CERN Ideas and Plans for a Neutrino Factory

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NuFact'00 Workshop
Monterey
May 22-26, 2000

CERN Neutrino Factory Working Group

Steering Group:

Bruno Autin	(deputy)
Roland Garoby	(2.2 GeV linac)
Helmut Haseroth	(chair)
Colin Johnson	(secretary)
Eberhard Keil	(RLAs, decay ring)
Alessandra Lombardi	(frontend, muon linac)
Helge Ravn	(target)
Horst Schonauer	(accumulator, compressor, RCSs)

Collaboration with outside labs:

RAL

CEA

INFN

et al.

NuFact'00 Workshop May 22-26, 2000

Preferred Scenario for a Neutrino Factory Study

- **Proton Driver (2.2 GeV - 75 Hz - 4MW - 10^{16} p/s):**
  - 2.2 GeV H- Linac (re-using most of LEP-2 RF hardware)
  - Fixed energy Accumulator & Compressor Rings (in the ISR tunnel)
- **Target:**
  - Hg jet with magnetic horn focusing
- **Muons bunch rotation and cooling**
  - 40 MHz (2MV/m) and 80 MHz (4MV/m) RF and ~~mini~~-cooling
- **Muon acceleration**
  - 3 GeV superconducting (200 MHz) Linac
  - Two Recirculating Linacs with supraconducting RF (with around 200 MHz and 400 MHz?)
- **Muon storage ring**
  - 50 GeV storage ring with 10^{21} circulating muons, sending neutrino beams towards 2 remote experiments (Gran-Sasso + ???)

CERN Ideas and Plans for a Neutrino Factory

- Following the NuFAct'99 workshop (Lyon - 07/1999), a possible design for a 2 GeV proton driver has been prepared.
- Based on the 2 GeV Linac accelerating H-, protons are accumulated in a first ring and transferred in a second one for bunch rotation after the end of accumulation. The time structure of the beam is close from the requirements of the american scenarios, delivering 12 bunches of 1E13 protons every 10 ms, for a total beam power of 4 MW.
- This design is evolving towards a reduced cycling rate (75 or 50 Hz) and reduced requirements for the Linac front-end (more realistic performance of the H- source and of the low energy chopper).

Motivation for improving high intensity proton beams at CERN

- **Planned uses**

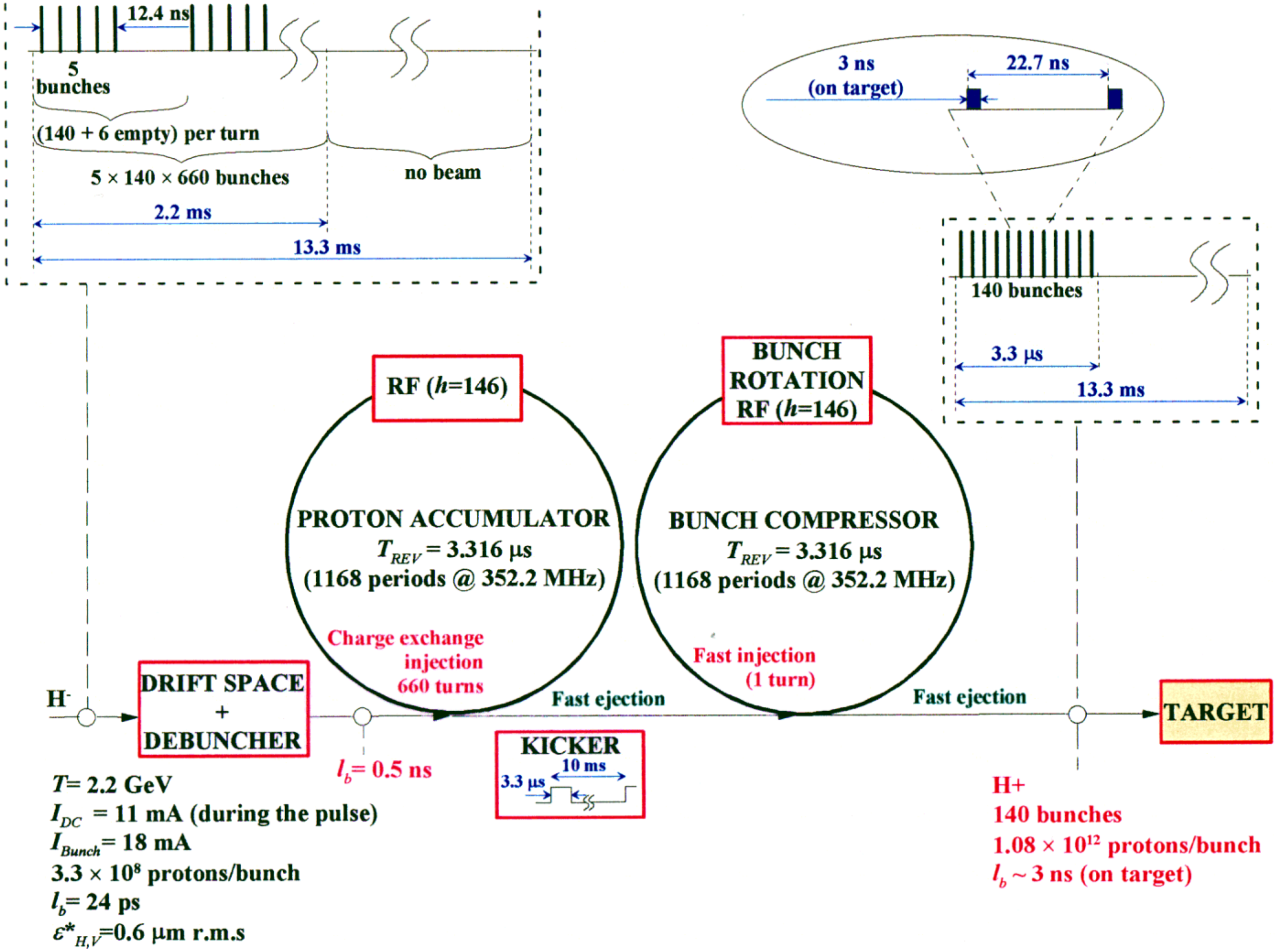
  and interesting directions of improvement :
  - LHC: increased beam brightness
  - CERN Neutrinos to Gran Sasso (CNGS): higher proton flux*
  - Anti-proton Decelerator: idem*
  - Neutrons Time Of Flight (TOF) experiments: idem*
  - ISOLDE: idem*
- **Potential uses :**
  - Fixed target Physics with low to medium energy muons and neutrinos
  - "Neutrino Factory" based on a muon storage ring

SPL beam specifications: Case 2

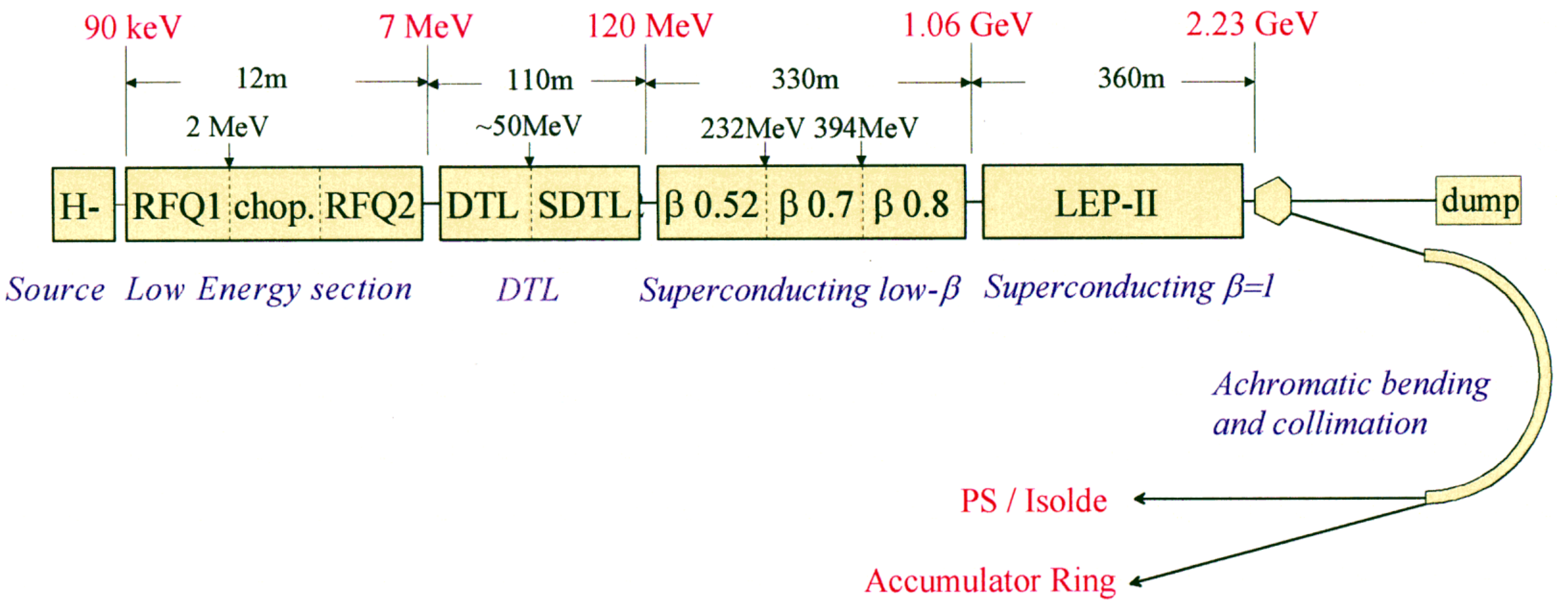
	Parameter	Value	Unit
MEAN PARAMETERS	Ion species	H-	
	Kinetic energy	2.2	GeV
	Mean current during the pulse	11	mA
	Duty cycle [mean beam power]	16.5 [4]	% [MW]
	Pulse frequency	75	Hz
	Pulse duration [number of H- per pulse]	2.2 [1.51 E 14]	ms [H^-/pulse]
FINE TIME STRUCTURE	Bunch frequency [minimum distance between bunches]	352.2 [2.84]	MHz [ns]
	Duty cycle during the beam pulse [number of successive bunches/number of buckets]	61.6 [5/8]	%
	Number of bunches in the accumulator [total number of buckets – empty buckets]	140 [146-6]	
	Maximum bunch current [maximum number of charges per bunch]	18 [3.3 E 8]	mA [H^-/bunch]
BUNCH CHARACTERISTICS	Bunch length (total)	~ 0.5	ns
	Energy spread (total) [relative momentum spread (total)]	~ 0.4 [~ 0.16 E-3]	MeV
	Normalized horizontal emittance (1σ)	0.6	µm
	Normalized vertical emittance (1σ)	0.6	µm
	Energy jitter during the beam pulse	Within +- 0.2	MeV
	Energy jitter between beam pulses	Within +- 2	MeV

Accumulator-Compressor scheme for a Neutrino Factory: Case 2

2.2 GEV PROTON DRIVER SET-UP



SPL layout

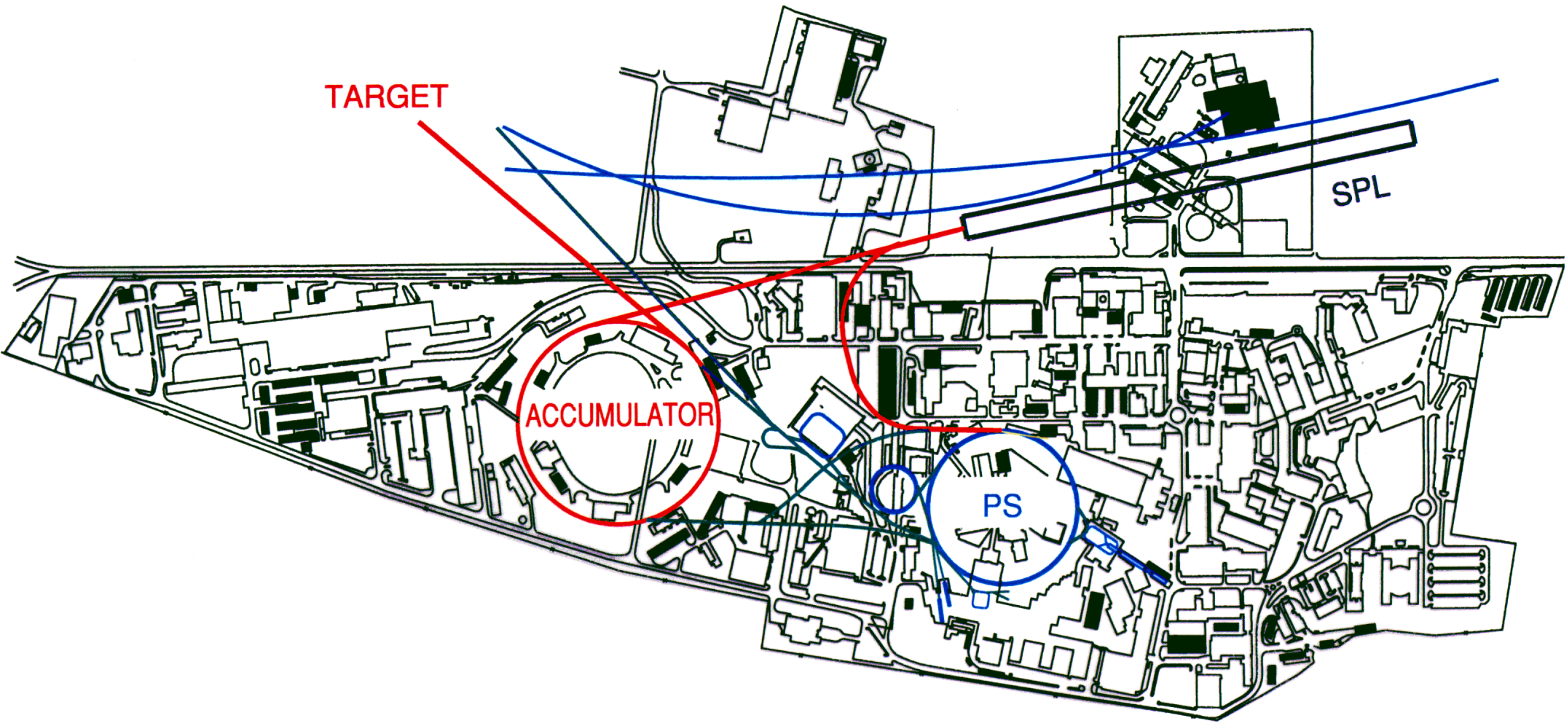

90 keV
7 MeV
120 MeV
1.06 GeV
2.23 GeV
12m
110m
330m
360m
2 MeV
~50MeV
232MeV 394MeV
H-
RFQ1
chop.
RFQ2
DTL
SDTL
β 0.52
β 0.7
β 0.8
LEP-II
dump
Source
Low Energy section
DTL
Superconducting low-β
Superconducting β=1
Achromatic bending
and collimation
PS / Isolde
Accumulator Ring

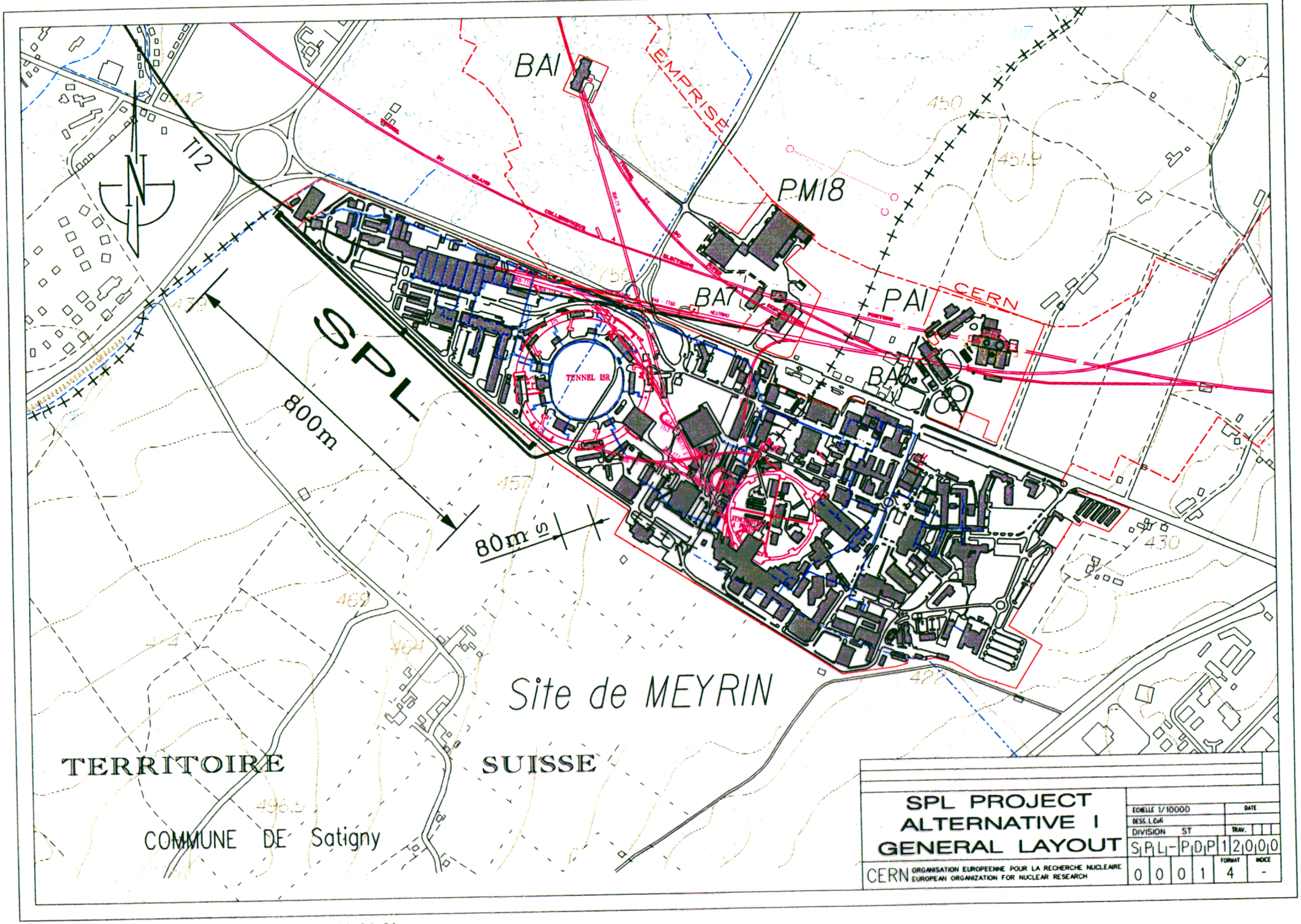
Basic Sections Parameters

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	*120*	352.2	35	7.0	(6)*	110
SC β=0.52	*232*	352.2	42	1.2	(6)*	95
SC β=0.70	*394*	352.2	36	1.8	(5)*	85
SC β=0.80	1060	352.2	48	7.3	12	148
SC - LEP II	2235	352.2	116	12.9	15	357
TOTAL			279	31.2	29 (+17)	~ 802

* Under investigation: power tetrodes could be preferred to help the operation of field regulation loops and improve beam stability

Tentative Layout





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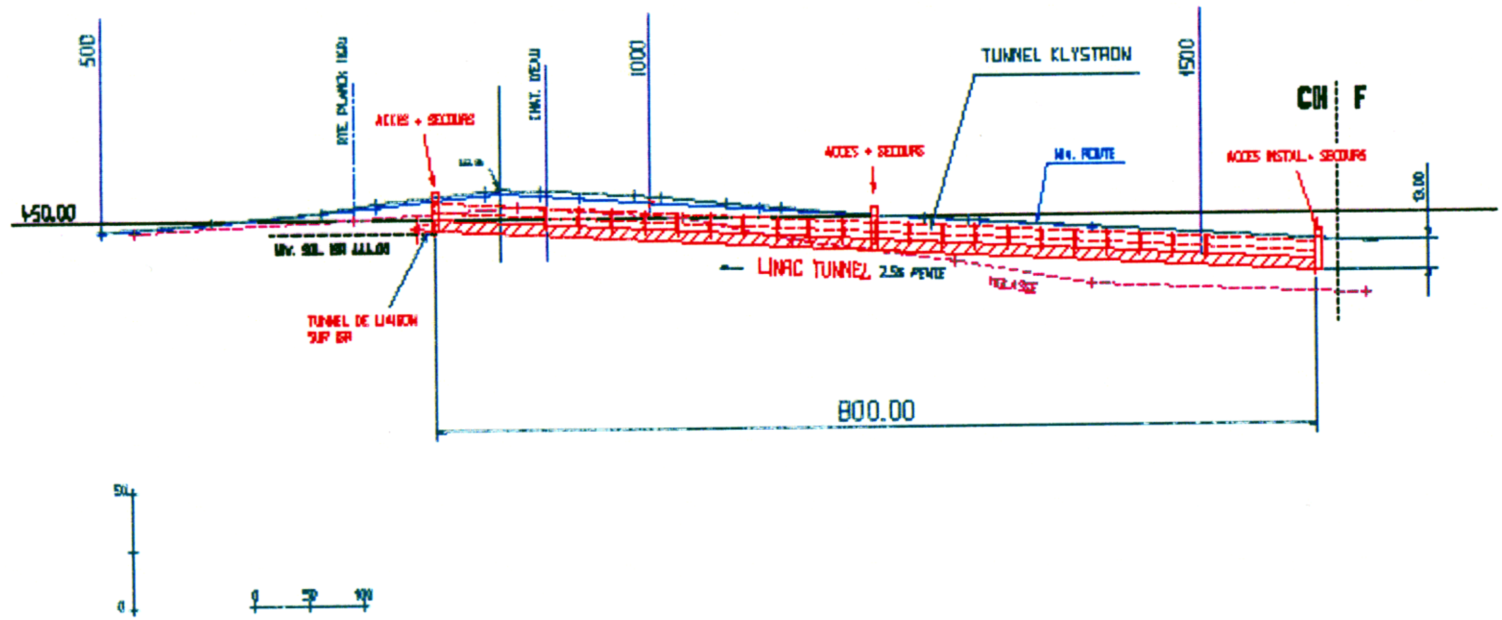
COUPE LONGITUDINALE PARALLELE RTE. GREGORY



SPL PROJECT
LINAC – KLYSTRON TUNNEL
EXECUTION EN SURFACE
COUPE LONGITUDINALE

ECHELLE SCALE	DES/DRA.	A. VITAL	2000-05-11
	CONTROLLED		
	RELEASED		
	APPROVED		
	REMPLACE/REPLACES		

SIZE 3 IND.

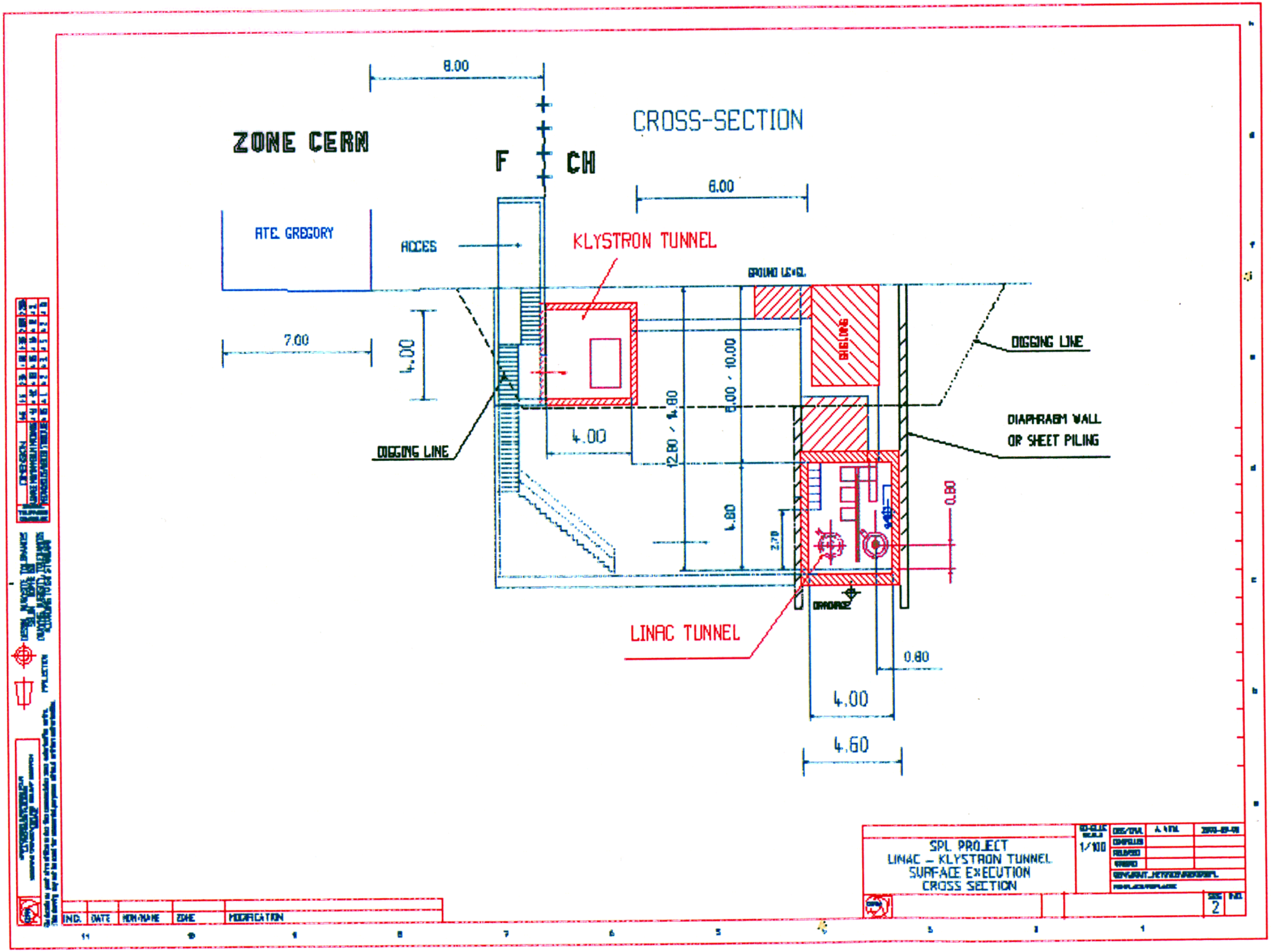
IND.	DATE	NOM/NAME	ZONE	MODIFICATION

DESIGN, AUGUSTE TOLERANCES SELON NORME ISO
DRAWING, RUGOSITY, TOLERANCES ACCORDING TO ISO STANDARD

PROJECTION

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
GENEVE

CERN


ZONE CERN
CROSS-SECTION
8.00
F
CH
6.00
RTE. GREGORY
ACCES
KLYSTRON TUNNEL
7.00
4.00
DIGGING LINE
DIAPHRAGM WALL
OR SHEET PILING
4.00
4.80
0.80
LINAC TUNNEL
0.80
4.00
4.60
SPL PROJECT
LINAC – KLYSTRON TUNNEL
SURFACE EXECUTION
CROSS SECTION
1/100
IND.
DATE
NOM-NAME
ZONE
MODIFICATION

CERN Ideas and Plans for a Neutrino Factory

***Apart from computations and paper-work, some hardware developments are being done*:**

- a multi-cell beta=0.7 SC cavity (Niobium sputtering technique) is being built and will be tested at high gradient before this summer,

- the 4 cells beta=0.8 SC cavity will be tested at high power level and in pulsed mode before June,

- a CERN-type drift tube for the DTL is being designed and will be compared to the CEA design in a test tank during the year,

- designs for the chopper and its driver amplifier are under investigation, looking for hardware tests before the end of 2000.

Proton Driver Rings

In view of the uncertainty of some crucial specifications like pulse repetition rate a threefold way has been chosen for 4 MW proton driver scenarios:

A CERN-specific 2 GeV / 100 Hz scenario using the SPL combined with an Accumulator and a Compressor ring in the ISR tunnel.

Both rings feature high γ/γ_t lattices ensuring fast debunching of the linac microbunches as well as very fast rotation (~7 turns) in the compressor.

The feasibility of H- injection (600 turns - foil heating!) and of the final bunch rotation has been shown. The accumulator lattice is designed, the intersecting compressor is being studied. More refined simulations including the effect of space charge on momentum compaction and of the microwave instability are planned.

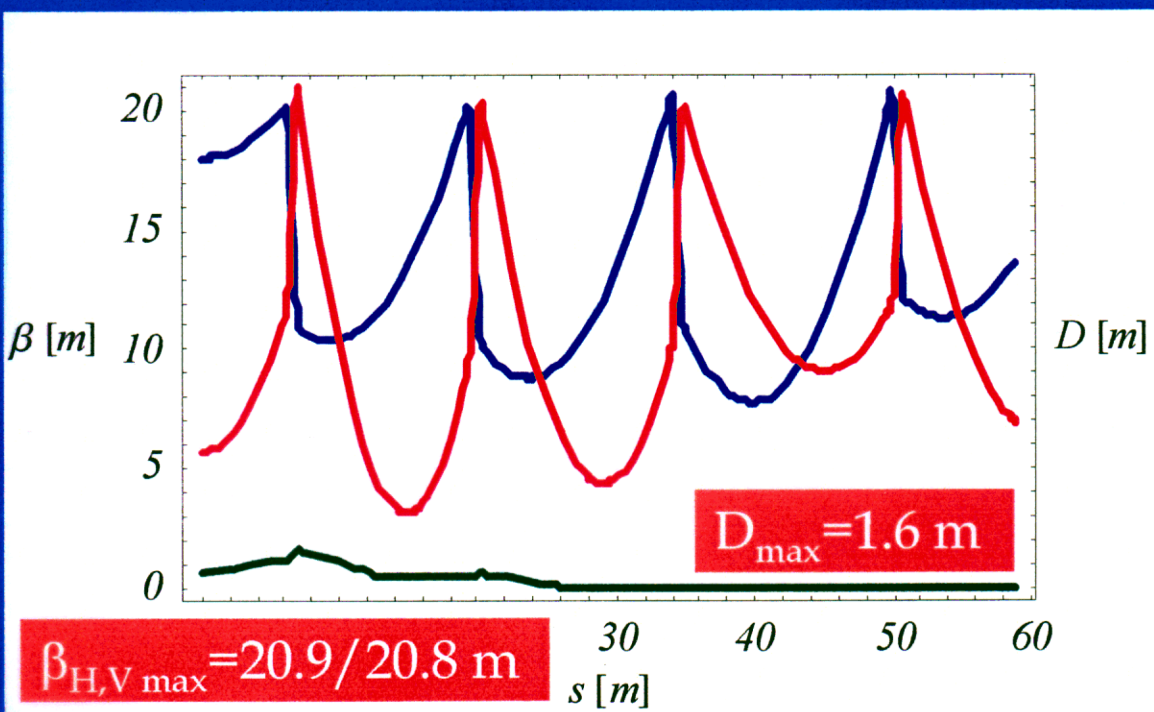
Accumulator & Compressor parameters

PDAC 1	PDAC 2
E_{kin}=2 GeV	E_{kin}=2.2 GeV
12 macro-bunches (h=24)	140 macro-bunches (h=146)
$\tau_{bunch.Acc}$=50 ns	$\tau_{bunch.Acc}$=17 ns
$\tau_{bunch.Com}$=6 ns	$\tau_{bunch.Com}$=6 ns
$\Delta p/p_{Acc}=\pm1.5\times10^{-3}$	$\Delta p/p_{Acc}=\pm1.5\times10^{-3}$
$\Delta p/p_{Com}=\pm13\times10^{-3}$	$\Delta p/p_{Com}=\pm5\times10^{-3}$
$\varepsilon^N_{H,V}$=50 μm (1σ)	$\varepsilon^N_{H,V}$=50 μm (1σ)

Output parameters

CERN Compressor (6) version 15 April 2000

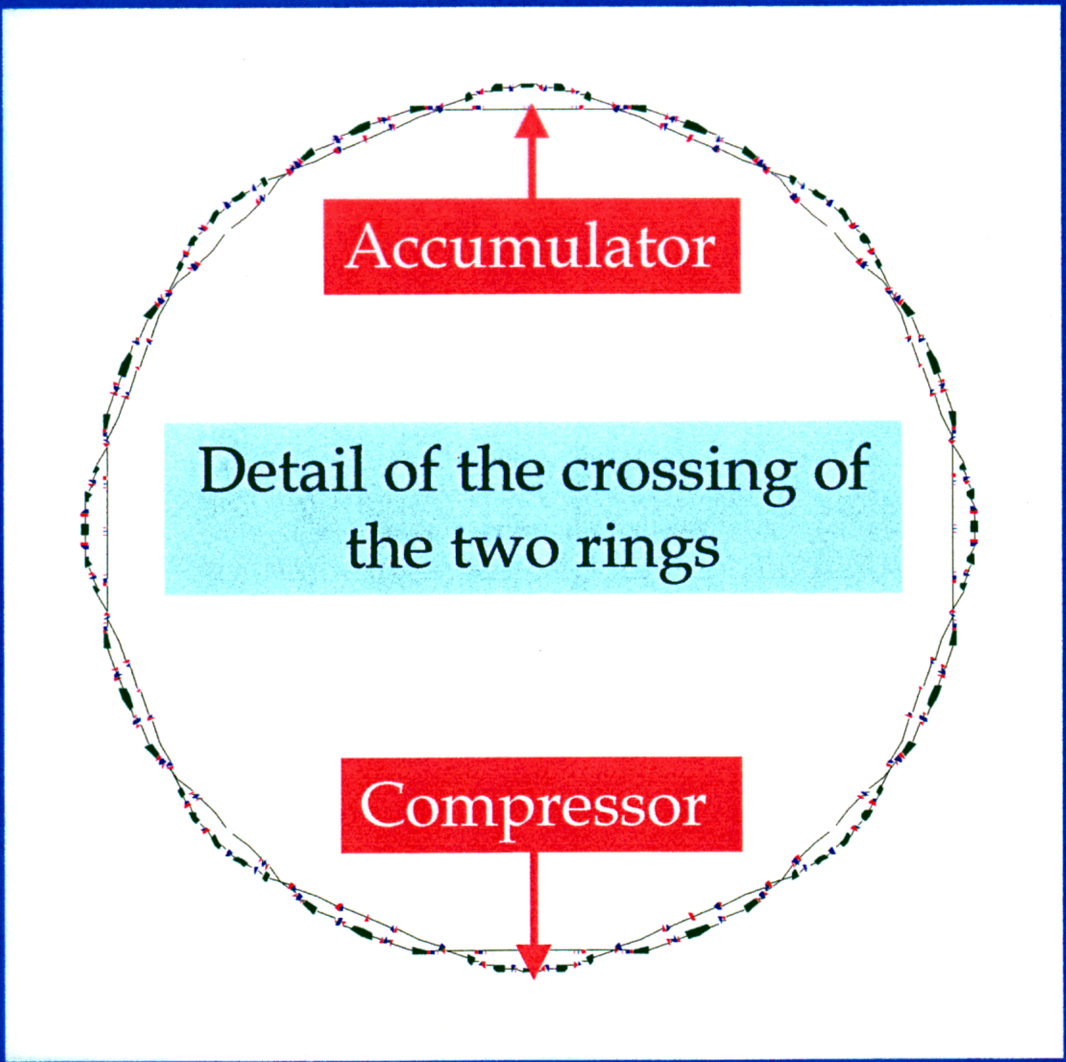
Compressor optical parameters



- Collins lattice, 14.9 m max drift length
- η=-0.087 γ_t=18.78
- $Q_{H/V}$=18.6/12.6
- Dipole field=1.0 T
- Max quadrupole gradient=15.6 T/m

RAL Accumulator & CERN Compressor (2)

Accumulator & Compressor



A collaboration with RAL was established for the design of a site-independent synchrotron scenario. A 5GeV / 50 Hz and recently, also a 15 GeV/25 Hz scenario was investigated, lattices designed and H- injection and final bunch compression was studied and shown to be feasible. The front end is very similar to the existing ESS design which can be easily adapted to the scenario.

In case that slow repetition rates will ultimately be needed, we opted for a 30GeV / 8Hz configuration, using the ISR tunnel for the driver. The high γ_t-lattice of the latter provides naturally short bunches without compression. The feasibility of the approach has been demonstrated by tracking studies including resonant longitudinal impedances. The lattices designed so far need refinements.

Target work

The contacts to the community of people and laboratories outside CERN who expressed interest to participate in high power target and beam-dump development at the NuFact99 workshop is maintained and is being extended to new laboratories. The details of two target concepts in which either solid or liquid target-material is recirculated in the beam are being addressed by simulations and discussions.

A number of ideas are being under consideration which in principle should allow to dispose of the power deposited in the target by an up to 4MW proton beam. The crucial problems are mechanical movements in high magnet fields, heat transfer, material stress, radiation damage and radioactivity confinement.

Not much more progress can be achieved by simulations and workshop discussions. Laboratory tests of the simulations and determination of engineering parameters should be the next step in order to select the future directions among the many ideas around. Equipment and expertise on liquid Mercury technology exists at CERN this maybe the most promising direction.

Suggested R&D program:

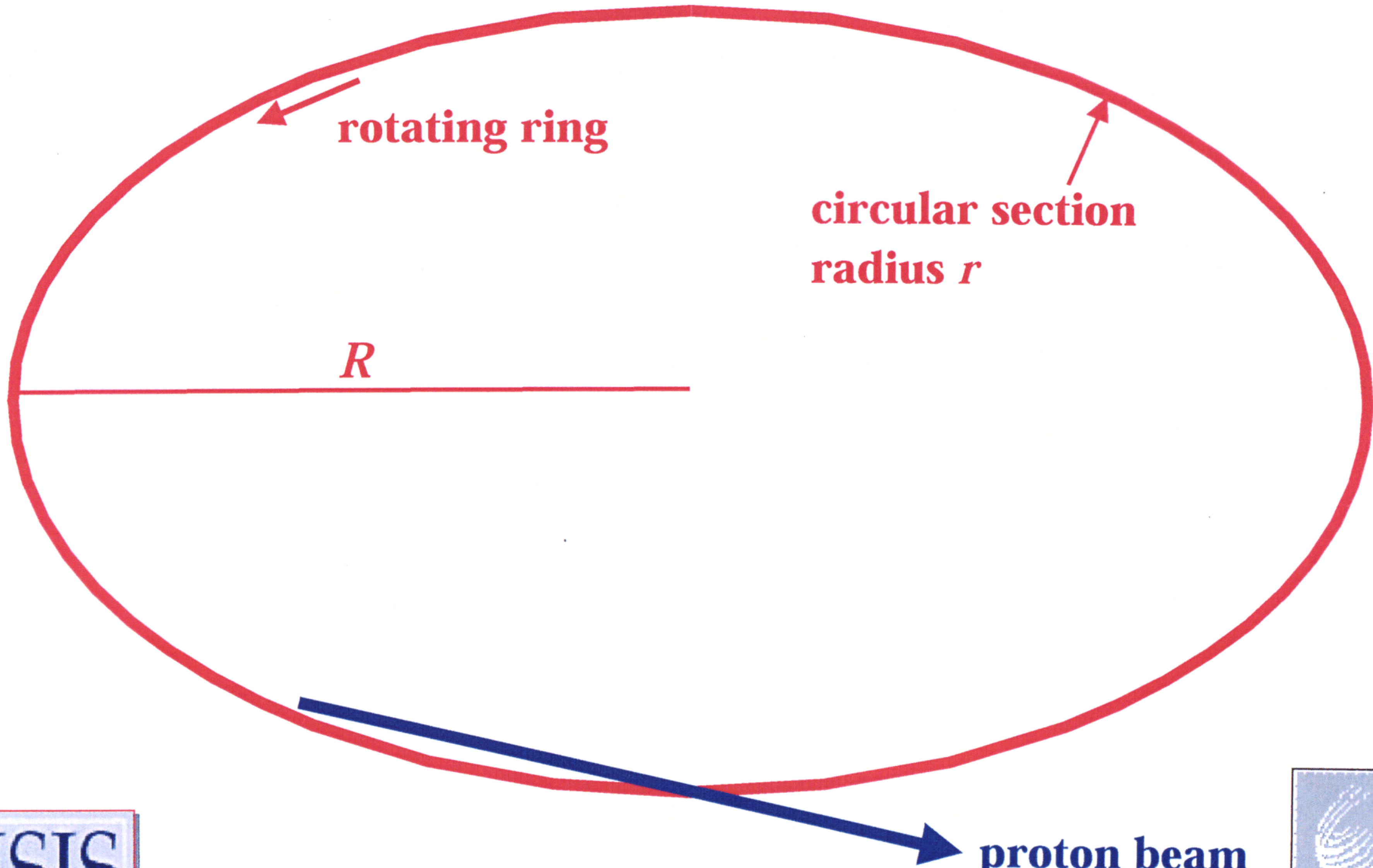
1. Make a plan for which parameters of liquid metal targets should be experimentally determined, what equipment is needed for their measurement. Identify the theoretical calculations the experimental results should be compared to.

2. Move the liquid jet equipment to the ISOLDE chemistry laboratory and demonstrate its function with Mercury.

3. Organize a test in Europe of the injection of the Mercury jet into a strong magnetic field.

4. Start planning the in-beam tests of the Hg-jet in the ISOLDE target area.

Schematic Diagram of the Toroid

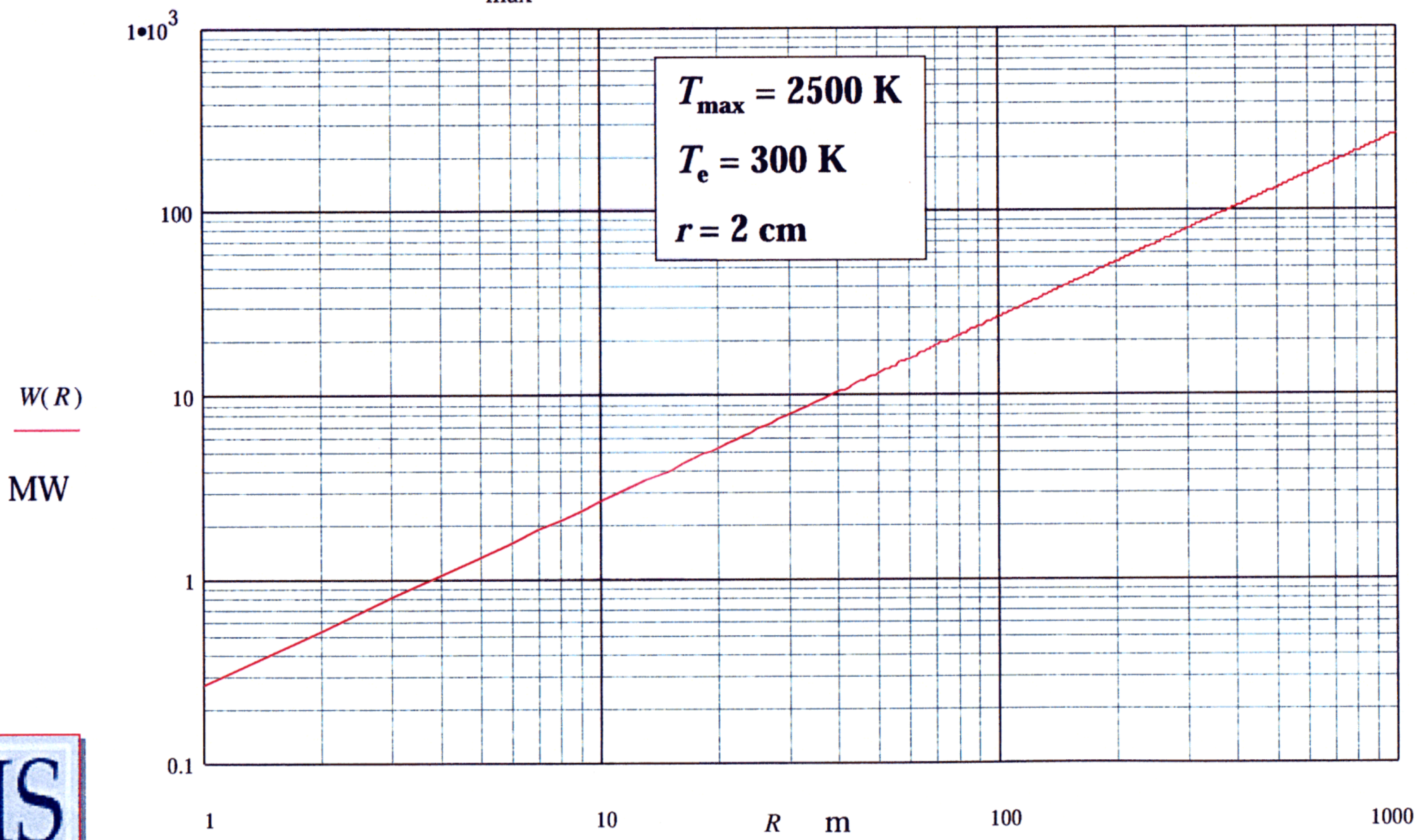


Maximum Power Dissipation

The maximum power that can be dissipated in a given size (surface area) target is found when the target rotates very fast and the whole target is at the maximum temperature. The power dissipation is given by:

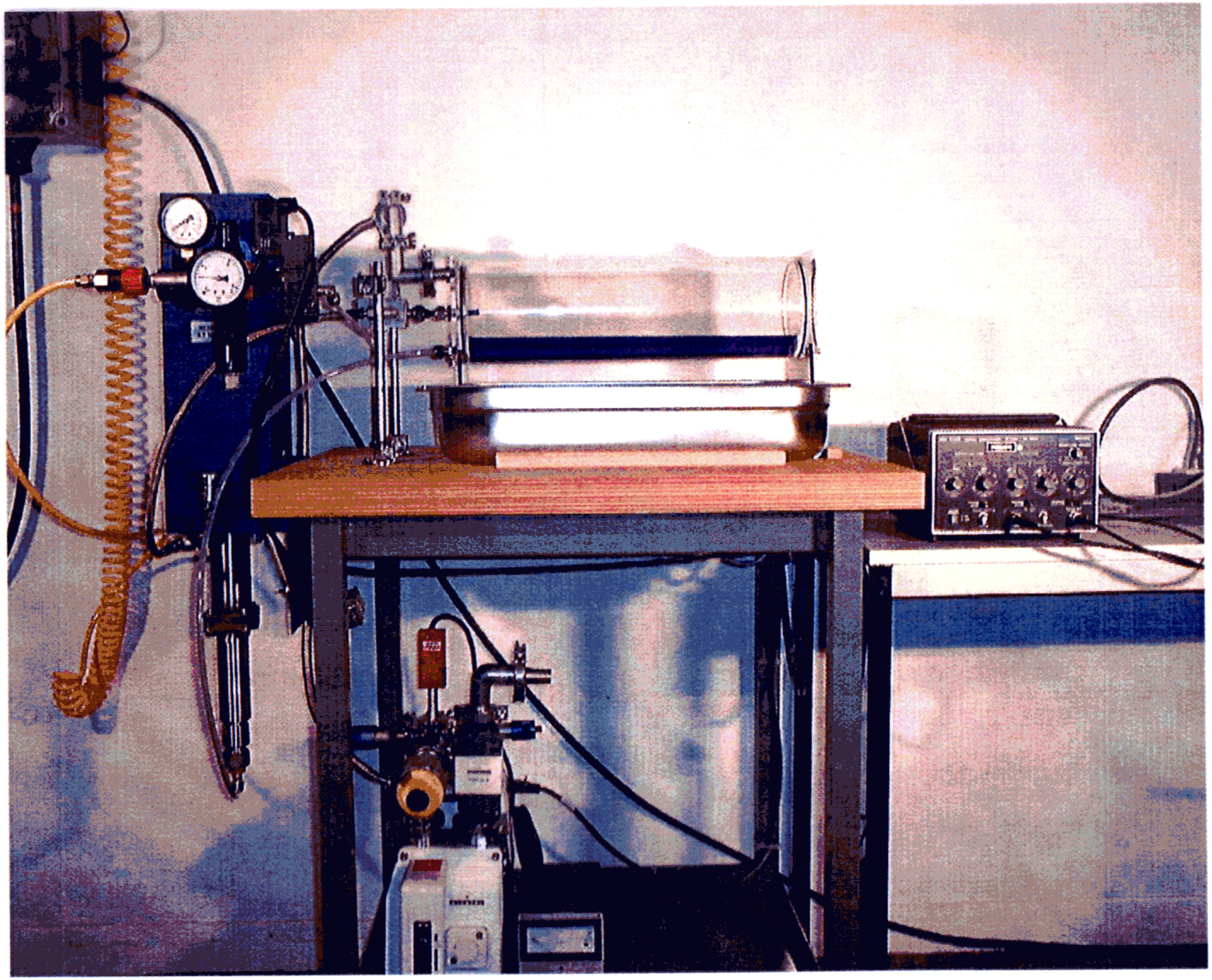
$$W_{max} = 2\pi r 2\pi R \varepsilon \sigma g \left(T_{max}^4 - T_e^4\right)$$

$$W_{max} = 2.622 ?10^3 ?R$$

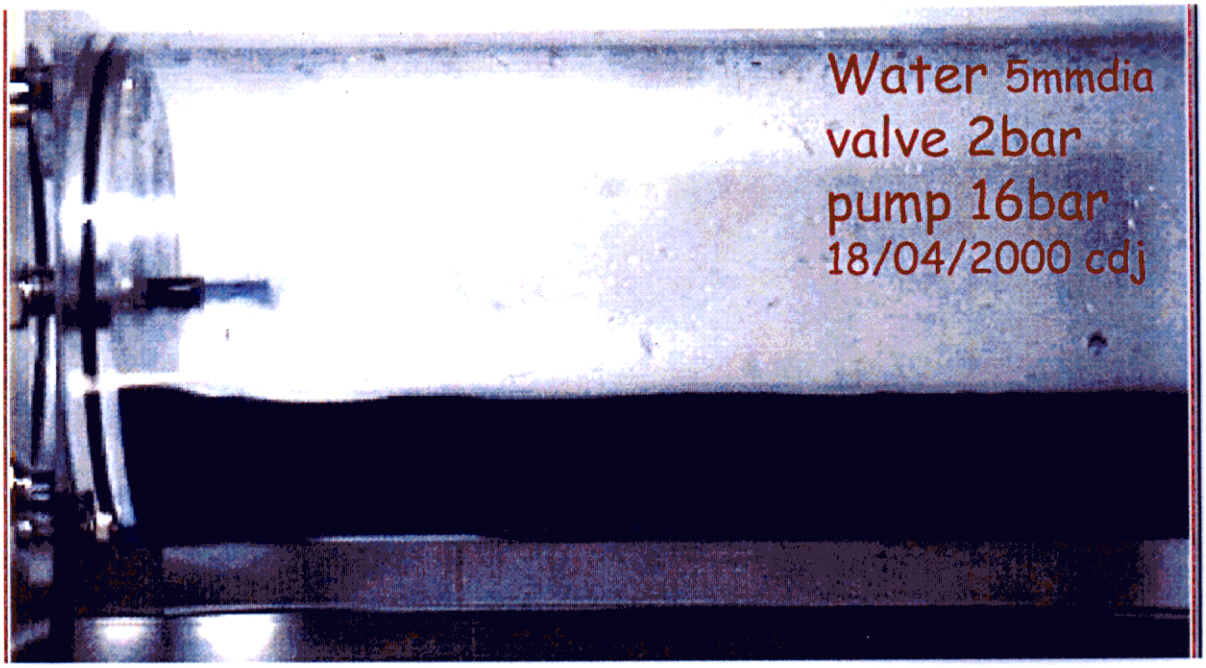


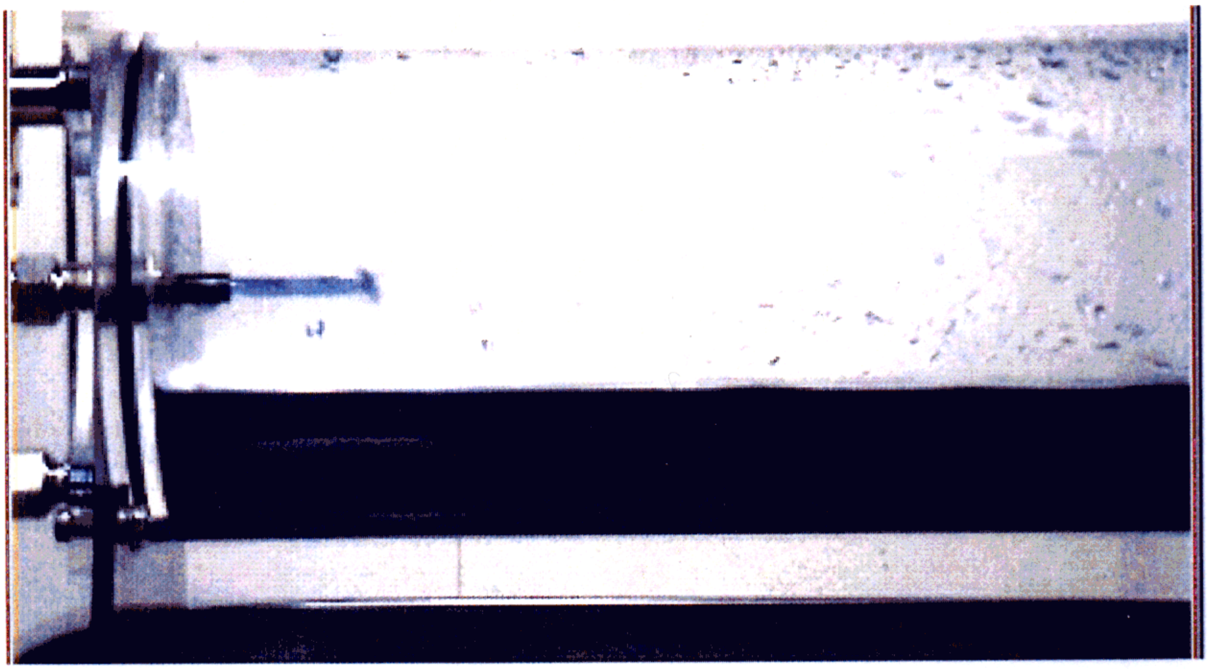
ISIS

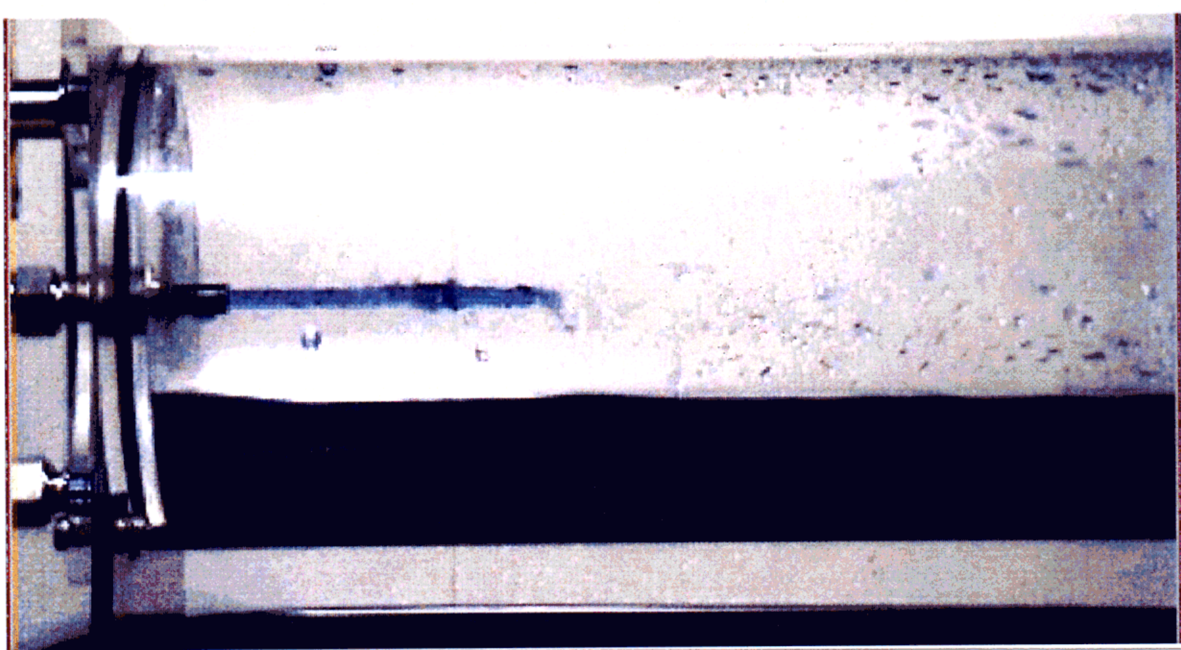
CLRC

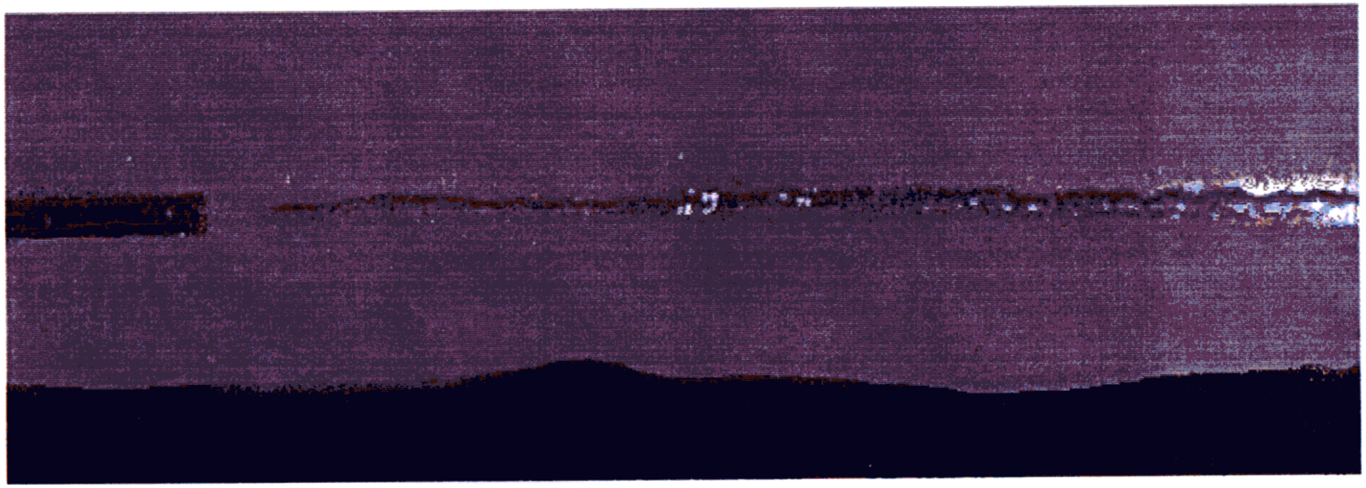


cdj 18/04/00

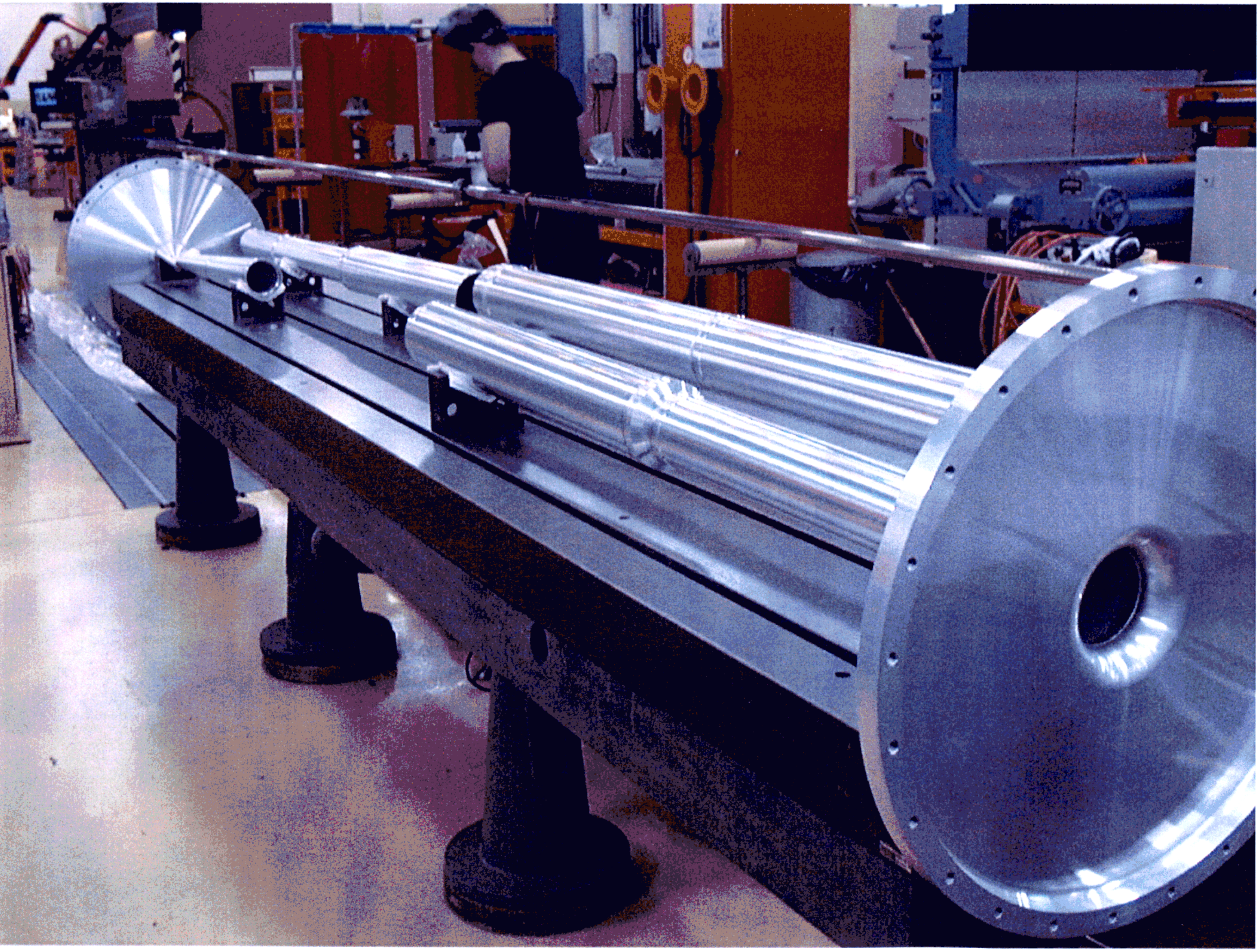

Water 5mmdia
valve 2bar
pump 16bar
18/04/2000 cdj

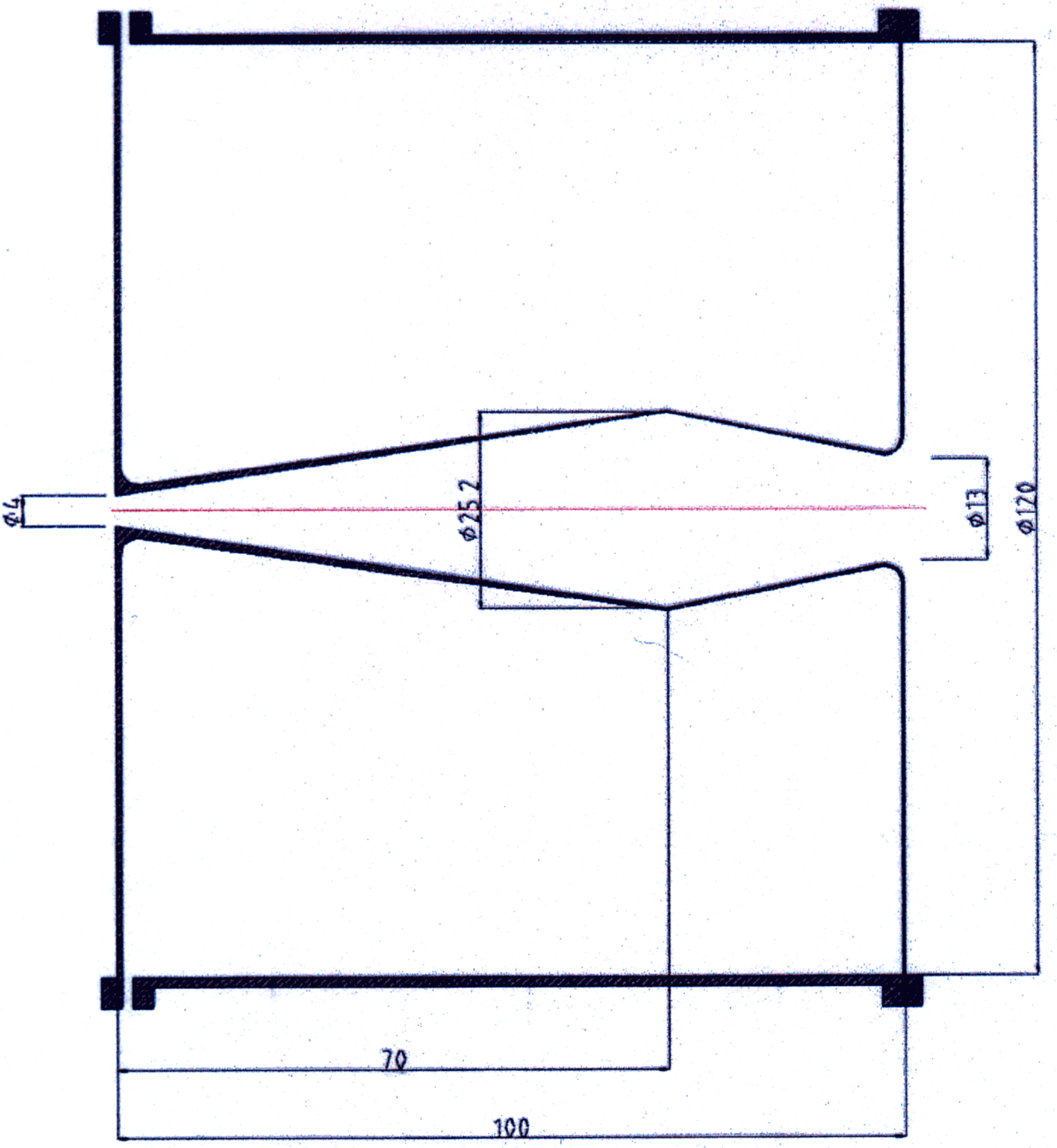






Tail end of jet - 20 m/s (retouched)



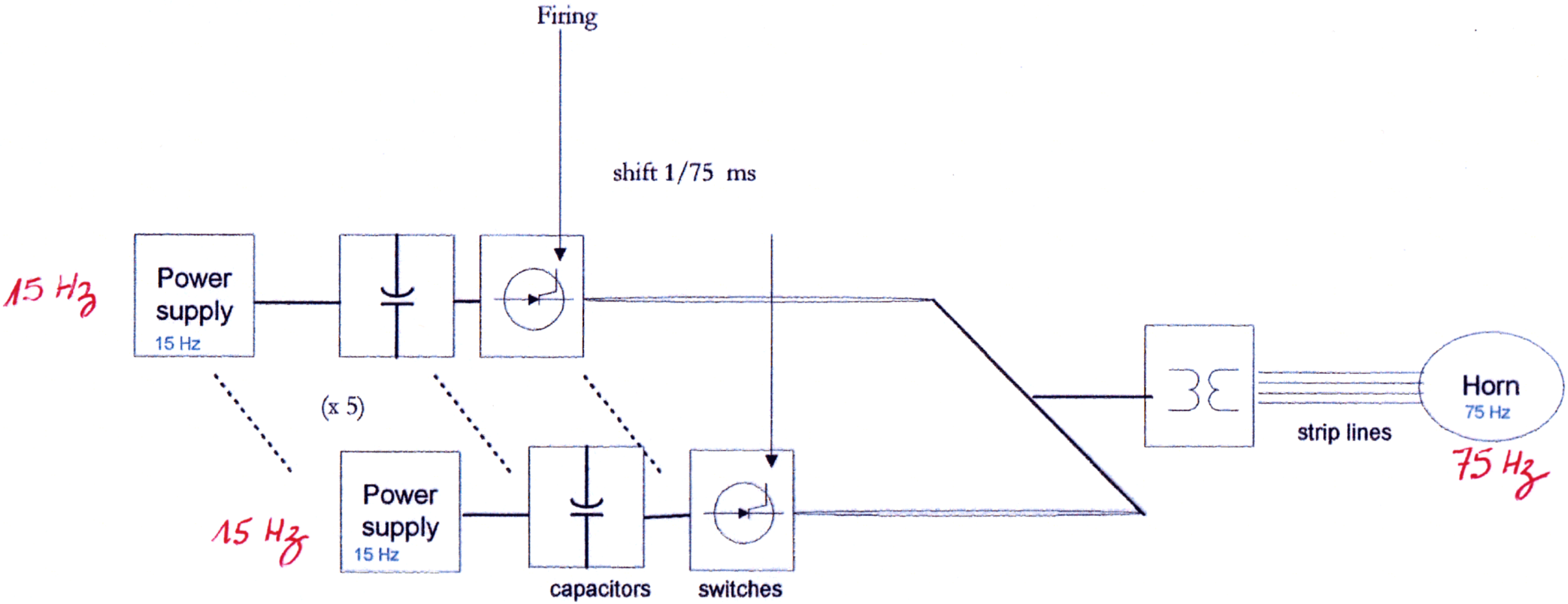


NEUTRINO FACTORY HORN REFERENCE

Dimensions in cm

Proposed technical layout

Medium or high voltage horn



400 kA - 75 Hz horns compared to existing projects

	Units	High Voltage 75 Hz	Medium Voltage 75 Hz	Mini Boone	KEK Horn	CNGS Horn
Distance of capacitor & switching unit location	m	10	10	10	50	1000
Transformer					m = 10	m = 16
Peak current in horn	kA	400	400	170	250	150
Inductance horn	μH	0.42	0.42	0.68	1.03 103 primary	2.15 550 primary
Inductance additional	μH	0.20	0.20	0.66	45 primary	240 primary
TOTAL inductance	μH	0.62	0.62	1.34	148 primary	790 primary
Resistance horn	μΩ	128	94	230	210 21040 prim.	405 104000 prim.
Resistance additional	μΩ	200	200	770	15210	119000 prim.
TOTAL resistance	μΩ	328	294	1000	36250 prim.	223000 prim.
Total capacitance for 1 switching section	μF	1075	4300	1500	6000	2270
Pulse duration (half period)	μs	81	162	143	3000	4300
Skin depth	mm	1.0	1.4	1.3	5.8	7.0
Charging voltage	V	9700	4900	5350	4702	7210
Energy stored in 1 sectio	kJ	50.5	51.6	21.5	66.4	59
Efficiency		0.66	0.65	0.48	0.49	0.41
Total energy stored	kJ	5 x 50.5	5 x 51.6	21.5	66.4	2 x 59
Voltage on element	V	6570	3300	2714	470	450
Charging current with recuperation	A	9.4	33.4	14.1	7.4	3.9 X 2
Charging power	kW	91.2 x 5	164 x 5			
Duty cycle	Hz	75 13.333 ms	75	15 66.666 ms	0.5	2 pulses in 6s 50ms apart
r.m.s. current in horn	A	22066	31227	5669	6900	4008
r.m.s. current density in smallest section	A/mm2	22.0 for 1000 m	31.2 for 1000 m	14.9 neck=target	14.1 neck=target	9.7
Mean power dissipation in horn by current *	kW	62.3	91.7	7.4	10.0	6.4
r.m.s. current in horn with 15 pulses / s	A	9868	13965	5669		
Mean power dissipation in horn by current with 15 pulses / s *	kW	12.4	18.3	7.4		
Water flow needed in l/min with $\delta\theta$ = 20°C	l/min	45	66	5.3	7.2	4.6
Number of pulses in 1 month of operation		2×10^8	2×10^8	0.39×10^8	1.296×10^6	0.864×10^6
life time expected		10^9	10^9	2×10^8	1×10^7	4×10^7

* power dissipation due to beam absorption has to be added

300 kA- 75 Hz horns compared to existing projects

	Units	High Voltage 75 Hz	Medium Voltage 75 Hz	Mini Boone Horn	KEK Horn	CNGS Horn
Distance of capacitor & switching unit location	m	10	10	10	50	1000
Transformer					m = 10	m = 16
Peak current in horn	kA	300	300	170	250	150
Inductance horn	µH	0.42	0.42	0.68	1.03 103 primary	2.15 550 primary
Inductance additional	µH	0.20	0.20	0.66	45 primary	240 primary
TOTAL inductance	µH	0.62	0.62	1.34	148 primary	790 primary
Resistance horn	µΩ	128	94	230	210 21040 prim.	405 104000 prim.
Resistance additional	µΩ	200	200	770	15210	119000 prim.
TOTAL resistance	µΩ	328	294	1000	36250 prim.	223000 prim.
Total capacitance for 1 switching section	µF	1075	4300	1500	6000	2270
Pulse duration (half period)	µs	81	162	143	3000	4300
Skin depth	mm	1.0	1.4	1.3	5.8	7.0
Charging voltage	V	7275	3675	5350	4702	7210
Energy stored in 1 section	kJ	28.4	29.0	21.5	66.4	59
Efficiency		0.66	0.65	0.48	0.49	0.41
Total energy stored	kJ	5 x 28.4	5 x 29.0	21.5	66.4	2 x 59
Voltage on element	V	4928	2489	2714	470	450
Charging current with recuperation	A	7.0	25.0	14.1	7.4	3.9 X 2
Charging power	kW	51 x 5	92 x 5			
Duty cycle	Hz	75	75	15	0.5	2 pulses in 6s 50ms apart
r.m.s. current in horn	A	16550	23420	5669	6900	4008
r.m.s. current density in smallest section	A /mm2	16.5 for 1000 mm2	23.4 for 1000 mm2	14.9 neck=target	14.1 neck=target	9.7
Mean power dissipation in horn by current *	kW	35.0	51.5	7.4	10.0	6.4
r.m.s. current in horn with 15 pulses / s	A	7400	10474	5669		
Mean power dissipation in horn by current with 15 pulses / s *	kW	7.0	10.3	7.4		
Water flow needed in l/min with $\delta\theta = 20°C$ *	l/min	25	37	5.3	7.2	4.6
Number of pulses in 1 month of operation		2×10^8	2×10^8	0.39×10^8	1.296×10^6	0.864×10^6
life time expected		10^9	10^9	2×10^8	1×10^7	4×10^7

* power dissipation due to beam absorption has to be added

POSSIBLE TESTS

- Thermal transfer for the requested shape with spray water cooling for 5000, 10000, 15000, 20000 A – DC and with DC current density of 15, 20, 25, 30 A/mm2.
  This test can be done with modest effort.

- FE analysis to define optimum thickness (rough estimate indicate that a total section of 1000 mm2 is needed in the critical areas along the profile – extrapolated from KEK results).

??
- Measure limit of fatigue of Al Alloy for 10^{8} repeated tractions of short duration (100 μs) with a horn like system using an existing system . Test at the same time the basic thyristor .
  Study and construct this system with existing equipment.

- Detailed design of horn system taking in account mini-boone results.

- Construct one branch with one final horn prototype powered at 15 Hz. Design one power supply 10 kV, 10A , 15 Hz which can be also be used on the CNGS horn (7.2 kV, 2 x 3A, 4.5s charging time).
  This test will set the horn current limit for reliability.

- Use AD horn test area a 1 Hz to test:
  horn parameters
  thyristor switch arrangement

- study vibration problems (→ Mini Boone)

A 40-80 MHz System for Phase Rotation and Cooling

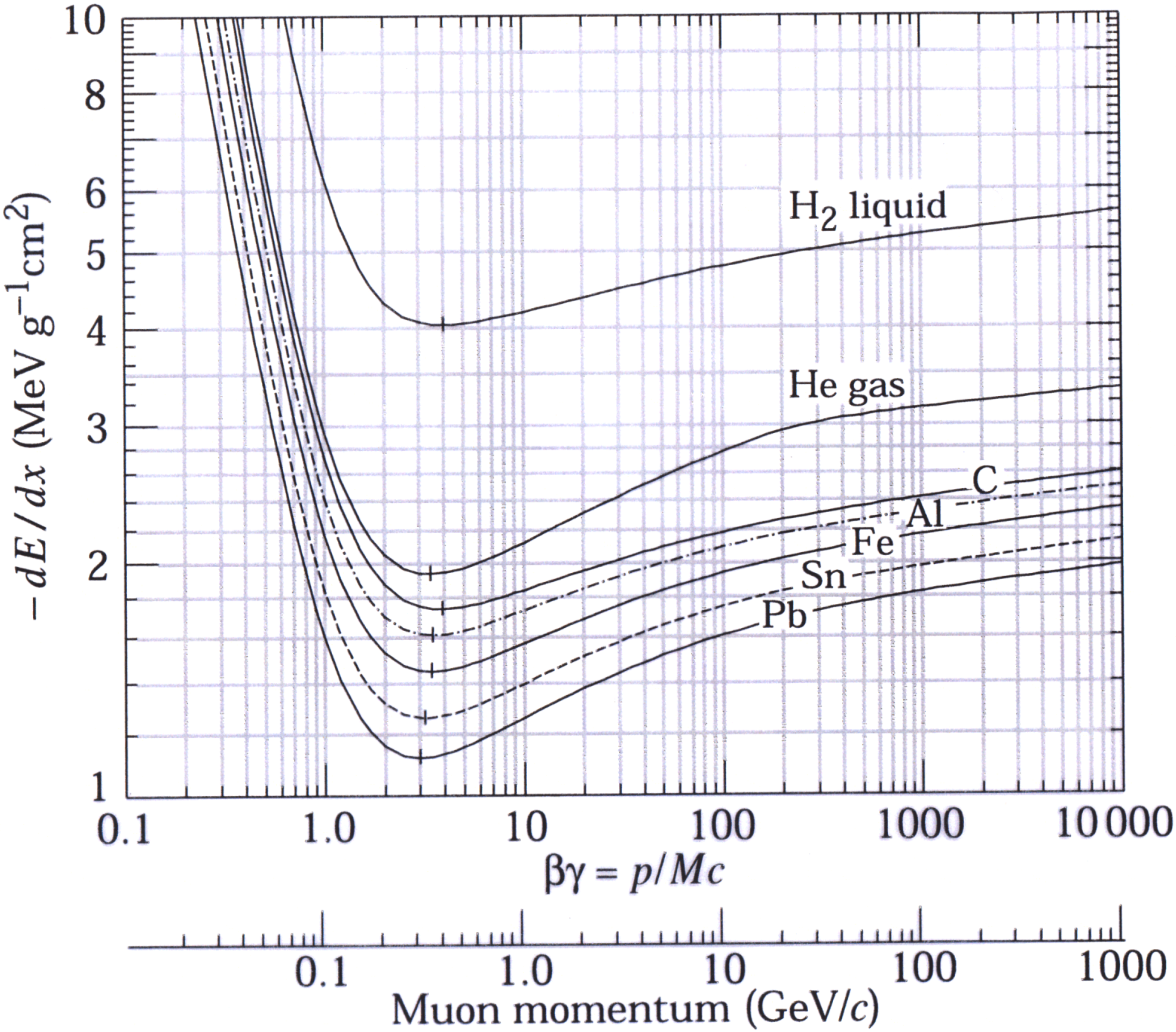
After the target the pions decay in a 30m long channel focussed by a 1.8 Tesla solenoid. At its end the particles within the energy range

100-300 MeV

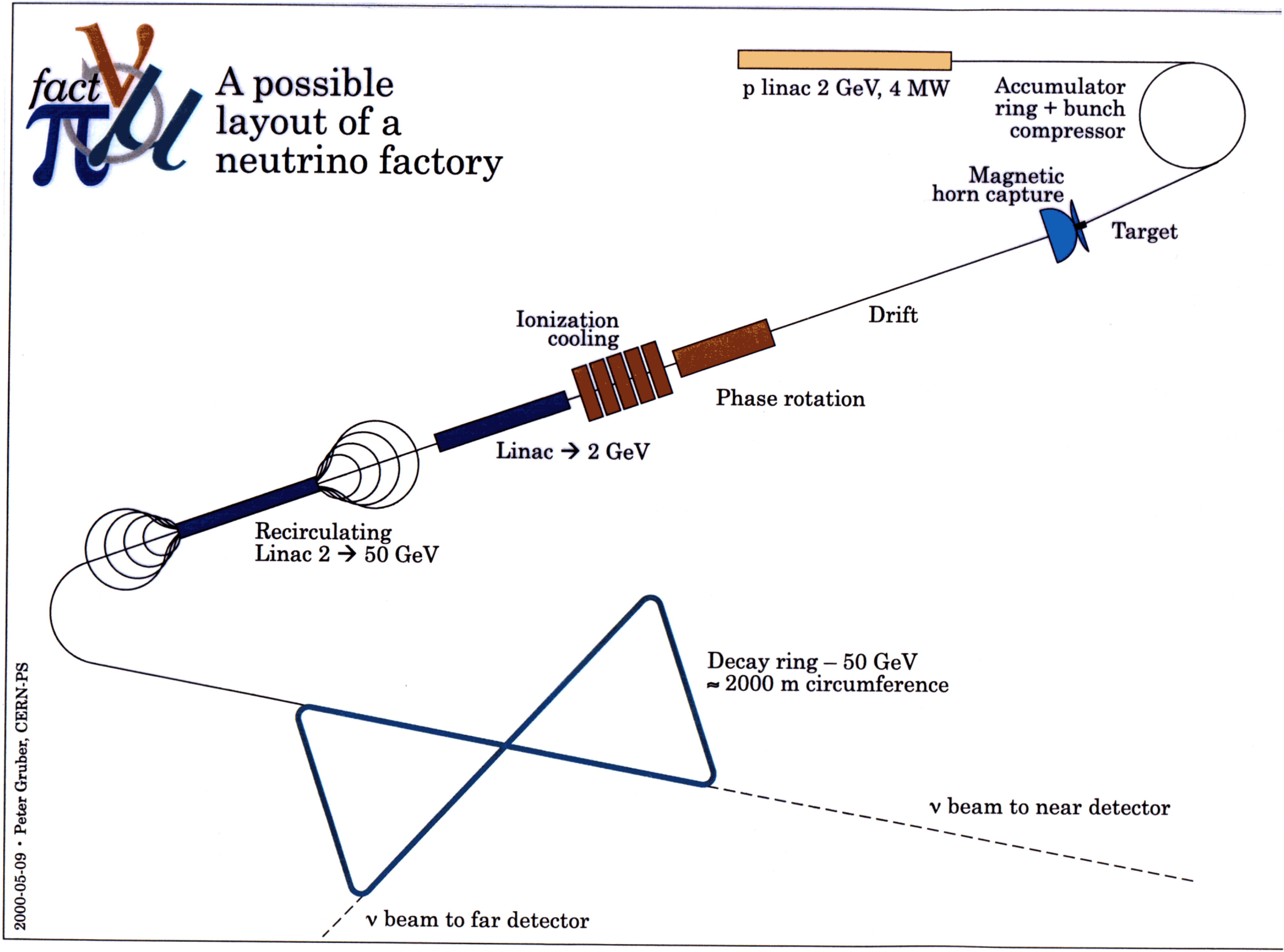
are captured in a series of 44 MHz cavities and their energy spread reduced by a factor two.

A first cooling stage, employing the same RF cavities, reduces the transverse emittances by a factor 0.6; thereafter the beam is accelerated to an average energy of 300 MeV. The beam phase width as well as the reduced physical dimensions of the beam allows to employ an 88 MHz cavity cooling system that will reduce the transverse normalised emittance to the required 15 pimm (re-circulator acceptance). The system will be continued at 88 MHz, at 176MHz and finally at 352 MHz until the final energy of 2 GeV is reached.

The muon yield of this system corresponds to 0.0156 m/proton, and again assuming 10^{23} proton/year, this system would produce 1.6 x 10^{21} m/year. If we remove the production mechanism from the count this system gives 0.09 μ/p collected in a 30 cm radius.



$-dE/dx$ (MeV g^{-1}cm^2)
10
8
6
5
4
3
2
1
H_2 liquid
He gas
C
Al
Fe
Sn
Pb
0.1
1.0
10
100
1000
10 000
$\beta\gamma = p/Mc$
0.1
1.0
10
100
1000
Muon momentum (GeV/c)

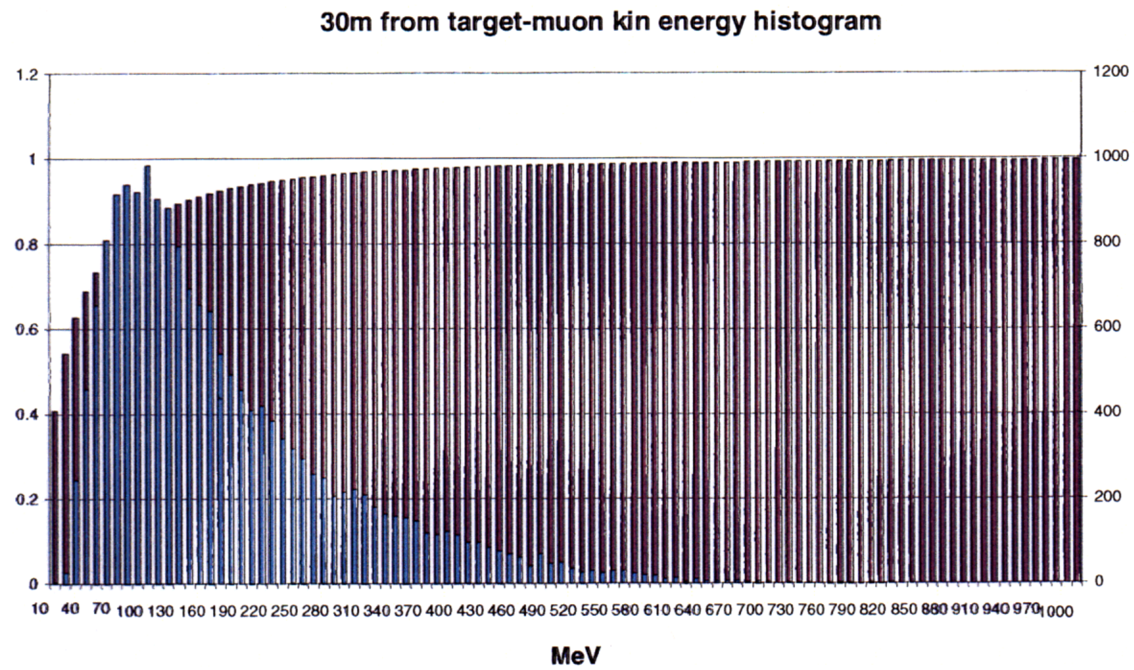

fact ν πμ
A possible layout of a neutrino factory
p linac 2 GeV, 4 MW
Accumulator ring + bunch compressor
Magnetic horn capture
Target
Drift
Ionization cooling
Phase rotation
Linac → 2 GeV
Recirculating Linac 2 → 50 GeV
Decay ring – 50 GeV
≈ 2000 m circumference
ν beam to near detector
ν beam to far detector
2000-05-09 • Peter Gruber, CERN-PS

THE OVERALL SYSTEM

(2 MV/m at 40 MHz,   4 MV/m at 80 MHz)

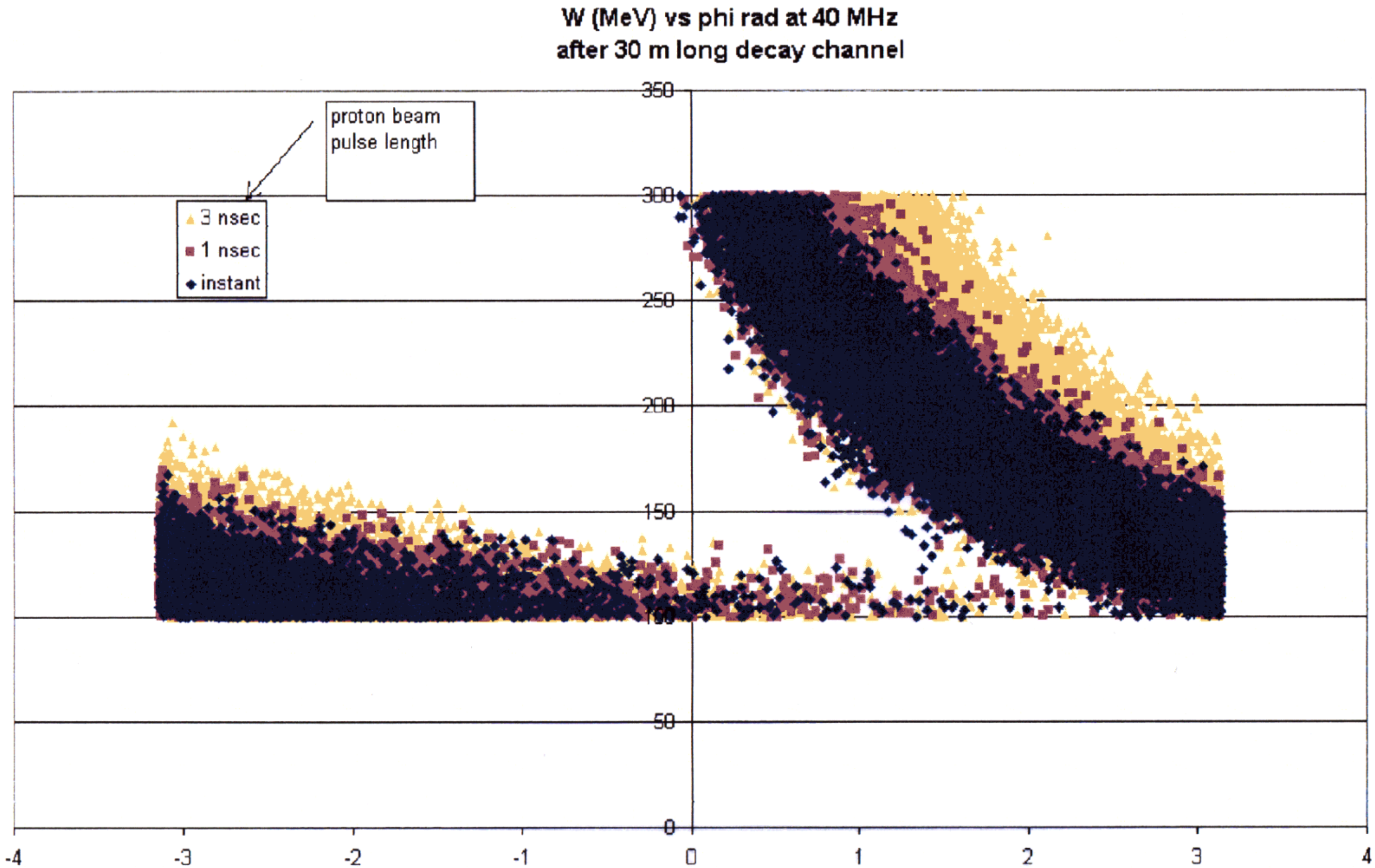
	Decay	Rotation	Cooling I	Acceleration	Cooling II	Acceleration
Length [m]	30	30	44	44	48	
Diameter [cm]	60	60	60	60	30	
Focalisation [T]	1.8	1.8	2.0	2.0	2.0	
Frequency [MHz]	[redacted]	40	40	40	80	

$\approx 10^{21}$ μ/year in
re-circulator acceptance



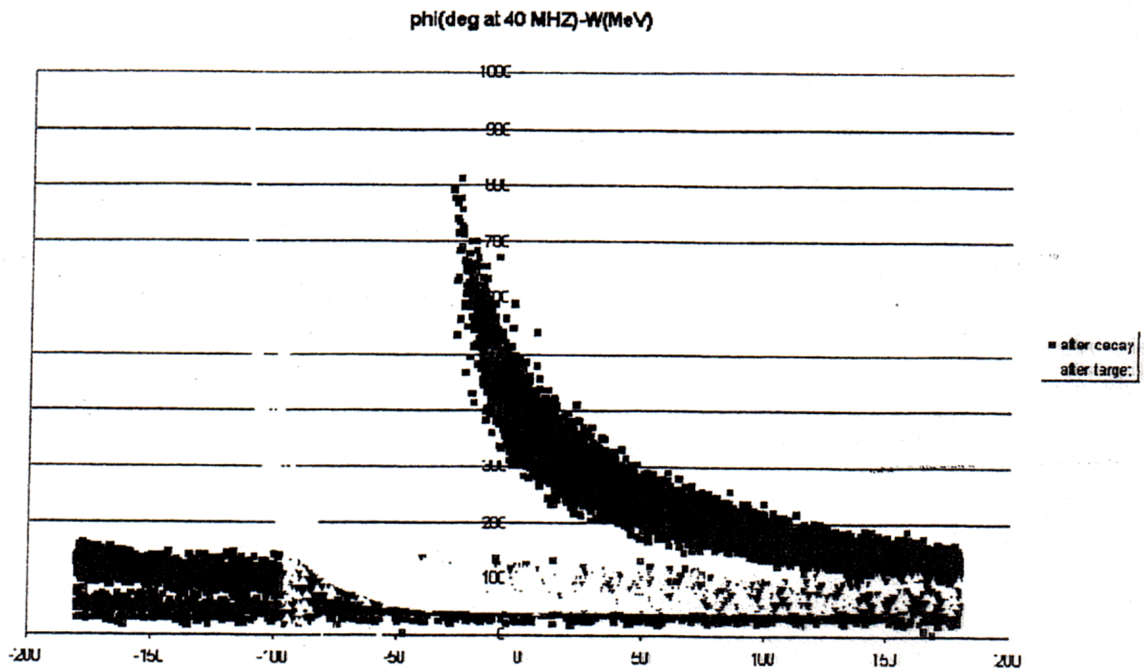
DEBUNCHING per METRE at 40 MHz :

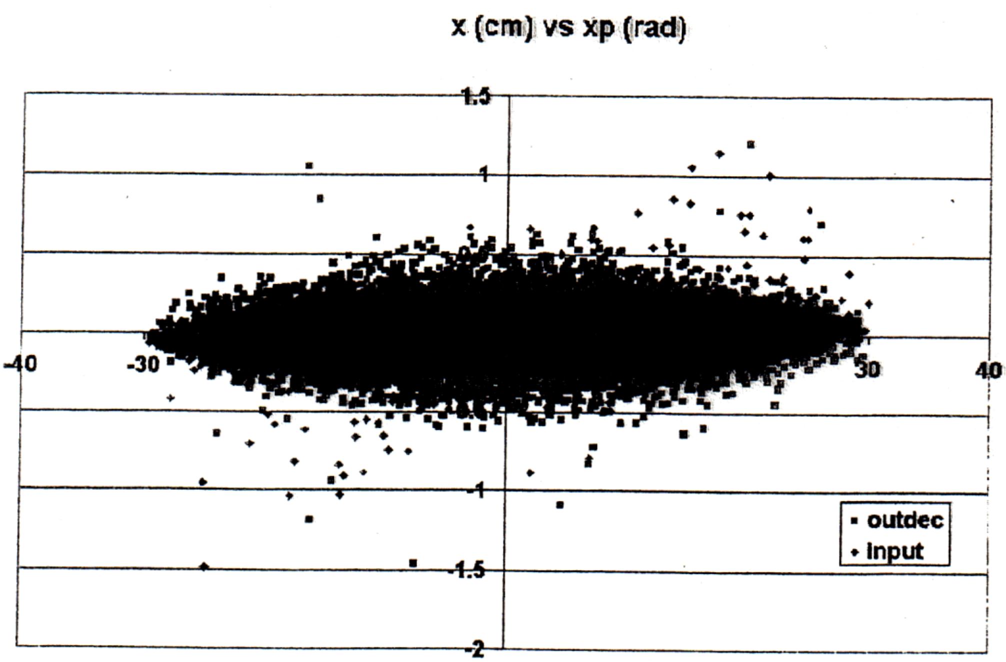
	+- 50 MeV	+-100MeV
150	4.7 degres	12.7
250	1.4	3.3
350	0.6	1.4



rotvspluselenght.gif

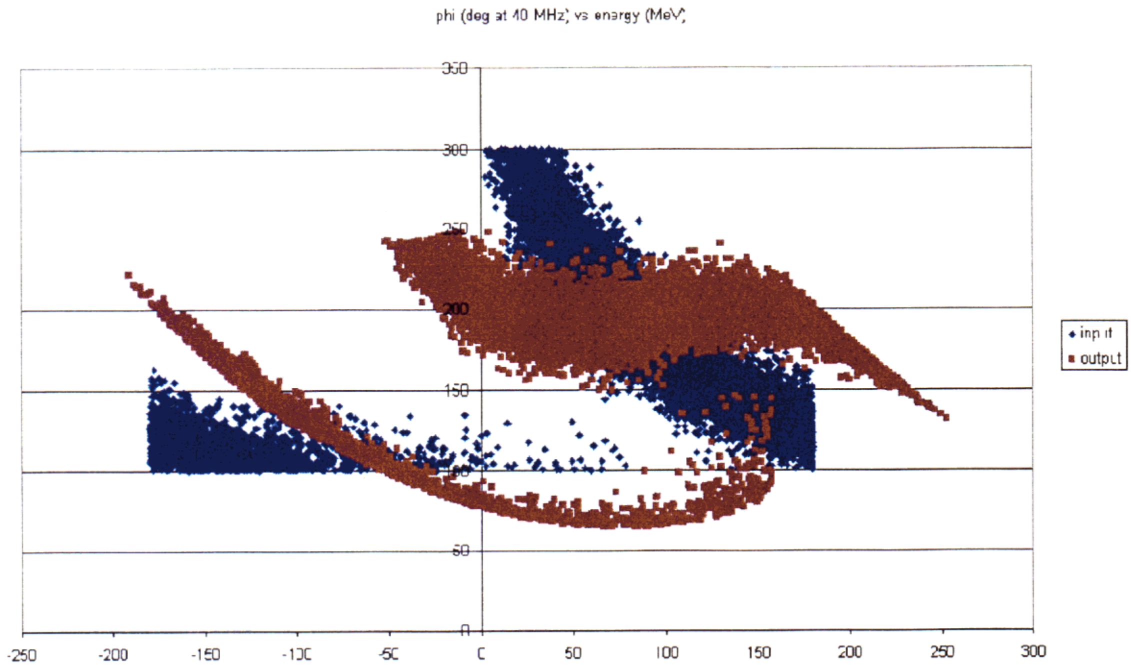
30 m long 1.8 Tesla solenoid, 60 cm bore diametre





ROTATION

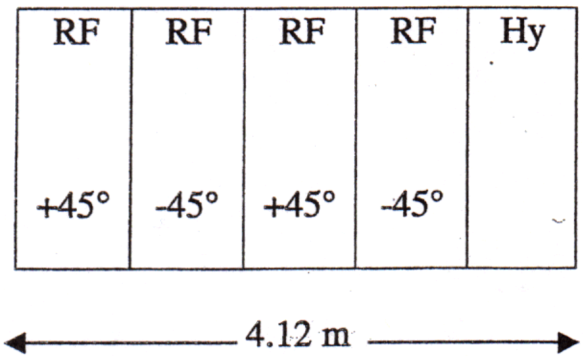
30 cavities , 1 m long, 40 MHz, 2MV/m, 1.8 Tesla solenoid around (or adjacent)



COOLING

first stage:

44 cavities , 1 m long, 40 MHz, 2MV/m, 1.8 Tesla solenoid



11 times

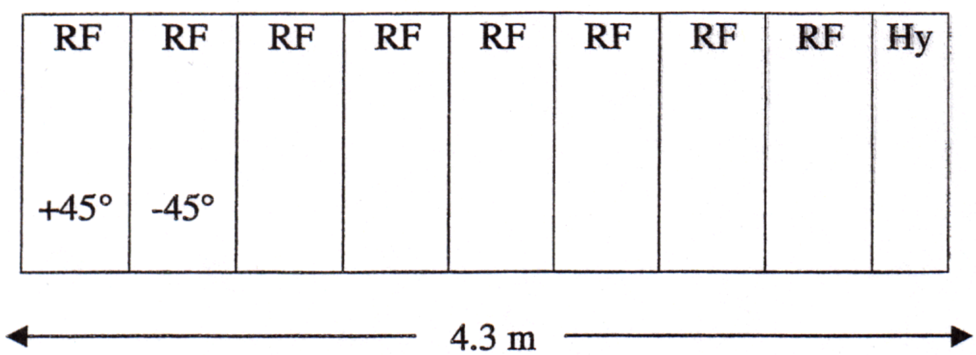
energy gain 4 MeV
energy loss 4 MeV

second stage:

as first stage without the absorbers, increase the average energy to 300 MeV

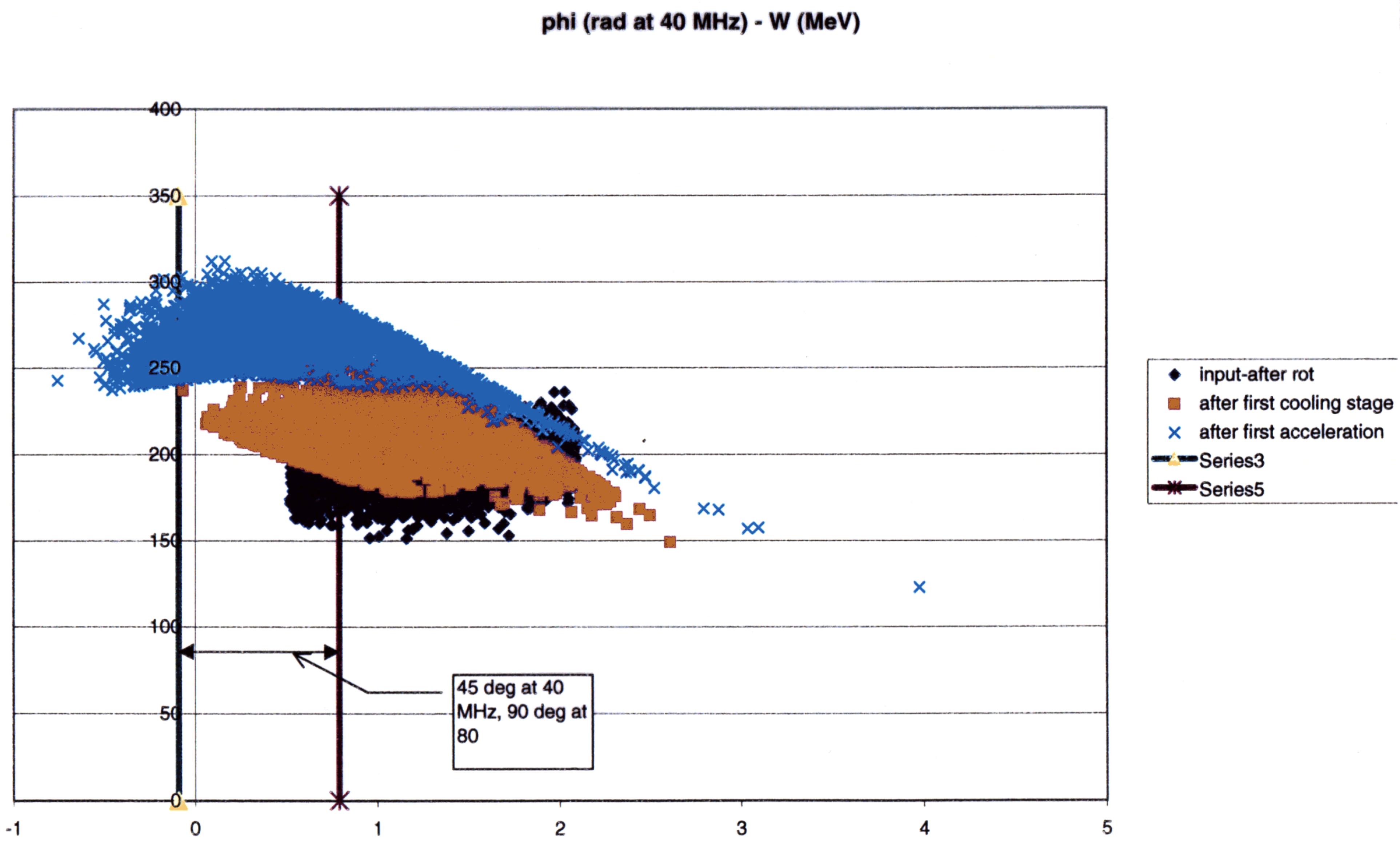
third stage:

96 cavities , 1/2 m long, 80 MHz, 4MV/m, 2.0 Tesla solenoid

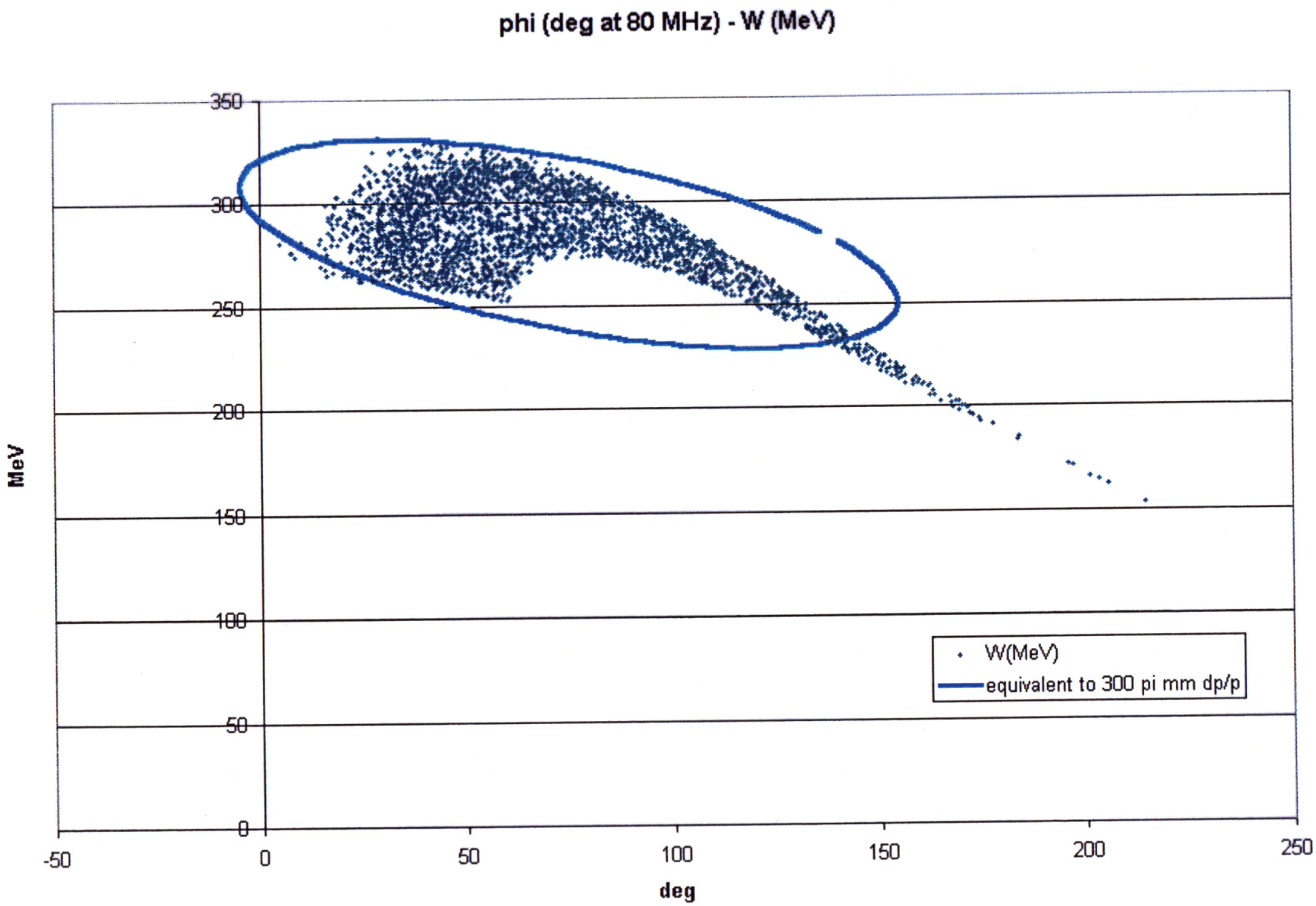


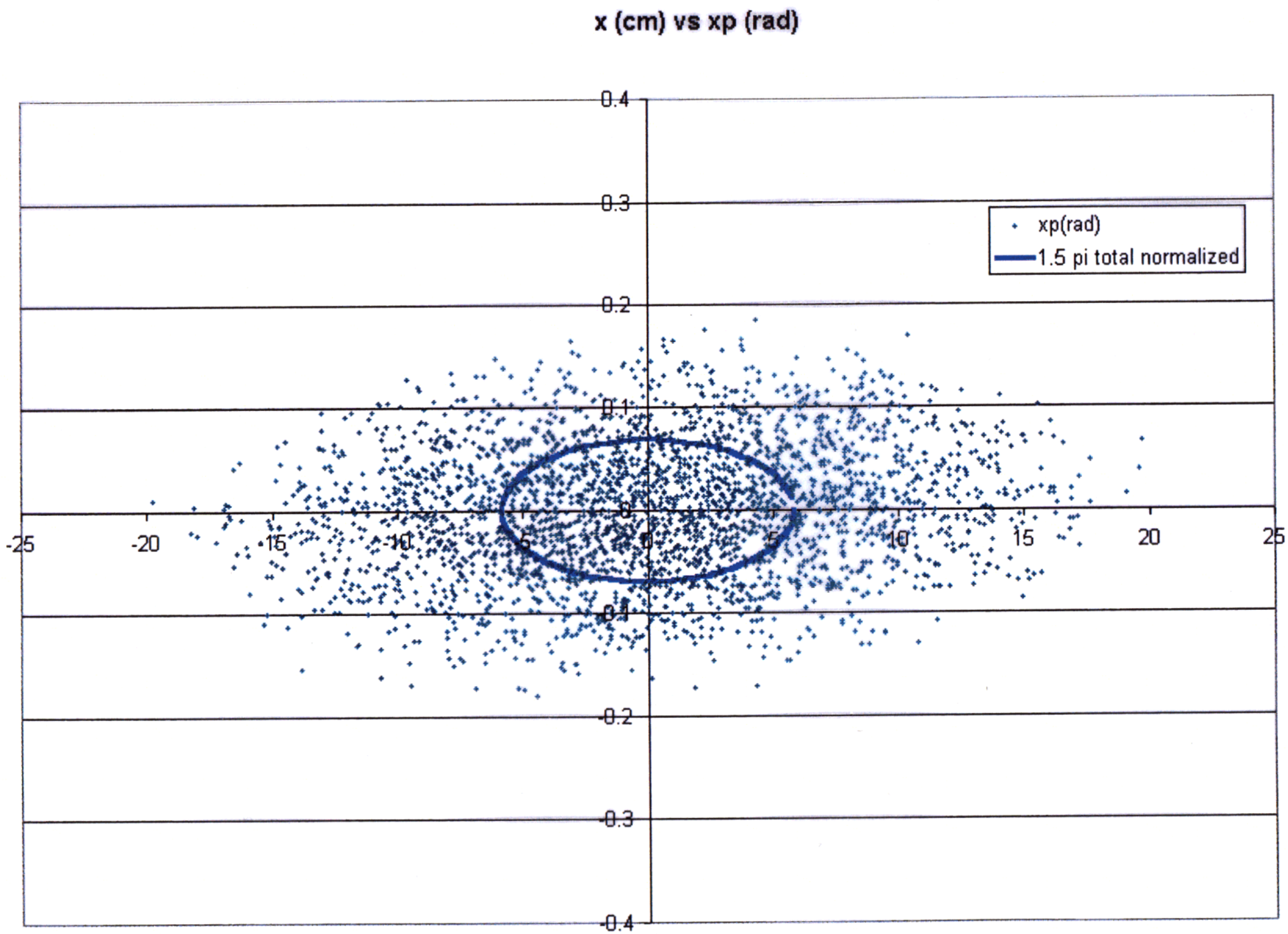
12 times

energy loss 8 MeV
energy gain 8 MeV



phi (rad at 40 MHz) - W (MeV)
400
350
300
250
200
150
100
50
0
-1
0
1
2
3
4
5
45 deg at 40 MHz, 90 deg at 80
input-after rot
after first cooling stage
after first acceleration
Series3
Series5


phi (deg at 80 MHz) - W (MeV)
MeV
deg
350
300
250
200
150
100
50
0
-50
0
50
100
150
200
250
W(MeV)
equivalent to 300 pi mm dp/p

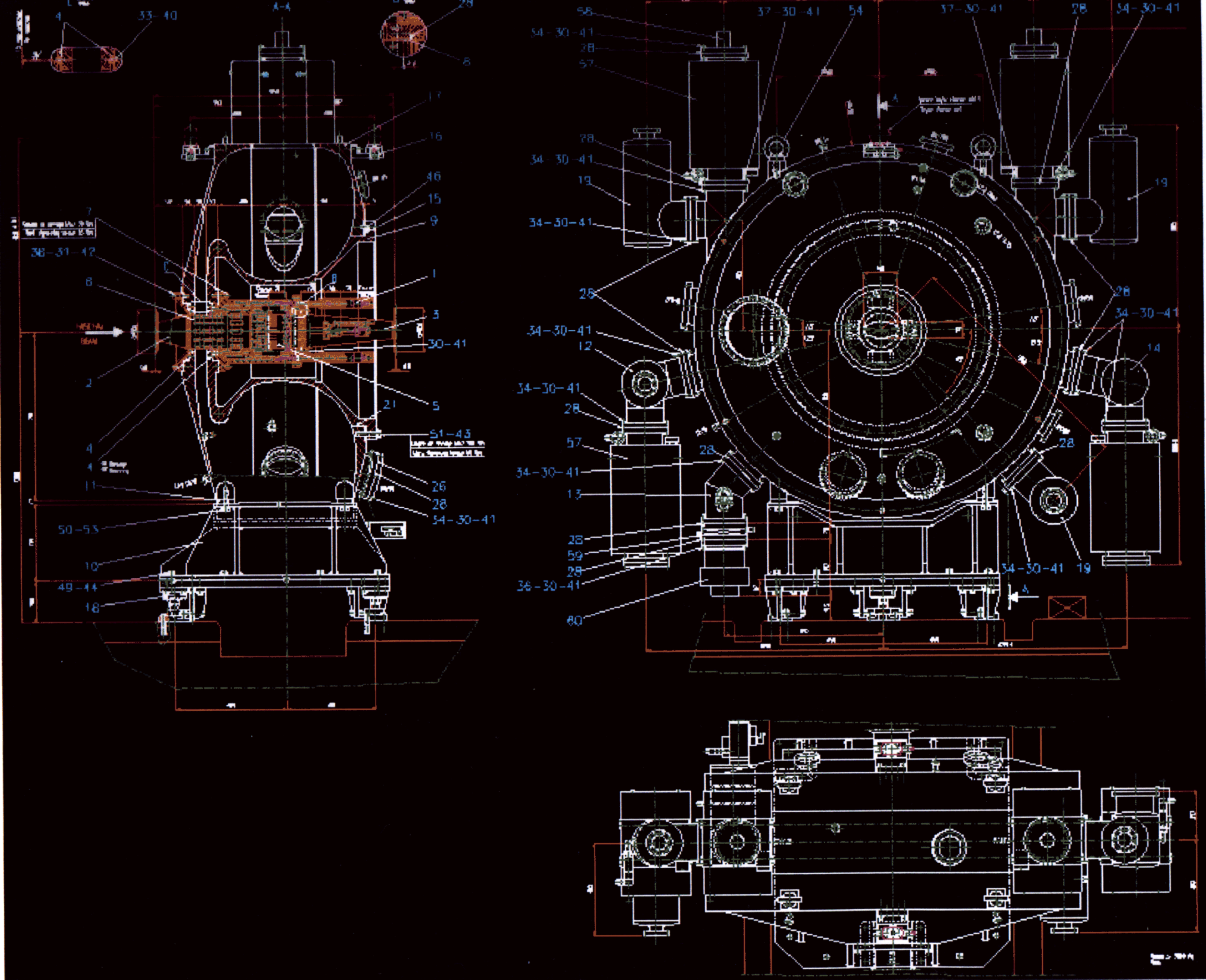

x (cm) vs xp (rad)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-25
-20
-15
-10
-5
0
5
10
15
20
25
xp(rad)
1.5 pi total normalized

PARTICLE BUDGET

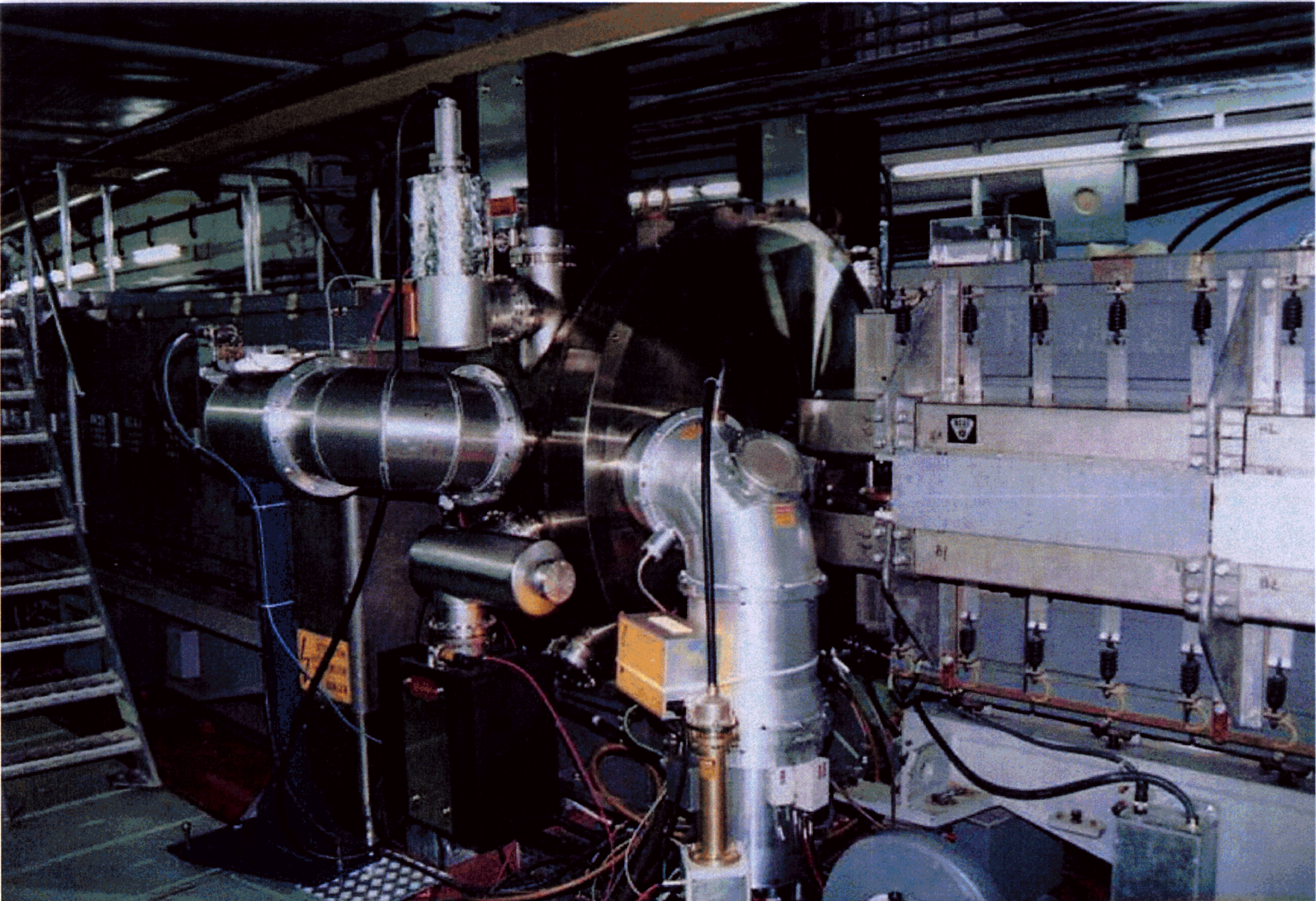
for 1000 protons impinging instantaneously on the target

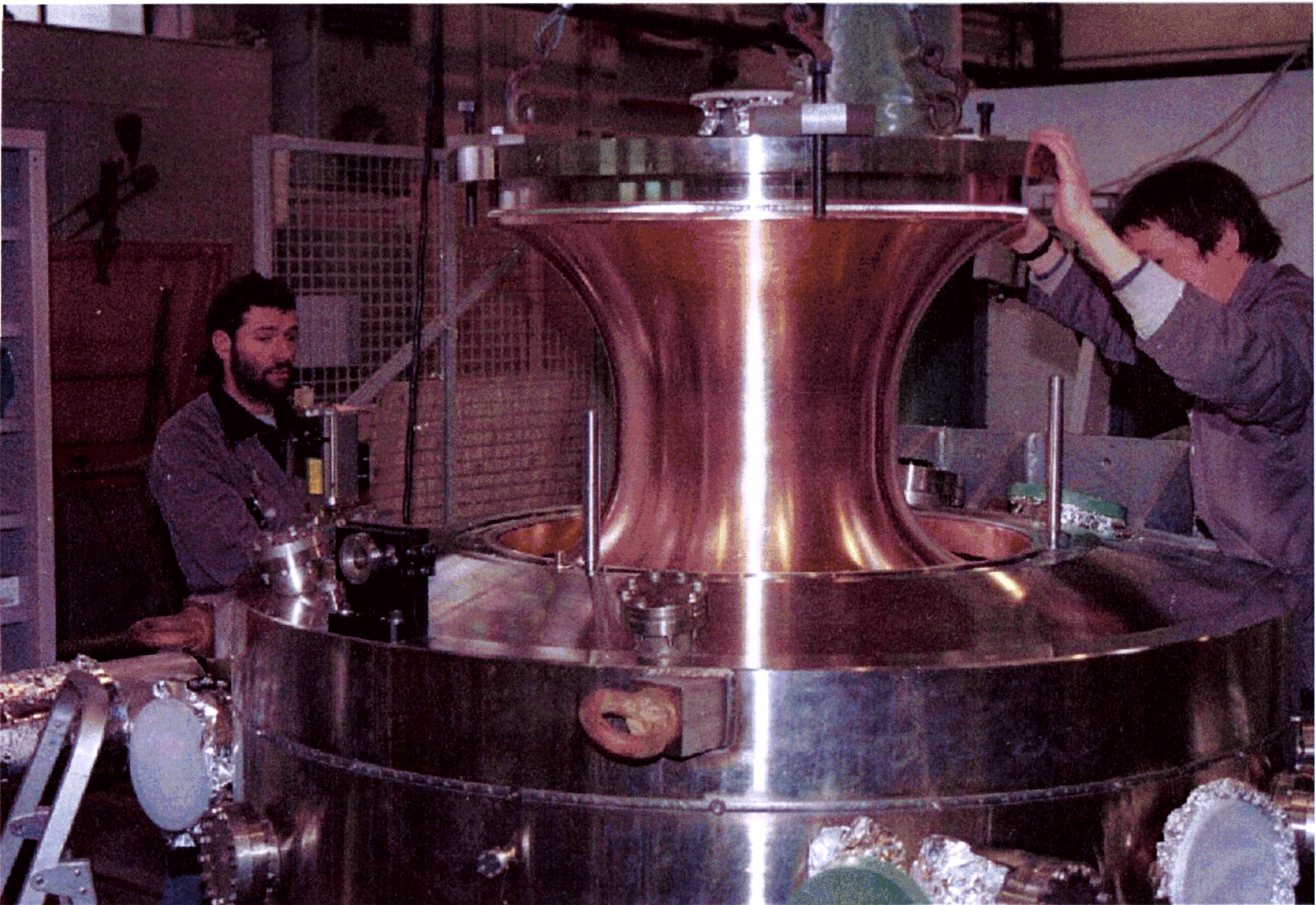
decay	in	180
	out	177
rotation	in	93
	out	93
cooling I	in	32
	out	31
acceleration	in	31
	out	31
cooling II	in	20
	out	15

proton pulse length(nsec)	μ/year (10^{21})
0	1.6
1	1.5
2	1.3
3	1.1



A-A
33-40
4
28
8
17
16
46
15
9
7
38-31-47
6
1
3
30-41
2
5
21
51-43
4
4
26
28
34-30-41
11
50-53
10
49-44
18
58
34-30-41
28
57
37-30-41
54
37-30-41
28
34-30-41
28
34-30-41
19
34-30-41
19
25
28
34-30-41
34-30-41
12
14
34-30-41
28
57
28
28
34-30-41
13
28
59
28
36-30-41
34-30-41
19
60





What makes this RF scenario attractive is its use of existing technology, e.g. that of the CERN PS 40MHz cavity. Results of exploratory SFH runs for a 44 MHz normal-conducting cavity of 30 cm bore radius are encouraging (1.6 MW power required for 2 MV/m). This cavity could accommodate a solenoid around the chamber.

Preliminary estimations of the power losses for 2 MV/m at 44 MHz and 4MV/m at 88 MHz give a figure of 10 MW for the entire phase rotation and cooling system for the 100 Hz pulse rate of the 2 GeV proton driver.

A choice in favor of a low energy proton driver will depend both upon the existence of such an optimized scheme and on the demonstration of the production of an adequate flux of pions/muons by low energy protons (result expected from the HARP experiment planned at the CERN PS).

Muon Linac

Some work has been going on the design of a muon linac after the beam has been cooled.

Preliminary results show that up to an energy of about 1 GeV a solenoidal type focusing is required. The muon linacs will be slightly different for the induction linac option and for the RF option. In the first case the linac will start with 176 MHz cavities, whereas in the latter with 80 MHz.

Muon Recirculating Linear Accelerator Design

E. Keil

NFWG – 19 Apr 2000

~keil/MuMu/Doc/NFWG/19Apr00/19apr00.pdf

Energy Spread

- Relative energy spread $\sigma_{\rm bi}$ from μ source damped $\propto 1/\gamma$
- Constant relative energy spread $\sigma_{\rm RF}$ from RF wave form at circular frequency ω and bunch length σ_z causes a severe limit on σ_z

$$\sigma_{\rm RF} = \frac{1}{\sqrt{2}}\left(\frac{\omega\sigma_z}{c}\right)^2$$

- μSR designed for energy spread $\sigma_e \approx 0.005$
- Impose condition $\sigma_{\rm bf}^2 \approx \sigma_{\rm RF}^2 \leq \sigma_e^2/2$ and find with $f_{\rm RF} = 352.209$ MHz

$$\sigma_z \leq 9.58 \text{ mm} \qquad \sigma_{\rm bf} \leq 3.54 \cdot 10^{-3}$$

- Scale $\sigma_{\rm bf}$ to input end of μRLA1 and μRLA2, and obtain

$$\sigma_{\rm bi1} \leq 8.84 \cdot 10^{-2} \text{ and } \sigma_{\rm bi2} \leq 1.77 \cdot 10^{-2}$$

- Very small bunch area in conventional units $A = \pi\sigma_{\rm bf}E_{\rm f}\sigma_z/c = 0.018$ eVs

Beam Loading of RF Cavities II

- Accelerating voltage U, stored energy W_s, extracted energy W_e vs. pass number
- Leading bunch sees voltages for passes 0 to 3, i.e. 36.62 MeV trailing bunch for passes 1 to 4, i.e. 34.36 MeV instead of 40 MeV

Pass	0	1	2	3	4
U/MV	10.0	9.44	8.87	8.31	7.74
W_s/Joule	97.4	86.8	76.7	67.2	58.4
W_e/Joule	10.7	10.1	9.46	8.86	8.26

- Energy difference between leading and trailing bunches is $\pm 3.1\%$
- Making up for extracted energy *during* passage of bunch train in 2 μs requires about 5 MW/cavity
- Cancel energy difference by adjusting bunch spacing such that later bunches travel closer to crest of RF wave?
- Increase U and/or f_r?

Geometrical Design of Spreaders and Combiners

- Spreaders installed at downstream end of linear accelerator section of RLA
- Spreaders feed beams of 4 different energies into 4 different arcs
- Spreaders can be horizontal or vertical, although I think in terms of vertical ones
- Combiners feed beams from 4 different arcs into upstream end of linear accelerator section of RLA
- Geometry of combiner at end of arc identical to that of spreader at beginning of arc
- Spreader concept developed for ELFE at CERN study in collaboration with Jacques Payet in Saclay and André Tkatchenko in Orsay
- Jacques Payet now works on μRLA
- *Mistake in my spreader design: Use low-energy emittance for high-energy beams, ignoring adiabatic damping* $\Rightarrow$ *radius of spreader magnets too large*
- Geometrical design with *Mathematica*

CERN Muon Storage Ring Parameters

Design momentum	50	GeV/c
Muon fluence	10^{14}	s^{-1}
Distances to far neutrino detectors	1000 & 3000	km
Vertical slopes	-78.6 & -237.9	mr
Normalised divergence at σ	0.1	
Configuration	Triangle	
Normalised emittance at σ	1.667π	mm rad
Aperture limit	3σ	
Frequency of RF system	352.209	MHz
Bunch spacing	multiple of 0.851178	m
Relative RMS momentum spread	0.005	

Comments on Recent Changes

- Shape changed from bow-tie to equilateral triangle
  - Efficient bow-tie has practically vertical pieces of arc with tunnel floor changing into ceiling, scaffolding for installation of and stairs for access to components
  - Experts in civil engineering, installation and access think this is very expensive
  - Equilateral triangle is "nearly horizontal"
  - Slopes of straight sections: -78.6, -237.9, $+319.6$ mrad
- Length of straight sections chosen such that vertical height of μSR is about 220 m and fits into molasse layer near CERN
- Circumference ≈ 2 km
- Fraction of muons decaying in one straight section: 27.5%
- About $10^{14}\mu/\mathrm{s}$ imply
  - 4 MW proton beam power on target
  - all assumptions and simulation results in PJK paper are correct
- A. Verdier has a triangular μSR with one long and two short straight sections

Energy Spread

- Relative energy spread σ_{bi} from μ source damped $\propto 1/\gamma$
- Constant relative energy spread σ_{RF} from RF wave form at circular frequency ω and bunch length σ_z causes a severe limit on σ_z

$$\sigma_{\mathrm{RF}} = \frac{1}{\sqrt{2}}\left(\frac{\omega\sigma_z}{c}\right)^2$$

- μSR designed for energy spread $\sigma_e \approx 0.005$
- Add quadratically and impose condition $\sigma_{\mathrm{bf}}^2 + \sigma_{\mathrm{RF}}^2 = \sigma_e^2$
- Bunch area in conventional units $A = \pi\sigma_{\mathrm{bf}}E_{\mathrm{f}}\sigma_z/c$
- Introduce maximum bunch length $\sigma_{z0} = (c/\omega)\sqrt{\sigma_e\sqrt{2}}$, eliminate σ_{bf}, and find for A as function of $x = \sigma_z/\sigma_{z0}$

$$A = x(1-x^4)^{1/4}$$

- Optimum value is $x = 1/3^{1/4} \approx 0.759836$
- With $f_{\mathrm{RF}} \approx 352.209$ MHz find for optimum bunch parameters

$$\sigma_z \approx 8.656\ \mathrm{mm} \qquad \sigma_{\mathrm{bf}} \approx 4.082 \cdot 10^{-3} \qquad A \approx 0.0185\ \mathrm{eVs}$$

- Scale $\sigma_{\rm bf}$ to input end of μRLA1 and μRLA2, and obtain

$$\sigma_{\rm bi1} \leq 10.21 \cdot 10^{-2} \qquad \sigma_{\rm bi2} \leq 2.04 \cdot 10^{-2}$$

- Halving the frequency $f_{\rm RF}$ doubles the allowed bunch length σ_z and the allowed bunch area A, without changing $\sigma_{\rm bf}$, $\sigma_{\rm bi1}$ and $\sigma_{\rm bi2}$
- Doubling the energy spread σ_e in μSR would double the energy spreads $\sigma_{\rm bf}$, $\sigma_{\rm bi1}$ and $\sigma_{\rm bi2}$, result in absurd values of $\sigma_{\rm bi1}$ and $\sigma_{\rm bi2}$, but it would quadruple the bunch length σ_z and increase the bunch area by a factor of eight
- Suspect a practical limit for σ_e from $\sigma_{\rm bi1}$ in the form $\sigma_e \approx 0.1 E_i/E_f$ where E_i and E_f are injection energies of μRLA1 and μSR, respectively
- Hence, increasing A implies smaller ratios E_f/E_i, i.e. a higher injection energy E_i into μRLA1, and perhaps a smaller frequency $f_{\rm RF}$

A design was completed for a muon storage ring that fully meets the requirements of the Neutrino Oscillation Working Group, i.e. 50 GeV muon energy, 1E14 muons/s arriving in the storage ring, two long straight sections feeding neutrinos to detectors at 1000 and 3000 km distance with a muon beam divergence of less than 0.1 mr. Several tens of thousand muons were tracked for the full muon lifetime. A problem caused by the fringe fields of the quadrupoles was overcome by doubling the lengths of six quadrupoles. A problem arising from decay electrons, originating in the long straight sections and hitting the W liner at the beginning of the arcs, is being investigated.

CERN Studies and Plans for R&D concerning a Neutrino Factory

- SC activities (E. Chiaveri) for low β
- SC cavities in pulsed mode (E. Chiaveri, G. Geschonke)

Ex-

R&D for Superconducting Cavities at CERN

(Information supplied by Enrico Chiaveri)

5 cell ß = 0.8:

on test stand for pulsed operation (end May?)

4 cell ß = 0.7:

bare cavity under construction, to be chemically treated and Nb coated

RF tests at 4.5 K in June/July

If all goes well:
High power pulse tests before the end of 2000

LEP cavities (ß = 1):

Pulsed test before end of 2000

200 MHz cavities for muon linac / recirculators:

Very big (1400 mm diameter),

Technical study till end of June

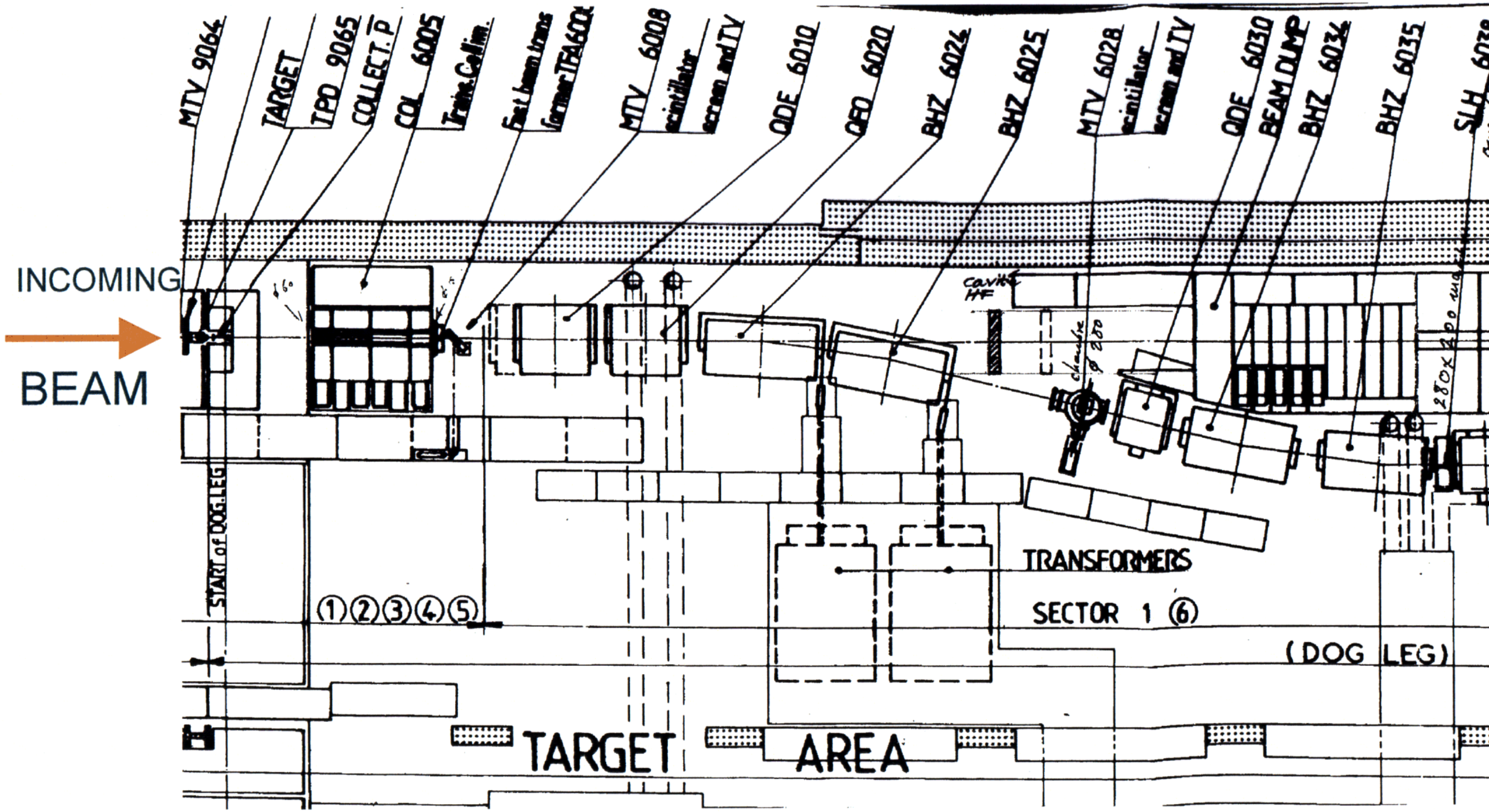
Problems:

Cu sheets material production

EB welds

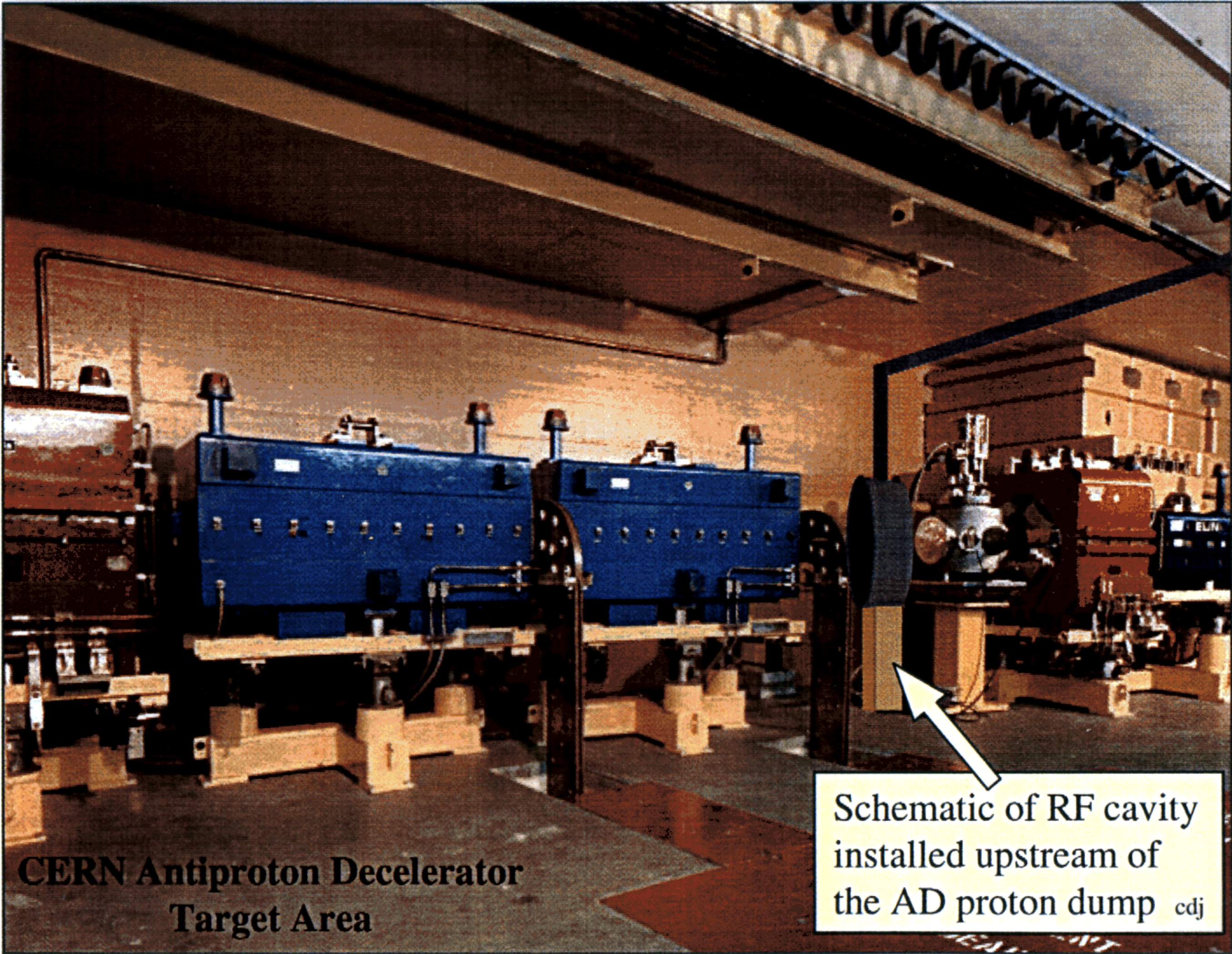
Chemical treatment and Nb coating

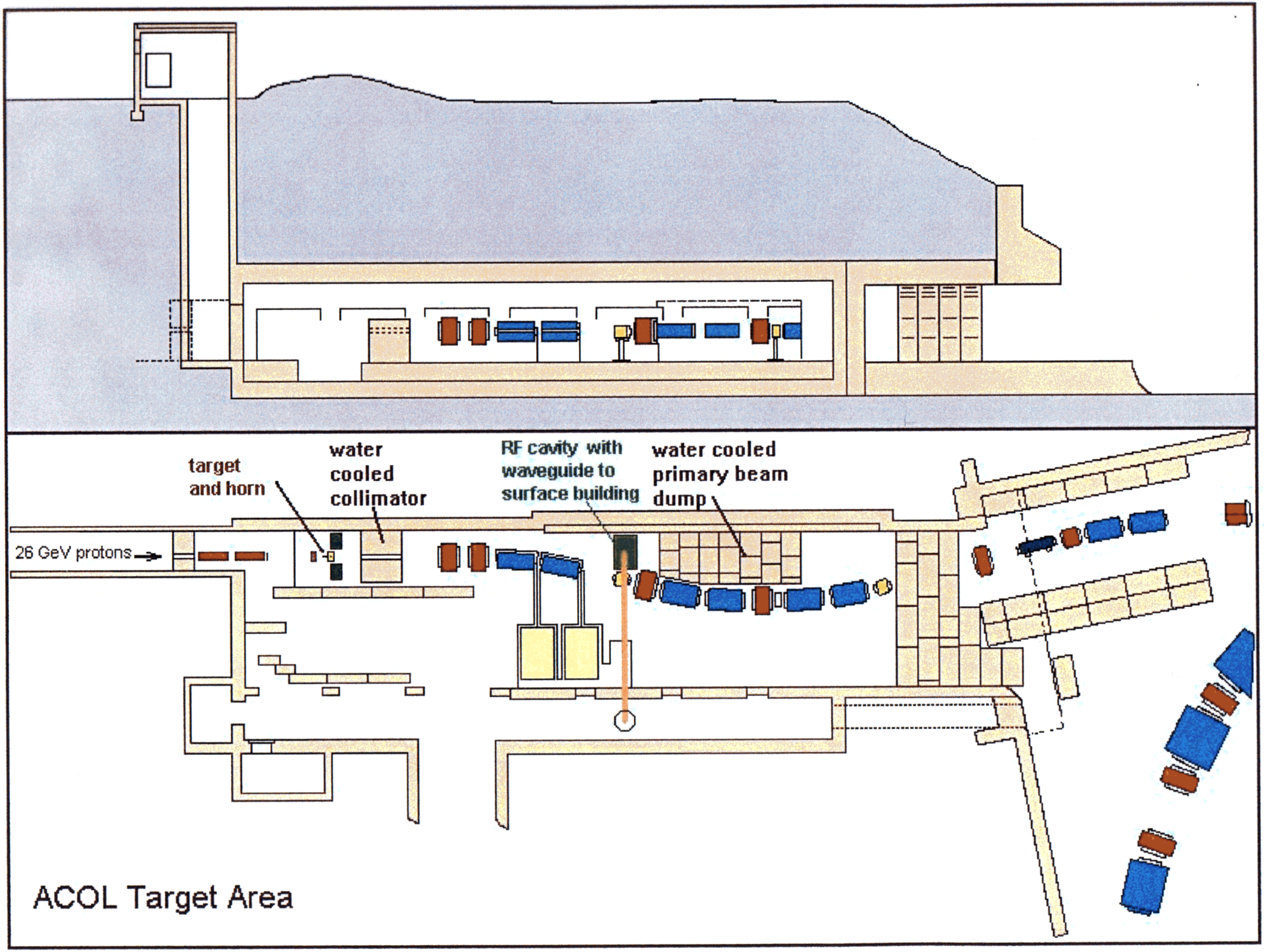
Cryostat (horizontal) for RF measurements at 4.5 K



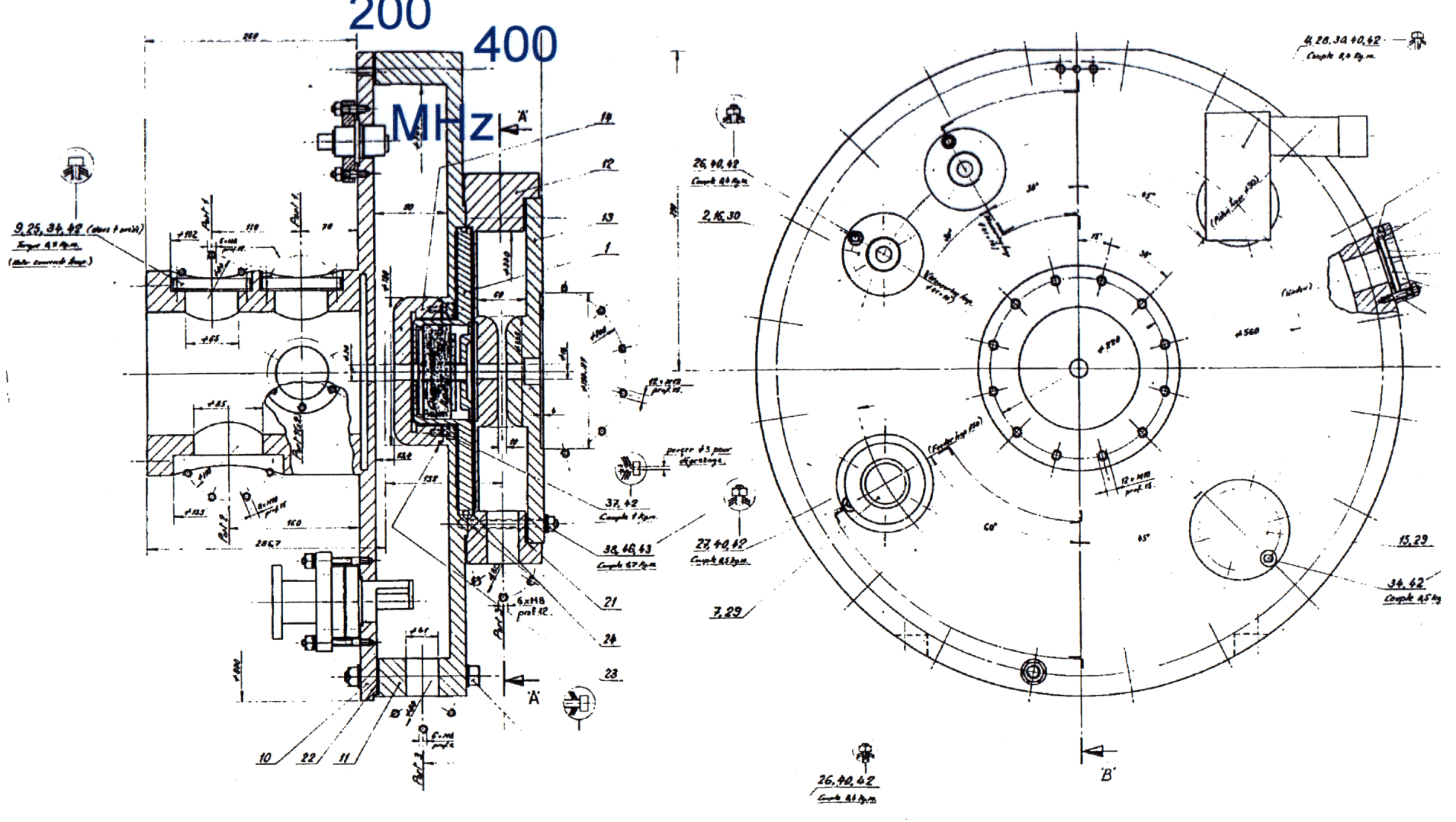
IRRADIATION TEST OF BUNCHER IN THE

TARGET AREA OF THE AD MACHINE


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



ACOL Target Area



BUNCHER LAYOUT

Study of μ scattering

Bill Murray, CLRC

A. Kirk, J.A. Wilson, K. Long, K. Nagamine, C.A. Baker,. G.H.Eaton, T.R. Edgecock, W.Murray, P.R.Norton, K.J.Peach, W.G.Scott, D. Attwood, K.Ishida, S.Nakamura, Y.Matsuda,S.Sakamoto

Univ. Birmingham, Imperial College London, Riken Japan, CLRC

Submitted to TRIUMF and PSI

- Why is this measurement wanted?
- What is proposed?
- Status.

Note that the experimental details are still being finalised.

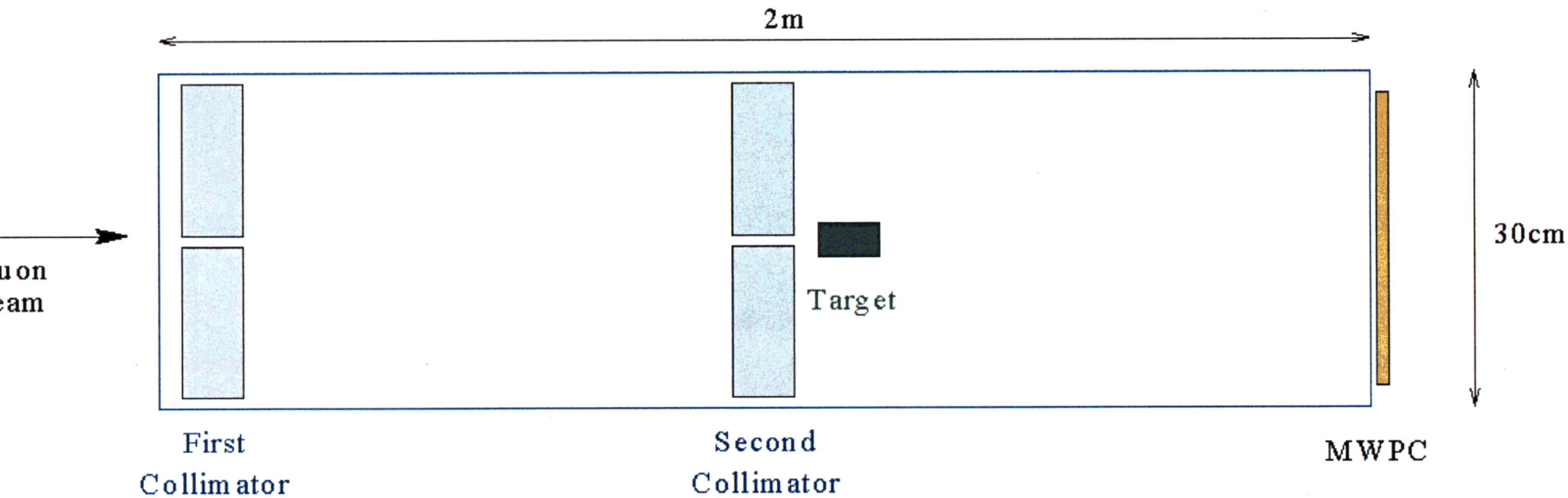
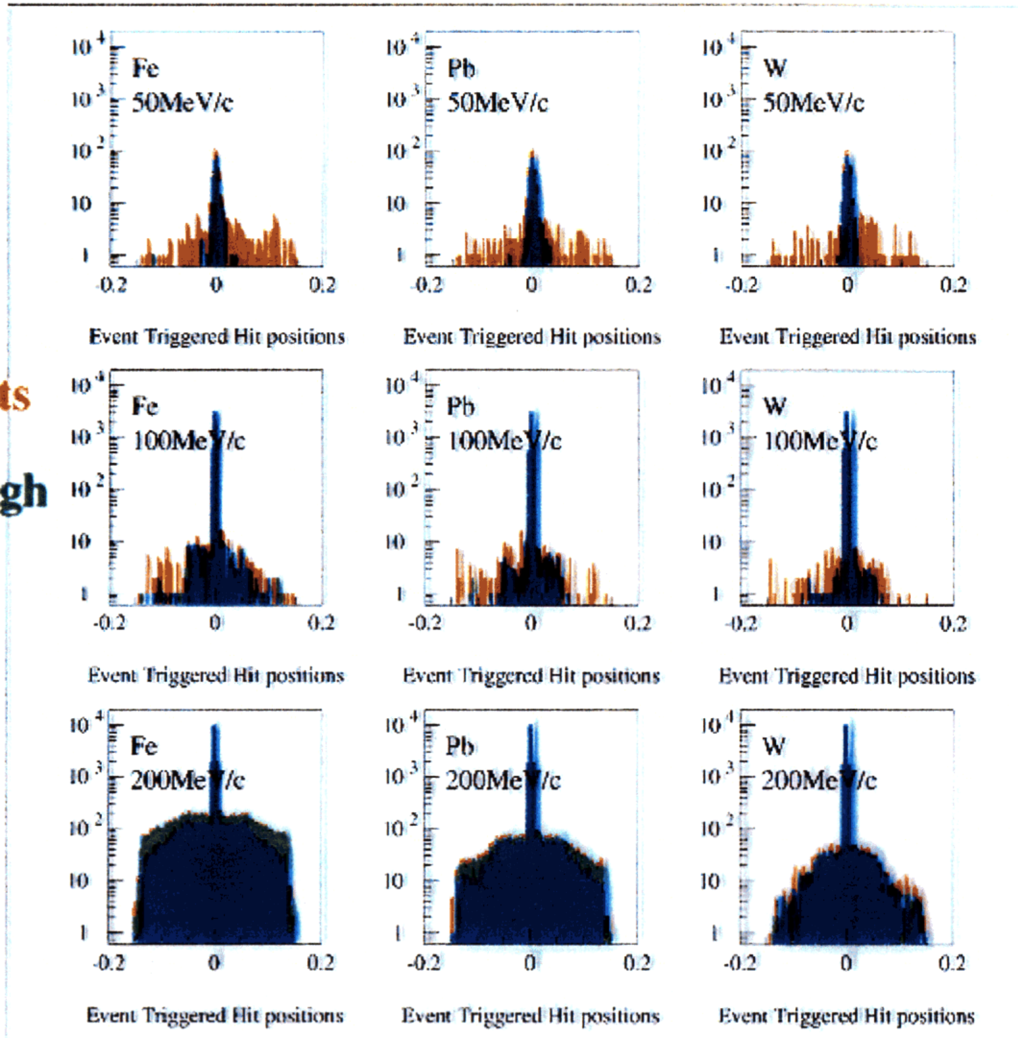


Fig. 3 Schematic longitudinal profile of the proposed muon scattering experiment

Effect of beam momentum variation

Red are multiple hits
Blue are single hits
Green punch-through

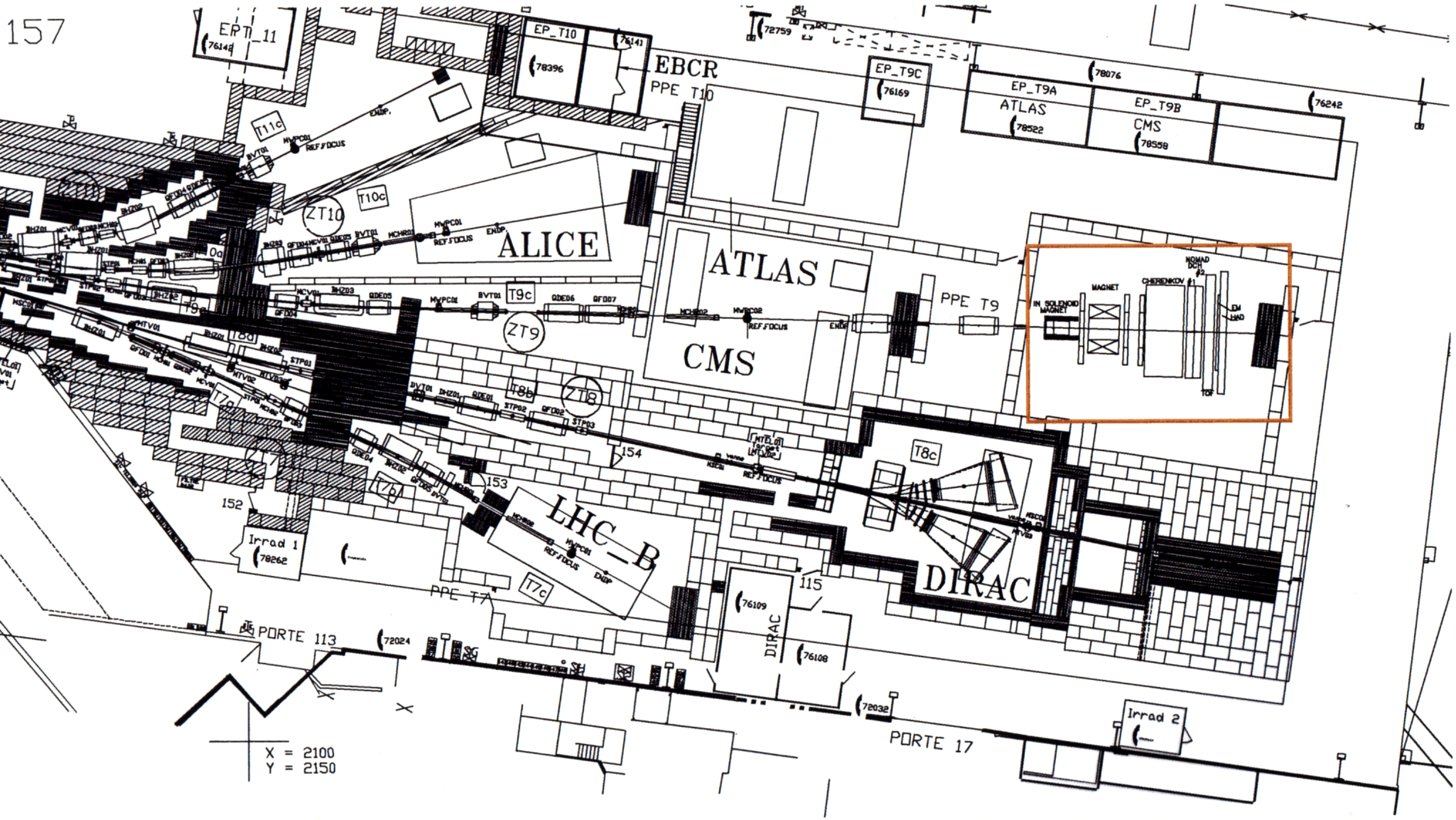


50MeV/c

100MeV/c

200MeV/c

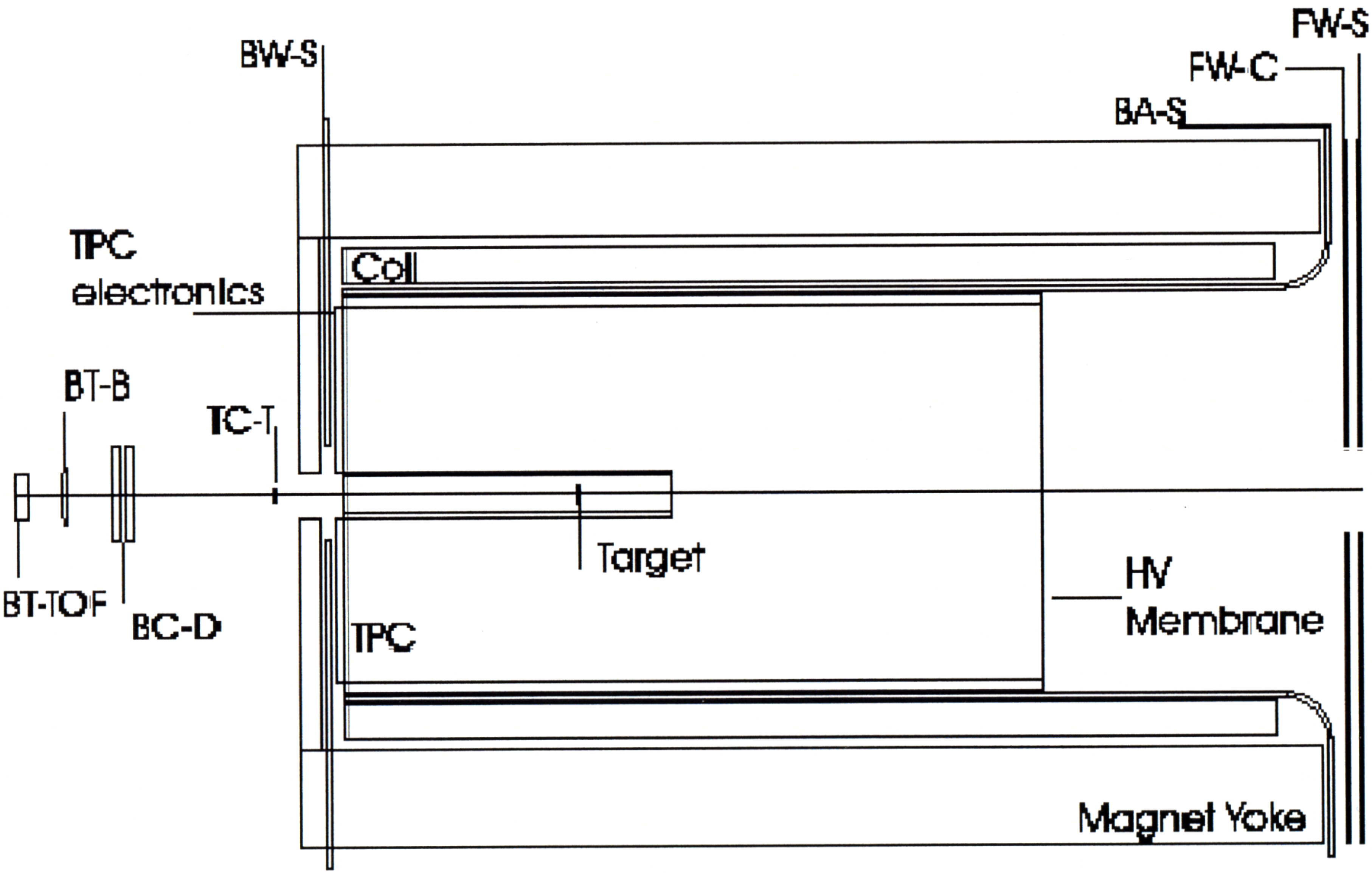
Iron Lead Tungsten



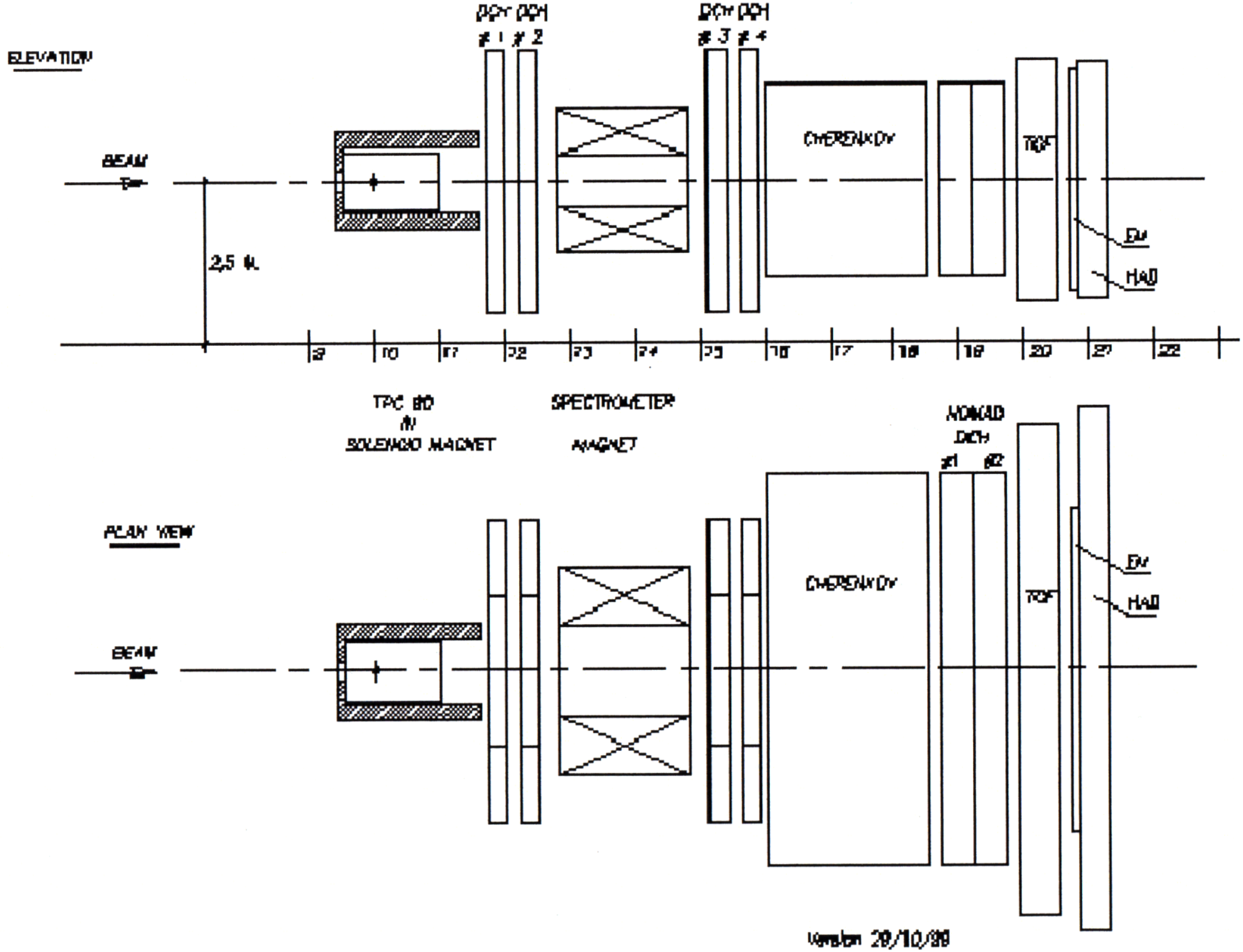
Layout of the experiment to study Hadron Production for

the Neutrino Factory

and for the Atmospheric Neutrino Flux



TIME PROJECTION CHAMBER (TPC)



Plan and Elevation Views of the Experiment

SPSC/P315

10 November, 1999

Proposal to study Hadron Production for the Neutrino Factory and for the Atmospheric Neutrino Flux

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M. Gostkin, S. Kotov, D. Kharchenko, O. Klimov, Z. Kroumchtein, Y. Nefedov, M. Nikolenko,
B. Popov, I. Potrap, A. Rudenko, E. Tskhadadze, V. Serdiouk, V. Zhuravlov.
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University of Valencia, Valencia, Spain
P. Gruber
Institut f˜ur Kernphysik, Technische Universit˜at, Wien, Austria
contact--person
2 now at CERN, Geneva, Switzerland

Set of envisaged targets

material	thin target (cm)	thick target (cm)
Solid		
Be	0.81	40.70
C	0.76	38.00
Al	0.79	39.44
Cu	0.30	15.00
Sn	0.45	22.36
W	0.19	9.58
Pb	0.34	17.05
Cryogenic		
H2	14.36	
N2	2.18	
O2	1.59	

Thin target = 1/50 interaction length   Thick target = 1 interaction length

SOME REMARKS ON PION PRODUCTION IN THE TARGET

It seems to follow from Isotopic Spin considerations and Clebsch-Gordan coefficients that:

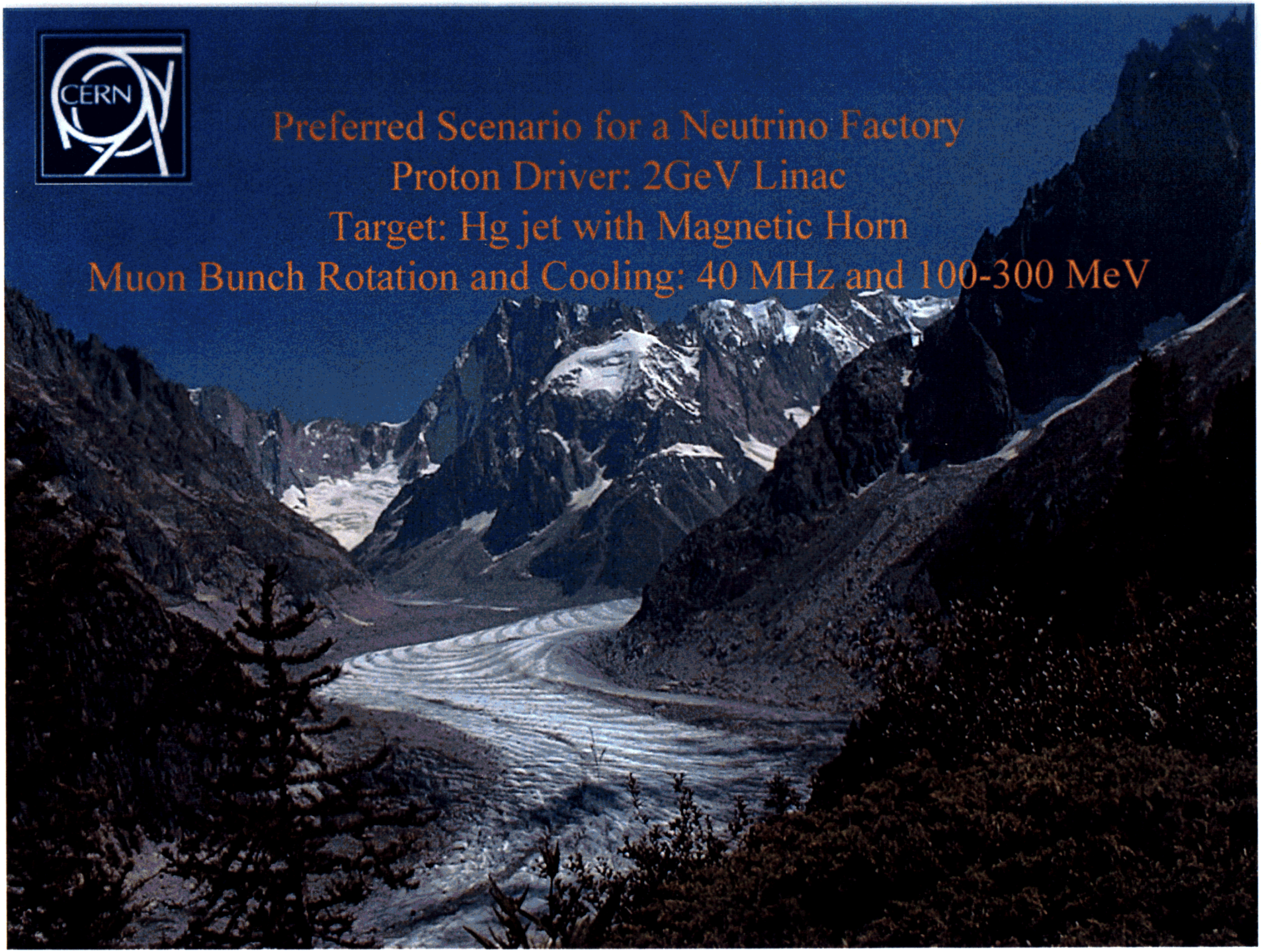
At low proton energies and light targets the production of π^+ *is favoured against the production of* π^-.

Even if the total production is identical, this means that experiments with π^- will take longer and with π^+ will take less time. If this asymmetry is large this will be a disadvantage.

However, it is evident that:

If this asymmetry is large and if the total production rate is independent of Z, when using a light material for π^+ production and a heavy material for π^- production, a substantial gain could be achieved.

This seems to be a unique occasion to profit from a low energy proton driver.


CERN
Preferred Scenario for a Neutrino Factory
Proton Driver: 2GeV Linac
Target: Hg jet with Magnetic Horn
Muon Bunch Rotation and Cooling: 40 MHz and 100-300 MeV