The main parameters of this linac scenario are listed in the following Table.

Linac beam parameters at injection point	Unit	Value
Av. linac current (particle amp)	A p	0.01
Peak linac current	A	0.1
Protons (H-) per bunch		1.8E+09
Duration of linac pulse	S	2.0E-03
Linac rf frequency	Hz	3.52E+08
Linac beam emittance (transverse)	mm mrad	1.2
dp/p of linac beam(at injection point)		2.00E-04
Linac half-energy width	eV	5.28E+05
Microbunch half-length	Linac rf deg	18
Microbunch half-length	m	0.040
Microbunch half-length	ns	0.142
Microbunch long. emittance	eV	0.00024
Local duty factor (chopping)		0.1
Macrobunch frequency	Hz	3.62E+06
Macrobunch long. emittance (excluding blow-up)	eVs	0.03
Macrobunch (10 microbunches) half-length	ns	13

Physical Limits and Constraints

At the NuFact'99 Workshop, a consensus on a beam power of 4 MW on the target has been achieved, but at the same time a limit to the repetition rate was identified. The latter, due to the rf power required for the bunch rotation after the target, is not yet clearly defined, but estimated to be around 50 Hz. As a consequence, the number of protons to be accumulated per pulse is about *six* times larger than in the aforementioned c.w. scenario, for which I have already issued some warnings at the Lyon Workshop [4].

In order to be able to evaluate quickly the consequences of a choice or change of a parameter, a spreadsheet has been created [5], in fact rather derived from the spreadsheet dealing with synchrotron scenarios. A typical output is attached at the end of the report.

The main quantities susceptible to assume unacceptable or unrealistic values, are listed below.

Matter	Concerning		Effect/Constraint	Cure
Space charge	Micro-bunch	longit.	**High peak field causes energy blow-up**	Pre-stretch microbunches → 1 km drift space Requires high γ_t to help debunching in ring
		transv.	Transverse field causes local tune shift	Idem
	Macro-bunch	longit.	**High field at bunch edges causes energy tails**	Barrier rf bucket
		Transv.	Tune shift N.B.: Spreadsheet results valid for smooth square bunch (no microstructure)	Increase: • Circumf. • Emittance • # of rings
Repetition rate[1)]	Larger # of turns injected		**Too many foil traversals:** • Overheating • Emittance blow-up • Losses	Increase: • Circumf. • Emittance • # of rings
	Lower: # of protons in ring		Enhanced space-charge effects	Increase: • Emittance • # of rings
# of macro-bunches[2)]	Bunch area via rf frequency		Ought to be <1 eVs to allow bunches of length 1 ns rms	Smaller ring
Bunch rotation	Rf voltage, # of rf cavities		$\gamma_t \sim \gamma = 3.15$ Not feasible for large circumference...	Smaller ring or High rf voltage
Circumference	Larger	R ~ 150 m	$\gamma_t >> \gamma$, Bunch rotation difficult	Smaller ring or High rf voltage
	Smaller	R ~ 50 m	# of injected turns prohibitive	Increase # of rings

Observations:

1) Ideally as high as possible, but limited by the R-F power required for the **l't** muon bunch rotator. d)

2) A limit to watch is a distance of >200 ns between bunches required for a possible induction (2^{nd}) muon bunch rotator. # > 4 excludes some scenarios for a muon collider!

Comments to the Parameters Calculated in the Spreadsheet

It may be noted that the longitudinal emittance of less than 0.1 eVs assumed in this scenario is by far smaller than the bunch areas of order ~1-2 eVs in the high-energy synchrotron scenarios. This is necessary as the bunch height in terms of momentum spread is $dp/p = 1/(\beta^2\gamma\ E_0)dE$, i.e. higher energies tolerate by a factor ~γ larger bunch areas.

Evaluating the various quantities from the scenario input parameters, as done and displayed in the spreadsheet, one recognises that high peak longitudinal fields occur in the injected microbunches. This effect does not depend on ring size nor repetition rates. For the assumed microbunch length of ~0.3 ns the longitudinal space-charge field assumes values of ~1 kV. In a ring operating close to transition, there would be no bunch lengthening and the bunch would practically explode in the energy height. A pre-stretching to about 0.9 ns instead of the assumed 0.3 ns appears necessary to prevent such excessive energy blow-up. According to analytical approximations due to K. Bongardt [6], debunching to these lengths requires drift spaces of 1000 and 330 m, respectively.

Therefore there are two competing requirements for the transition energy:

$\gamma_t >> \gamma$ to allow debunching of the injected rnicrobunches,

$\gamma_t \approx \gamma$ to reduce the rf voltage required for the final bunch rotation. This condition cannot be met in a large ring of ISR size.

The rf voltages needed for final rotation and quoted in the spreadsheet have been calculated for negligible space charge, i.e. for a square bunch where all microstructure has been smoothed out. This is one more argument for keeping away from transition.

Conclusions

It is not useful to draw any conclusions on the feasibility of the accumulator before the dynamics under space charge of the dense microbunches is studied. The latter may evolve through the different regimes of being short, of comparable length, and long with respect to the chamber radius during the debunching process.

In the attached spreadsheet, a pulse repetition rate of 100 Hz has been assumed, corresponding to about 600 turns to be charge-exchange injected into a ring of ISR size. Halving the frequency to 50 Hz entails injection over 1200 turns. Again, the feasibility of so many injected turns is doubtful. If not, one would simply need two rings.

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Appendix:

Handy Formulae to Compute the Electric Field in the Linac Microbunches

There are simple formulae for elliptic bunches *in free space.* As long as the bunch length is smaller than the radius of the vacuum chamber, this is a valid approximation. Although the exact solution is well known, the following approximation is more handy [8], [9].

The longitudinal field is given by

$$E_z = f \frac{\rho_0}{\varepsilon_0} z \ ,$$

and the transverse field by

$$E_x = \frac{1-f}{2} \frac{\rho_0}{\varepsilon_0} x \ ,$$

where ρ_0 is the density of the uniformly charged ellipsoid:

$$\rho_0 = \frac{3}{4\pi} \frac{e}{a^2 c_0}$$

and f is a form factor:

$$f(\xi) = \left(1-\xi^2\right)^{-1} - \xi\left(1-\xi^2\right)^{-1/2} \cos^{-1}\xi \ , \qquad \xi = c_0/a < 1 ,$$

$$f(\xi) = -\left(\xi^2 - 1\right)^{-1} + \xi\left(\xi^2 - 1\right)^{-1/2} \cosh^{-1}\xi \ , \qquad \xi = c_0/a > 1 .$$

$c_0 = \gamma c$ and a are the half-axes of the ellipsoid in the rest frame.

Charged bunches in a circular vacuum chamber have been treated in Ref. 10.

NEUTRINO FACTOTY Note 01

DRAFT

Rapid-Cycling Synchrotrons as the Proton Source for a Factory at CERN: 'Draft' Scenarios

H. Schönauer

Introduction

Studies of the feasibility of a neutrino factory at CERN are under way and should comparatively evaluate the possible routes. Looking at the proton source, the most salient options are:

1. Upgrading the PS complex as far as reasonably feasible.
2. Building a new, powerful Superconducting Linac (SPL) producing MW beam power at comparatively low energy of a few GeV.
3. To build one or more Rapid-Cycling Synchrotrons (RCS) of medium or higher energy, supplied by a low-energy (a few hundred MeV) linac.
4. A combination of (2) and (3): adding (possibly at a later stage) a RCS to the few GeV linac.

Ad 1. Following quotations of rather bold expectations by R. Palmer, a meeting gathering PS hardware specialists [1] concluded that a meaningful set of limits is described by a *PS cycling at 1 Hz up to 26 GeV/c with an intensity of 3.7 10^{13} p/pulse*. These figures correspond to *0.15 MW beam power*. Even this modest performance has subsequently been contested by other PS specialists, mainly because of the expected radiation damage.

Ad 2. A 2 GeV linac [2], that makes use of superconducting LHC rf cavities, has been suggested as an injector for the CERN PS. Studies to upgrade it to a c.w. machine delivering up to 20 MW beam power have been made but were discontinued. To serve a neutrino factory, addition of one or more accumulator ring(s) is required. Preservation of the microbunch structure (bunch lengths of 30 – 300 ps) in such a ring is not evident, yet it seemed to be attractive since it should allow a microbunch rotation of the pion beam emerging from the target. However, these pions, while decaying, induce an inevitable broadening to the order of a nanosecond of the muon beam, jeopardizing all the potential gain from the ultra-short linac bunches. Therefore, this idea was abandoned and R. Garoby [3] proposed an operating mode with a duty cycle of 10%, featuring bursts of 10 consecutive linac bunches separated by gaps of 90 empty buckets. Nevertheless the accumulation of this beam is by no means straightforward. Some known problems of the accumulator ring are described in [4].

Ad 3. This note searches for possible main parameters of such a configuration and ways of handling the beam power of typically MW. Two scenarios have been investigated, at the moment only about their feasibility.

(a) Recently, E. Keil proposed a set of target parameters that should cover possible physics alternatives [5]: 1 MW, 3 MW and 10 MW for the beam power on the target, and three beam energies: 3 GeV, 10 GeV and 30 GeV. Taking the set of beam power values as base line parameters, they almost suggest machine sizes fitting into the existing tunnels. A staged scenario providing 1 or 10 MW, respectively, such that the Booster RCS delivers 1 MW, also fulfils the injection requirements of the Driver RCS which is supposed to produce 10 MW at 30 GeV. The Driver fits well to the circumference of the ISR tunnel.

The Booster has been adjusted to fit into the Booster tunnel. Since the NuFact'99 Workshop at Lyon a beam power of 4 MW on target has been 'standardized', this scenario obviously is put off the mainstream, and the 1 MW/10 MW version will not be discussed further.

(b) Adapting the above site-specific scenario to standard 4 MW performance releases mainly the repetition rate and the ensuing otherwise stringent rf requirements.

(c) A site-independent scenario inspired by the experience gained at the design of ESS is proposed by the RAL collaboration partners: A 5 GeV scenario involving two pairs of RCS of 65 m and 32.5 m radius, respectively, plus a 150 MeV H- linac.

Ad 4. This option has not yet been evaluated, as it would be an upgrade to option 2 in case one wants to go beyond 4 MW beam power. G.H. Rees pointed out [6] that low-loss rf capture at GeV energies would require a very tight chopping factor of order 0.3. This value may be incompatible with either the chopping factor of 0.1 proposed for option 2, or another application like a neutron spallation source where chopping to about 0.7 is more appropriate.

Constraints from Muon Capture, Acceleration and Storage

The basic facility parameter like neutrino or muon flux, respectively, determine via estimated efficiencies and limits of the muon sections the proton beam power and other constraints.

- At the NuFact'99 Workshop, a consensus on a *beam power of 4 MW on the target*, independent of beam energy, has been achieved.
- At the same time a *limit to the repetition rate* was identified. The latter, due to the rf power required for the bunch rotation after the target, is not yet clearly defined, but estimated to *be around 50 Hz, preferably lower*.
- The major constraint comes from pion/muon capture and first bunch rotation: *The r.m.s. bunch length must not exceed 1 ns*.
- The length of the bunch train must not exceed the circumference of the muon decay ring. At present, this is quoted ~1 km. Looking further at muon collider scenarios, some of them limit the number of bunches to four.
- The distance between bunches should not be less than 200 ns (the rise plus fall time of an induction rotator for the second muon bunch rotation).

Option 3: Tentative RCS Scenarios

In order to produce 4 MW proton beam power at 5 - 30 GeV, the approach of having a chain of two RCSs ("Booster" and "Driver") is generally considered to be more economic than the combination high-energy linac plus Driver RCS of Option 4 above. Injection energies into the Booster not exceeding 150 MeV facilitate the handling of the rf capture loss, which is very difficult to suppress completely. Linac and Booster are similar to those being studied for MW spallation neutron sources. The Driver is in many parameters comparable to synchrotrons for a hadron facility.

Apart from the known problems of these high-current accelerators, one is faced with the requirement of extremely short bunch length of 1 ns r.m.s. of the extracted beam. Such values can only be achieved by bunch rotation on a flat top or in a separate ring. In order to remain within feasible -though extreme - rf voltages, one has to stay as close to transition as possible, and preferably below it. In the latter case, if one wants to avoid transition crossing, an additional rotator ring has to be added.

In order to be able to evaluate quickly the consequences of a choice or change of a parameter, spreadsheets have been created, in fact two (linked) spreadsheets per scenario, one for each type of RCS. Typical outputs are attached at the end of the report.

Comments on the Parameters of the Two RCS Scenarios

The Site-Independent 5 GeV Scenario (Studied at RAL)

The basic features are two stacked 50 Hz in-phase Boosters of 32.5 m radius which accelerate protons from a linac energy of 150 MeV to 1.2 GeV, while two twice that size main rings operate 180 degrees out of phase at 25 Hz and accelerate the protons to 5 GeV. The pulse frequency at the target is thus 50 Hz.

Required rf voltages are high: 250 kV for the Boosters at frequencies of 1.5 - 2.7 MHz, and about 600 kV are required for the Main Rings, at 8 - 9 MHz. The latter figure is higher than the spreadsheet value, which does not include acceptance checks with space charge. The values including space charge were computed with the RAMA code for a bunch area of 1 eVs. The really critical situation occurs at the final bunch rotation, where space-charge impedance and the inductive impedance of the vacuum environment become comparable. The sensitivity to this effect depends on the choice of the transition energy, which also determines the rf rotation voltage requirements, which are fairly dramatic anyway: 1 MW (at 26 MHz) for a (not uncritical, as $\gamma = 6.33$), $\gamma_t = 6.4$, 2.8 MV for $\gamma_t = 10.7$.

Lattices for $\gamma_t = 10.7$, 8, and 6 have been studied. The latter puts $\gamma_t < \gamma$, with dispersion going up to 3.8 m, which means adding a separate rotator ring.

The CERN Site-Specific 30 GeV Scenario

Due to the higher beam energy, less protons per second are produced and the Driver Ring of ISR size (R = 150 m) cycles slowly, at 5.5 Hz. The small booster of 25 m radius cycles at 50 Hz and six consecutive batches are boxcar-stacked on a flat bottom at 2 GeV. During six empty booster cycles, the Driver cycle rises and falls linearly up to 30 GeV and back. This cycle requires a rf voltage of 2.5 MV at 7 - 8 MHz to accelerate a bunch of 2 eVs. With this voltage, the natural bunch length at 30 GeV is already in the 1 ns r.m.s. region and no rotation is necessary. However, the sensitivity to the impedance of the vacuum chamber is even more pronounced than in the 5 GeV scenario. This fact suggest that 30 GeV is less favorable than a lower energy, despite its slow cycle rate which is apparently attractive for the muon bunch rotation.

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Synchrotron Option for Neutrino Factor Proton Driver

G H Rees and C R Prior, RAL

1. Introduction

As an initial study point, an energy of 5 GeV has been selected for the synchrotron option as this is the lowest energy at which it appears practical to achieve the specified final bunch durations of 1 ns rms. Other driver specifications are 4 MW beam power at 50 or 100 Hz, with 2 or 4 synchrotron bunches per pulse. The most difficult feature is the specification for the final bunch duration, and a low linac injection energy is chosen to assist in achieving this feature.

A number of laboratories have suggested the possibility of a common linac injector for a neutrino factory and a spallation neutron source. If adopted for the scheme proposed here, the gain would not be great however as the common linac energy would be low compared with the output energy of the spallation source linac. A separate possibility is a common R and D programme for the low energy linac stages of the two sources, but this is not feasible unless common linac frequencies are selected (the linac frequencies proposed for the revised ESS design are 280 and 560 MHz).

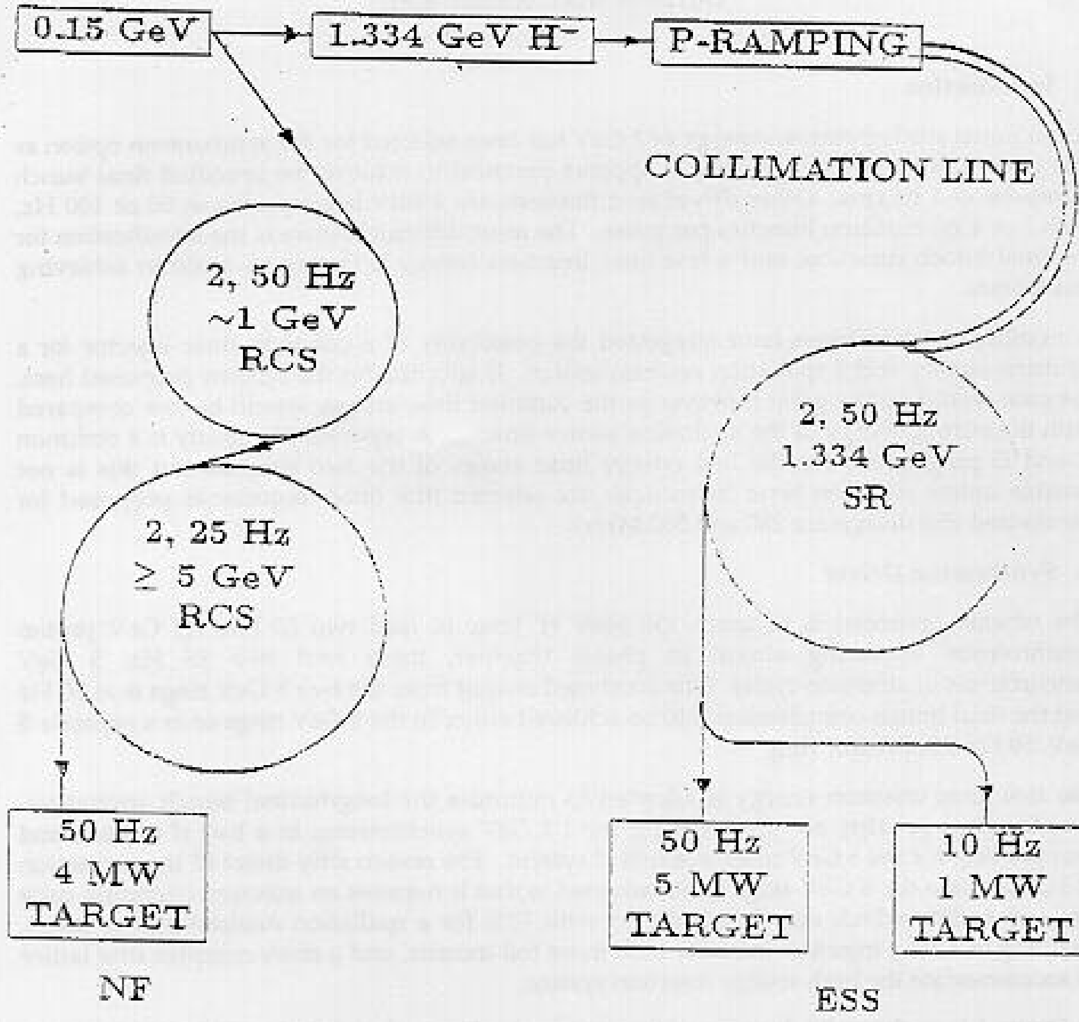
2. Synchrotron Driver

The scheme proposed is to use a 150 MeV H^- linac to feed two 50 Hz, 1.2 GeV proton synchrotrons, operating almost in phase; together, these feed two 25 Hz, 5 GeV synchrotrons in alternate cycles. The combined output from the two 5 GeV rings is at 50 Hz and the final bunch compression is to be achieved either in the 5 GeV rings or in a separate 5 GeV, 50 Hz compressor ring.

The low linac injection energy is adopted to minimise the longitudinal bunch emittances. Two bunches per ring are proposed for the 1.2 GeV synchrotrons, in a h=2 rf system, and four per ring for the 5 GeV rings in a h=8 rf system. The reason why direct H^- linac injection at 1.2 GeV into the 5 GeV rings is not adopted is that it requires an injection chopping duty cycle of < 25% (which may be compared with 70% for a spallation neutron source linac), resulting in a long injection interval, with more foil transits, and a more complex ring lattice to accommodate the high energy injection system.

In Figure 1 is a schematic drawing of the proposed scheme, showing the 150 MeV H^- injector linac as common to both the proton driver and a spallation neutron source. In Figure 2 is given a possible lattice for the 5 GeV rings, and in Figure 3, the related lattice functions. Figures 4 and 5 show the same features for the 1.2 GeV rings. It may be necessary to provide an enhanced range of adjustment for gamma-transition for the 5 GeV rings, in which case a different lattice would be required. A further lattice is also required for the separate 5 GeV compressor ring.

A number of bunch compression schemes have been studied by simulation. The most successful to date is one in which the bunches are transferred to the separate 5 GeV compressor ring, operating just above transition energy. The ring is equipped with a h=8 rf system of amplitude 1.5 MV (a h=12 system at 1 MV may also be considered). The combined focusing of the rf system and the longitudinal space charge forces provides 1.2 ns rms bunches, though the compression is sensitive to the value of gamma-t. The effect of the transverse space charge forces on gamma-t remains to be investigated but this unusual choice of operating just above transition appears to warrant more detailed study.



To reach 1 ns rms bunches, an extra SR may be needed

Figure 1 ESS - NF (Neutrino Factory) Option

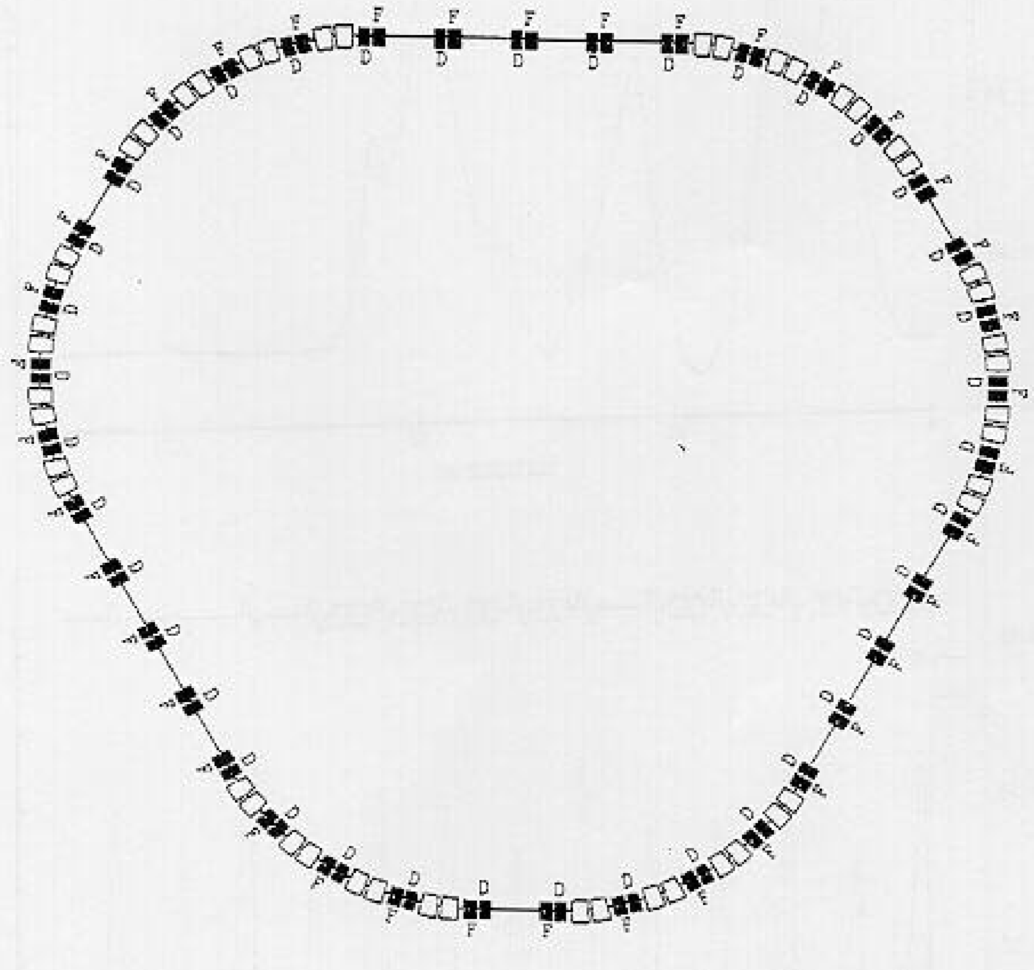


Figure 2   5 GeV RCS

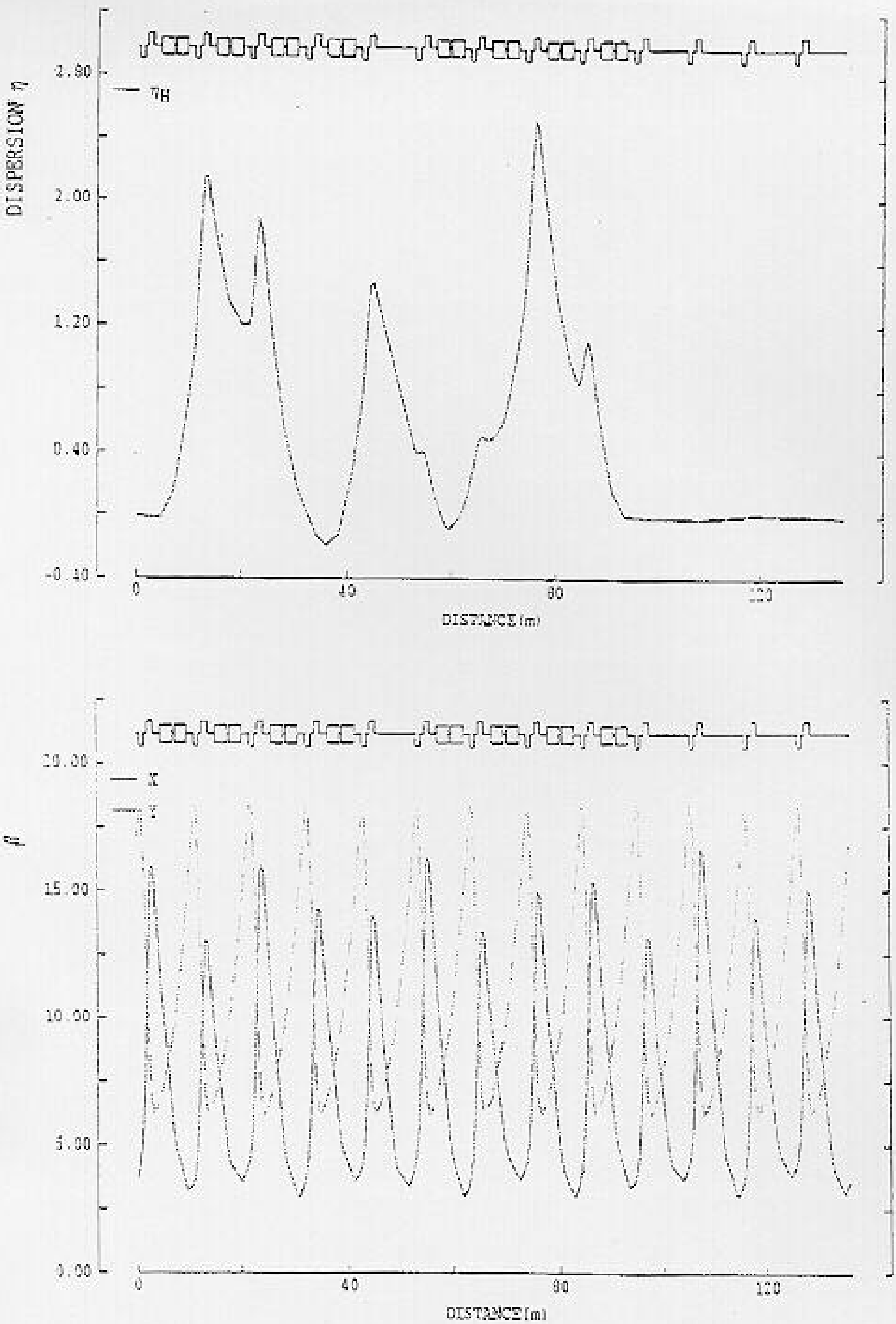


Figure 3 Neutrino Factory 5 GeV RCS

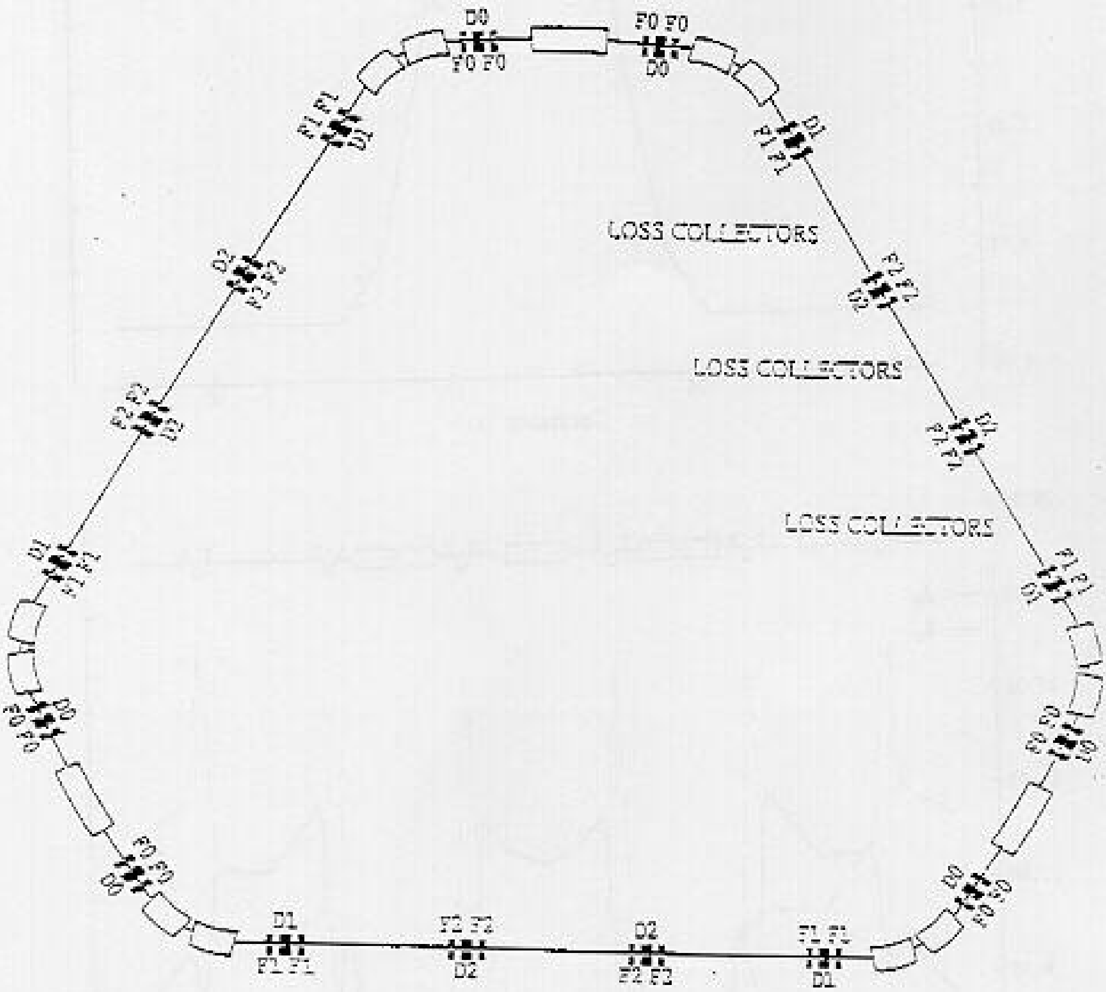


Figure 4 1.200000 GEV RCS

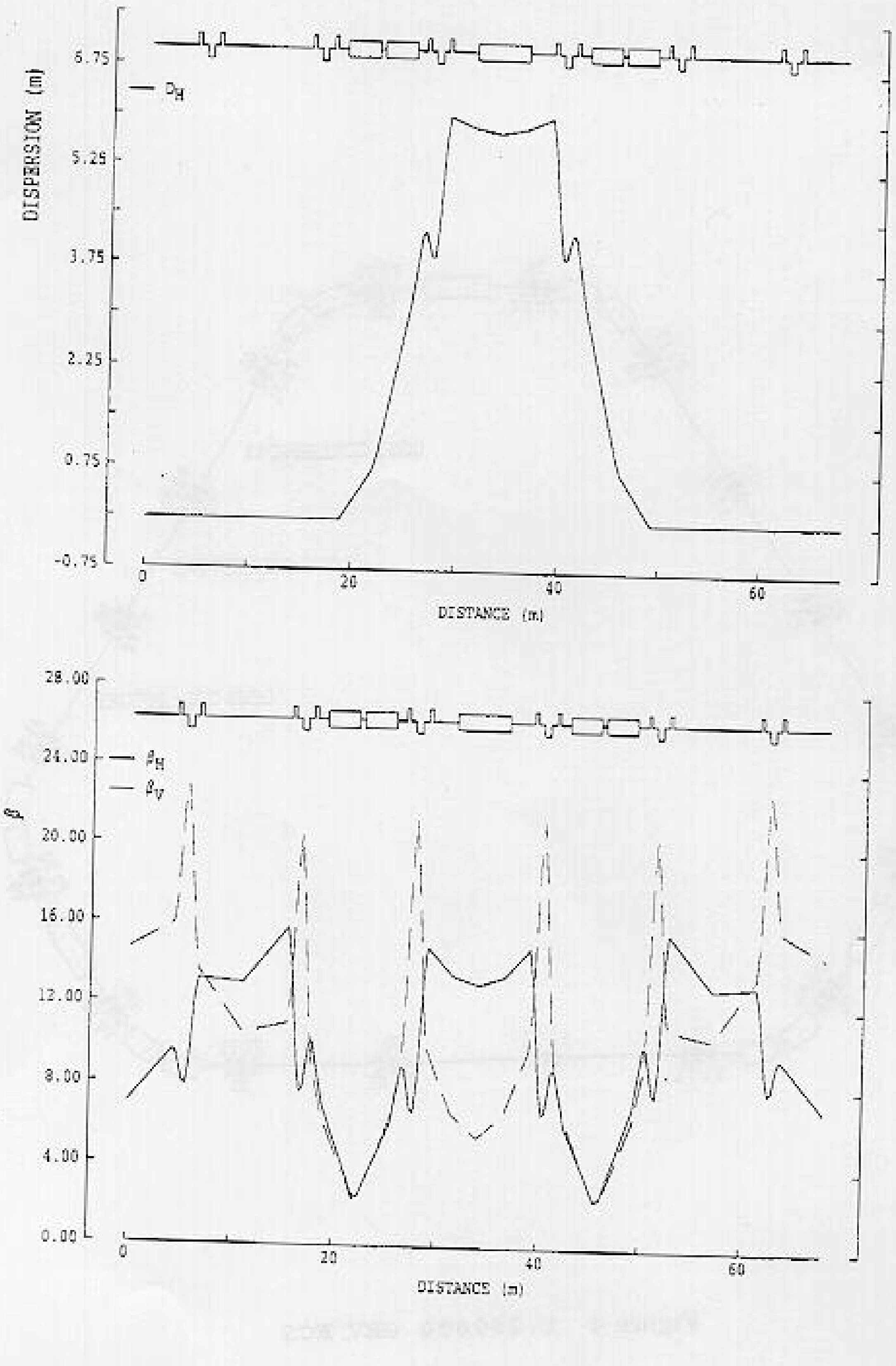


Figure 5 1.200000 GEV RCS

Three 5 GeV lattices have now been studied partially:

1. Gamma-t = 10.7, Dispersion(max) = 2.8 m,
2. Gamma-t = 8.2, Dispersion(max) = 1.8 m, and
3. Gamma-t = 6.0, Dispersion(max) = 3.8 m.

Synchrotron 1 and extra ring 3 should definitely work;
Synchrotron 2 and extra ring 3 should also work;
Synchrotron 3 alone might work, but needs detailed study.

The gamma-t is adjustable over a small range, and is insensitive to transverse space charge. It may be dangerous to consider large inductive wall Z/n values because of the fields involved when the peak current exceeds 1000 Amps.

Collaborations more or less under way or offers or contacts with:

INFN

CEA / IN2P3

FZ Juelich

GSI

RAL

LANL

BNL

FNAL

LBL