MAY 24, 2000 NUFACT 00

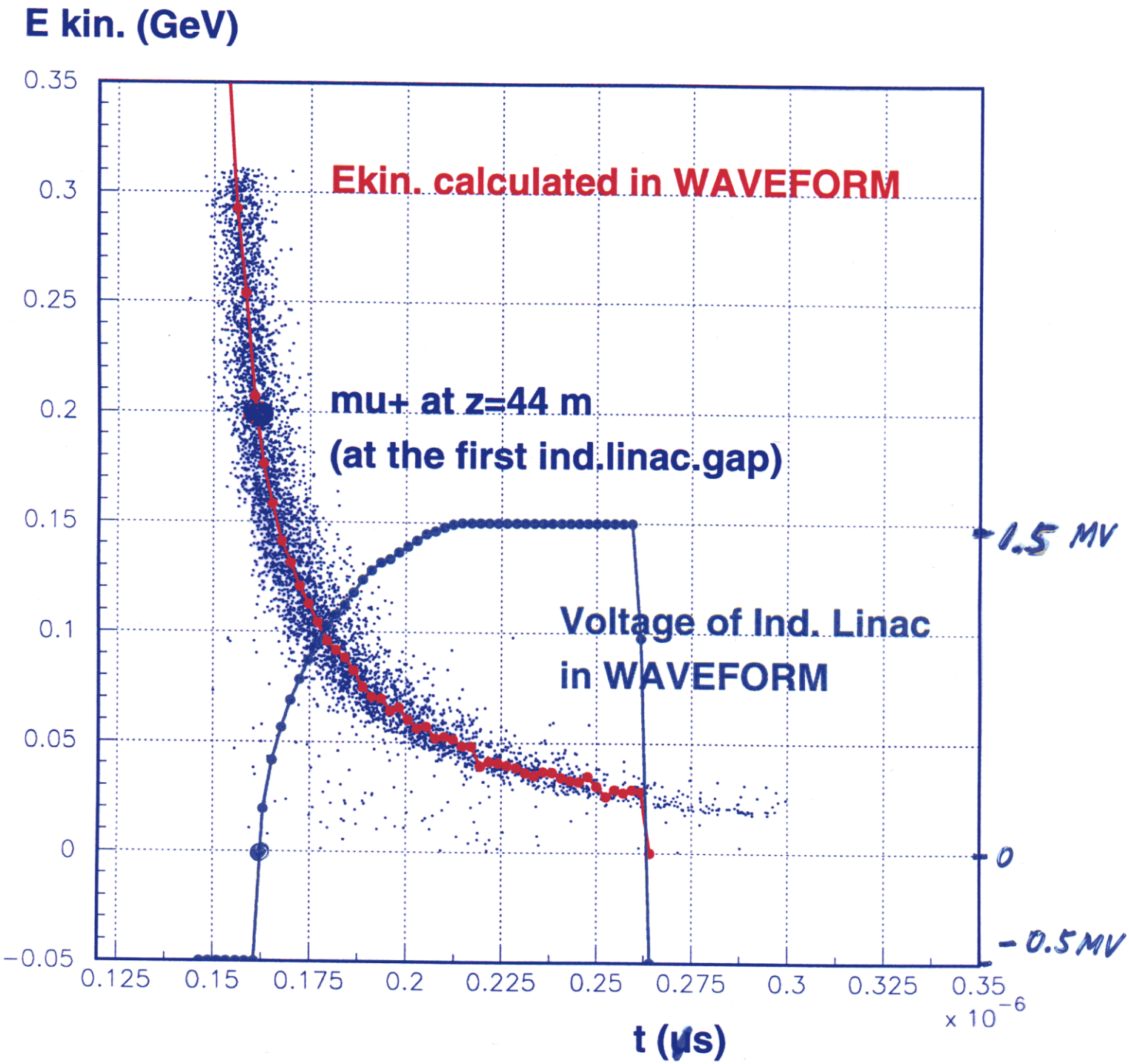
Phase Rotation with Induction Linac

YASUO FUKUI
UCLA, fukui@slac.stanford.edu

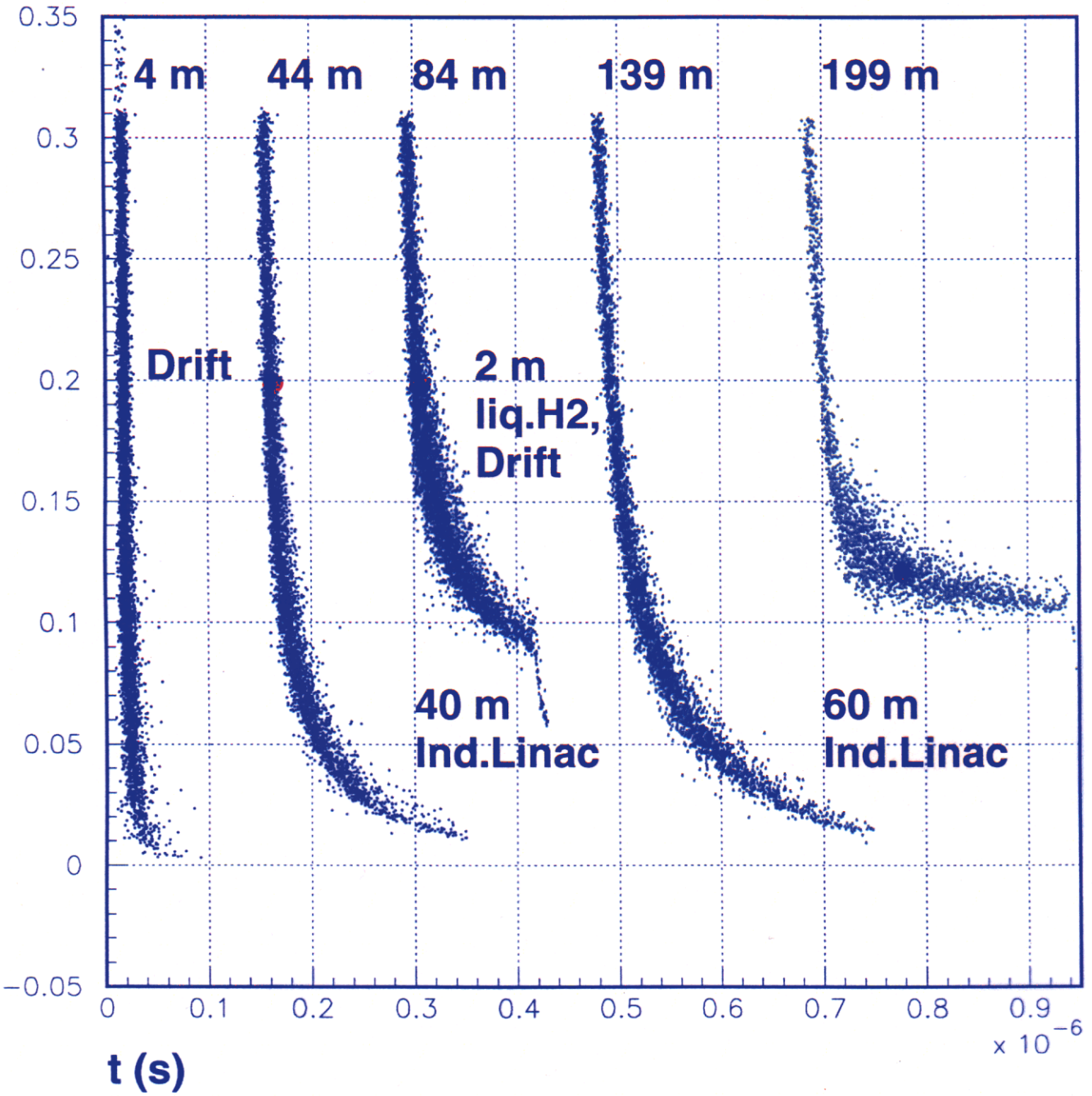
- History & near future
  - '96 Snowmass for $\mu^+\mu^-$ collider 1 bunch All RF
  - '99 LBL Frontend Workshop CASE1 RF + mini cool + Ind. Linac
    CASE2 Ind linac + mini cool + Ind. Linac
  - '00 Fermilab Feasibility study Ind. Linac + mini cool $\mu/p = 0.19$
  - '00 CERN study RF + cooling + ... $E_{kin} < .4$ GeV
  - '01 BNL Feasibility study RF + mini cool + Ind. Linac
- Use 100 m × 2 MV/m Ind. Linac

- Tools (~10% loss?)
  - MARS 2ndary π at $z = 4$ m 16 GeV Proton on 2λ C
    50 mrad angle
  - ICOOL v 2.4+
    - { waveform (automatic E_{kin} vs t curve)
    - { spin tracking $\mu/p = 0.12$ $E_{kin} \lesssim 0.3$ GeV

  (DPGEANT (GEANT3+))


E kin. (GeV)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
−0.05
0.125
0.15
0.175
0.2
0.225
0.25
0.275
0.3
0.325
0.35
x 10^−6
t (μs)
Ekin. calculated in WAVEFORM
mu+ at z=44 m
(at the first ind.linac.gap)
Voltage of Ind. Linac
in WAVEFORM
1.5 MV
0
−0.5MV

Kin.Energy(GeV) of μ^+ and π^+



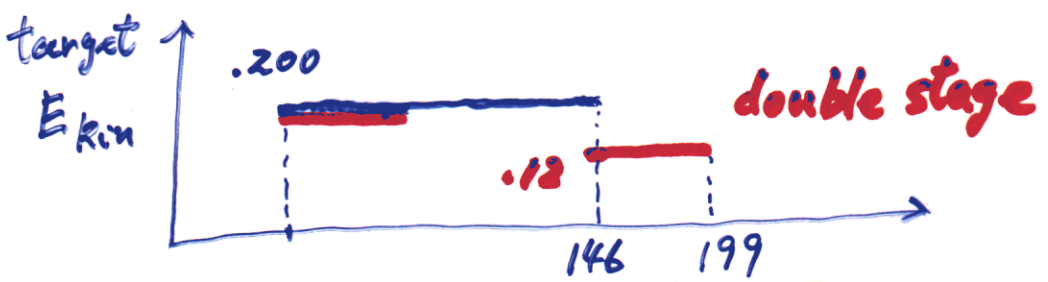
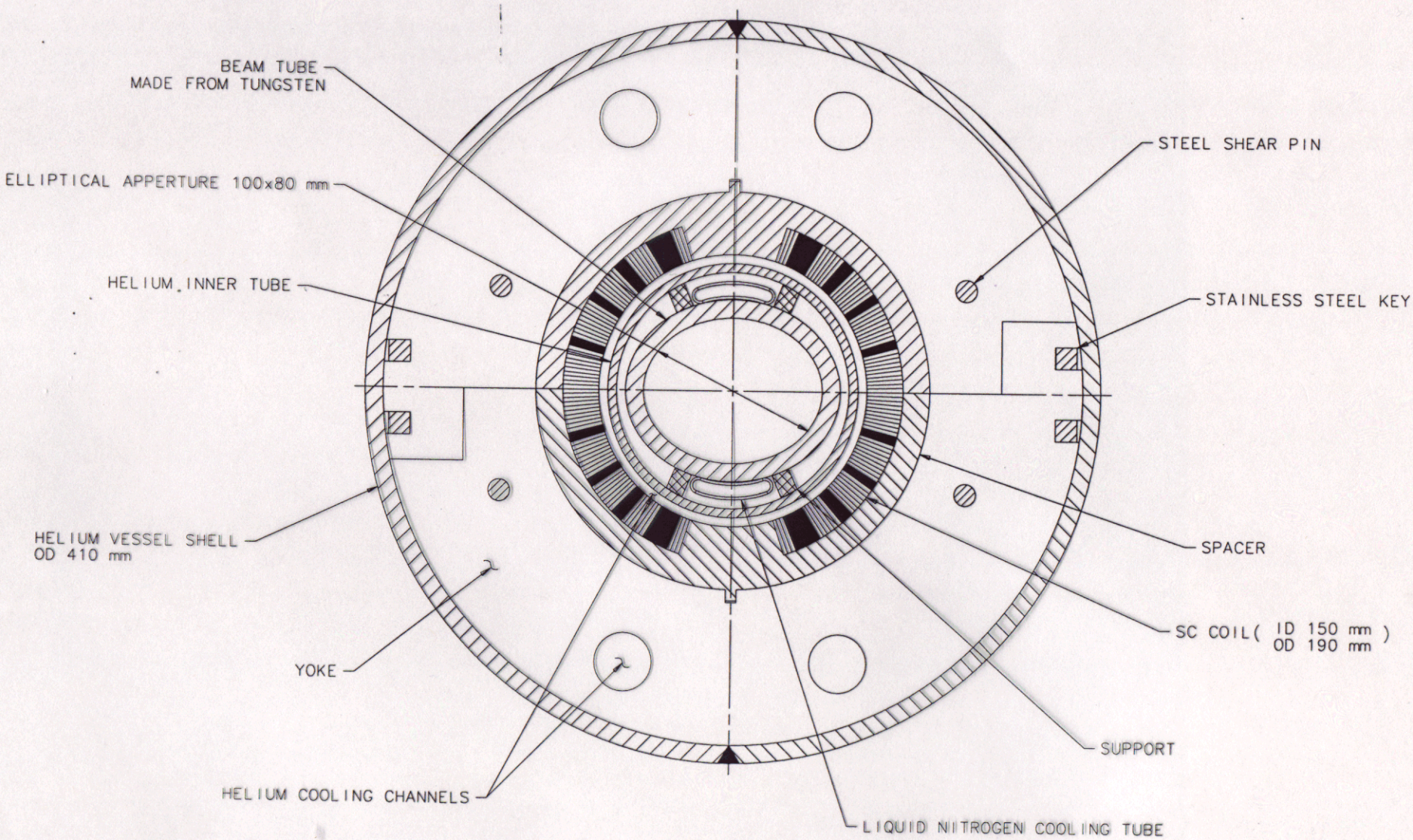


Table 1: Muon Storage Ring Design Parameters and Constraints

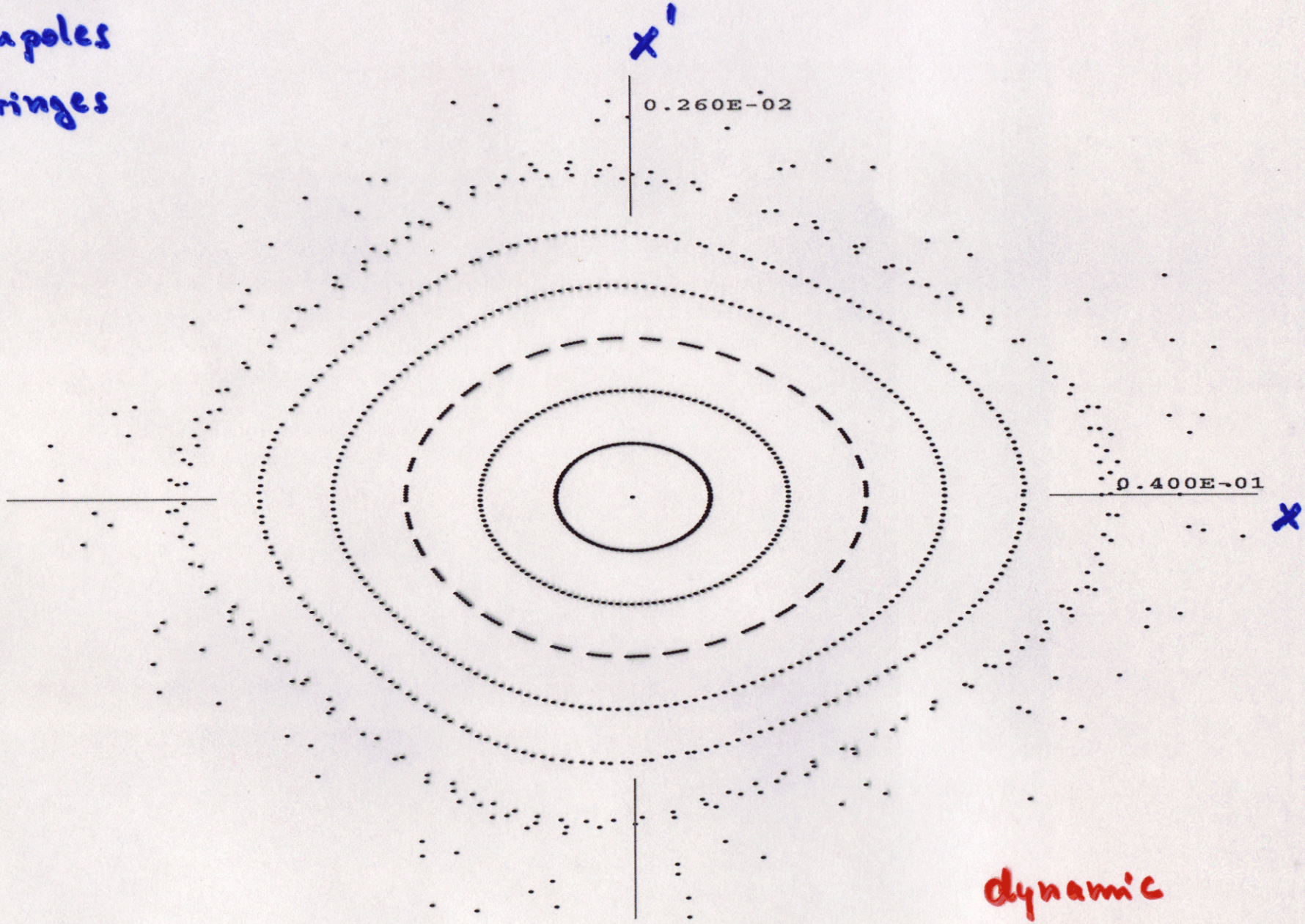
Storage Ring Geometry		racetrack
Storage Ring Energy	GeV	50
Vertical Descent Limit	m	≈183
Declination Angle	deg	≈13
Cross-sectional profile	m	813
ϵ_{rms} (normalized)	mm-rad	3.2π
dp/p (rms)	%	1
maximum poletip field	T	6.0
arc cell phase advance	deg	90

Quad bore ø= 14cm

MuSR DIPOLE CROSS SECTION

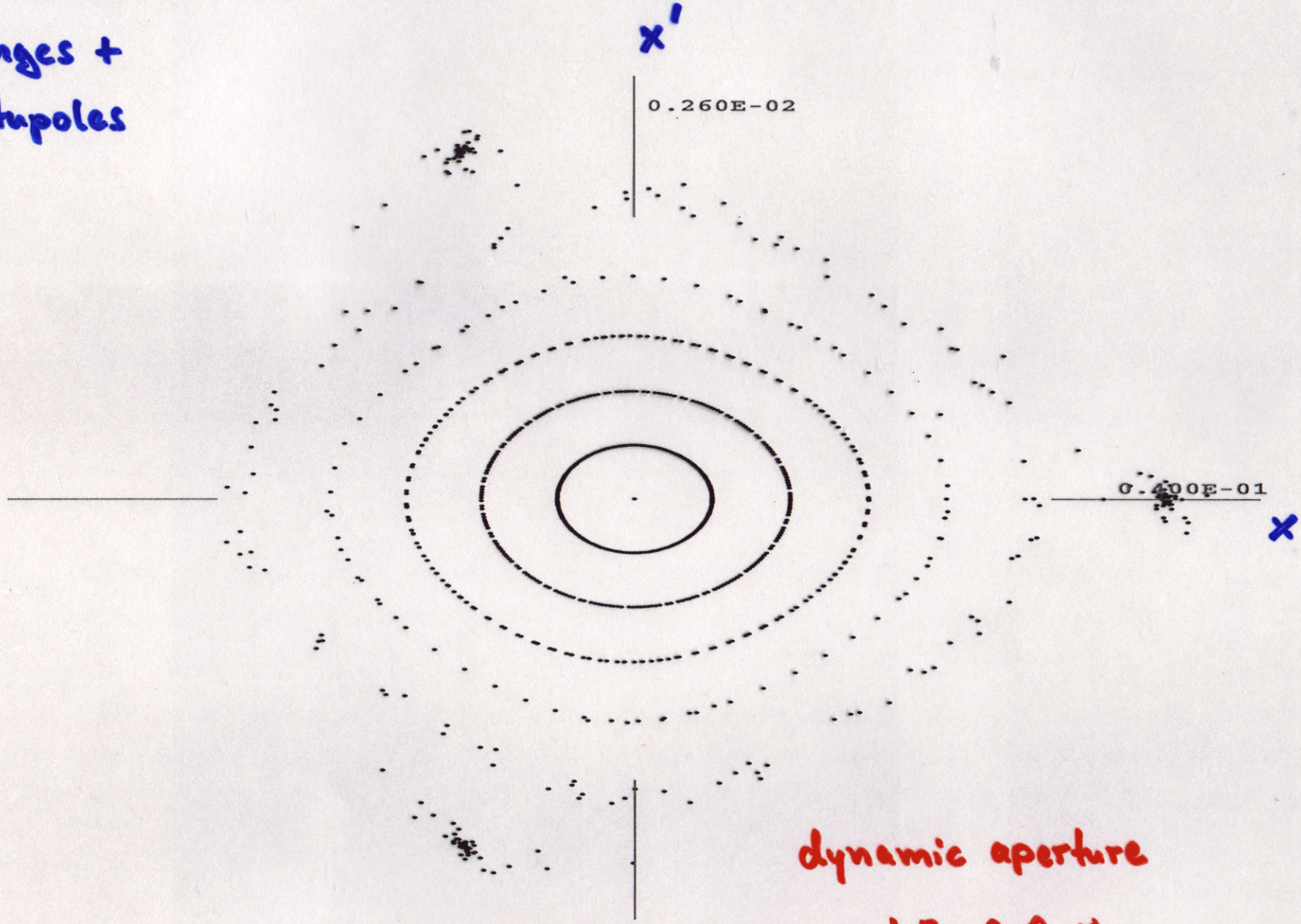


9th order
sextupoles
no fringes



dynamic
aperture
~2.5-3 σ

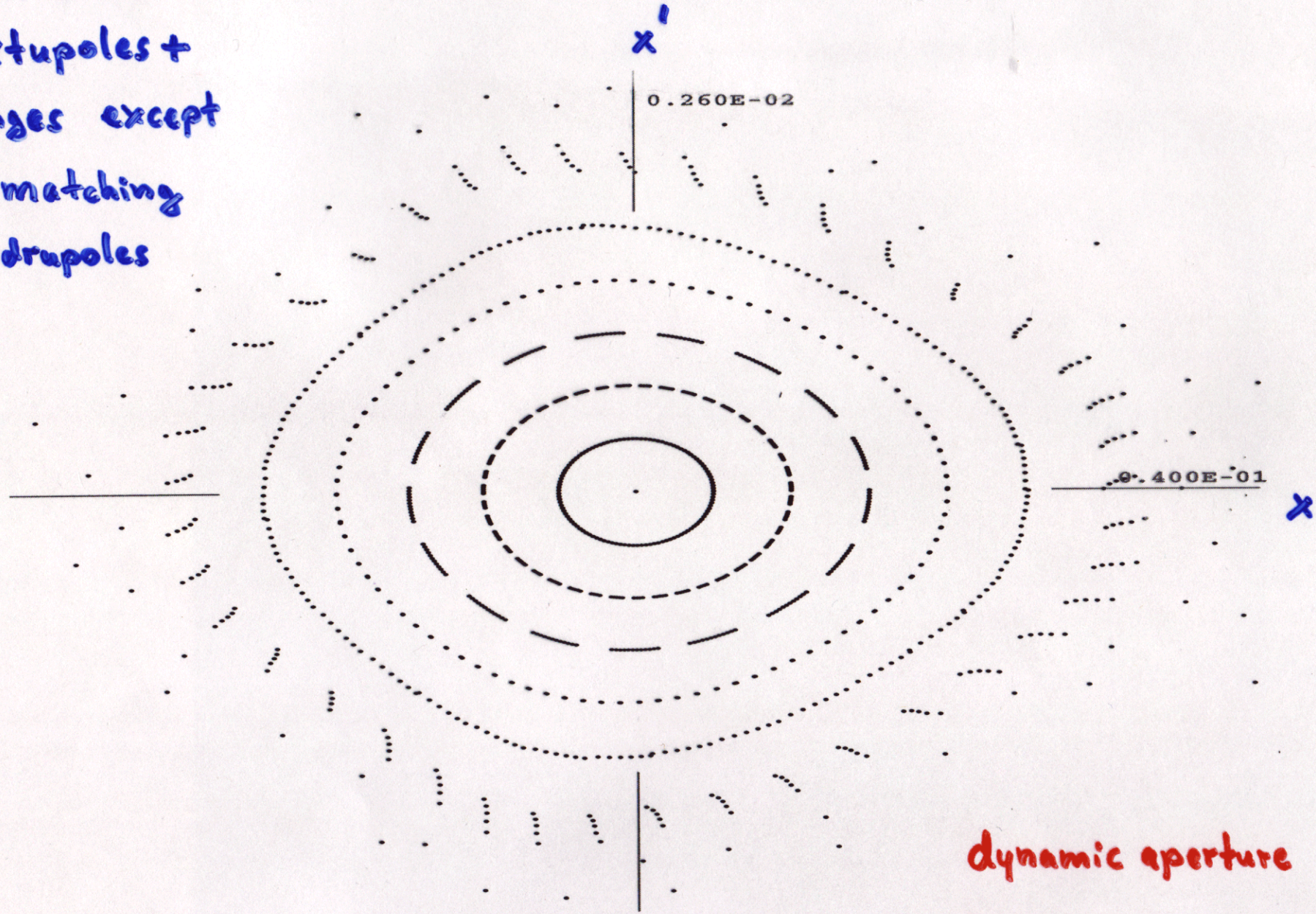
9th order
fringes +
sextupoles



dynamic aperture

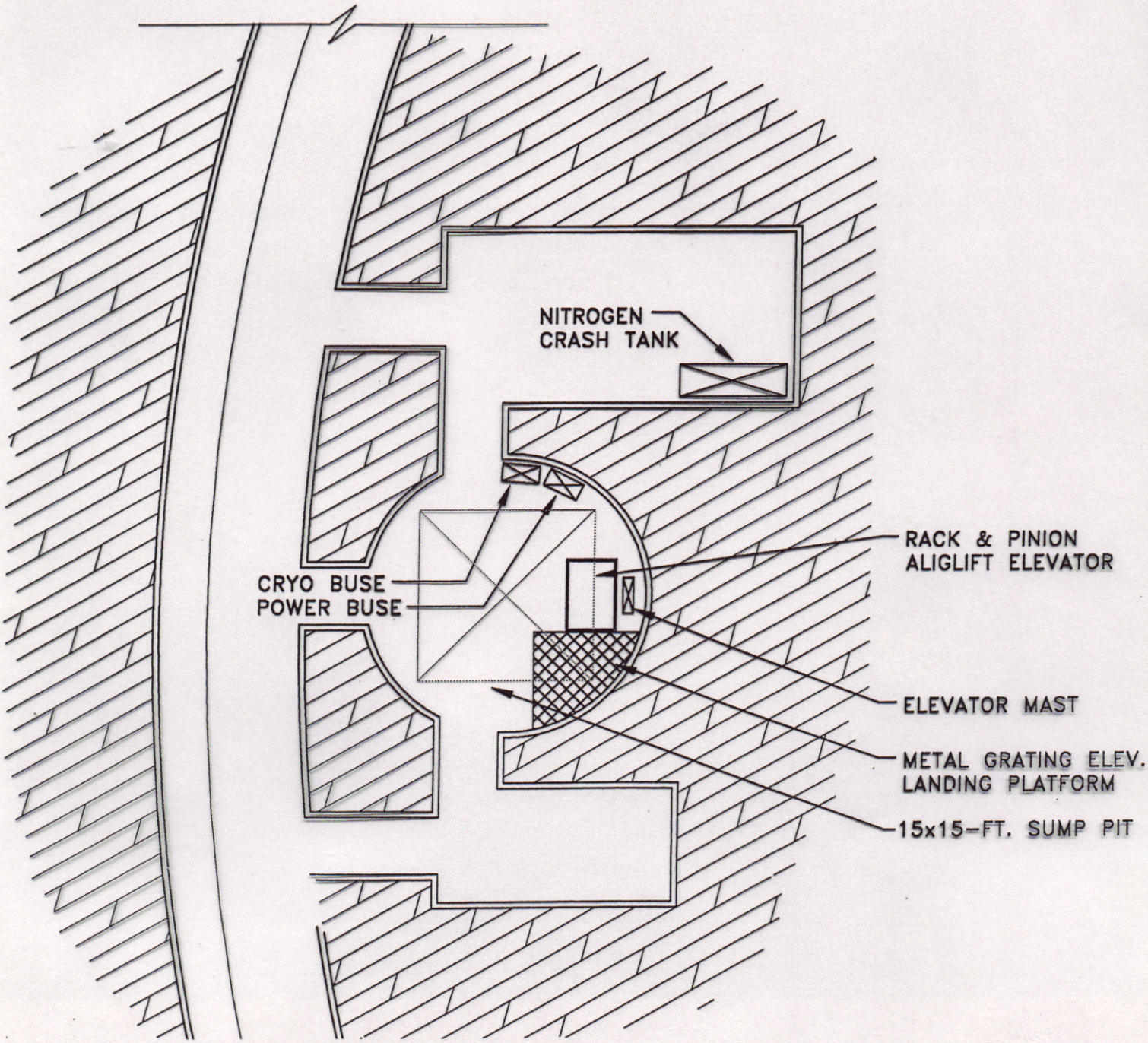
1.5 - 2.0 σ

9 th order sextupoles + fringes except in matching quadrupoles



dynamic aperture

2.5-3.0 σ



Little Radiation : access during operation

Superconducting Dipole Parameters for MuSR

Basic Parameters:	
Operating Field	6 T
Magnetic Length	2.4 m
Operating Current	15 kA
Operating Temperature	4.5 K
Beam Aperture (HxW)	80 x 100 mm
Tungsten Beam Tube Thickness	10 mm
Operating Temperature of Beam Tube	77 K
Coil:	
One Layer Cos(Phi) Type Design	
Number of Turns in Coil	70
Inductance	12.5 mH
Stored Energy	1.4 MJ
Structure:	
Cold Mass Diameter	410 mm
Length of Cold Mass	3 m
Weight of Cold Mass	3 t

W.G. 4

J. Gareyte, S. Kamada, M. Zisman

rep. J. Gareyte

ACCELERATOR THEORY

Gll. remark: progress since Nufact 99

- Mainstream studies
- Alternate proposals
- New ideas

Working Group 4 Members

B.	Autin, CERN	Y.	Mori, KEK
M.	Berz, MSU	D.	Neuffer, FNAL
R.	Cappi, CERN	R.	Palmer, BNL
W.	Chou, FNAL	G.	Penn, LBNL
J.	Corlett, LBNL	C.	Prior, RAL
J.	Delayen, Jlab	G.	Rees, RAL
G.	Dugan, Cornell	H.	Schoenauer, CERN
R.	Fernow, BNL	Y.	Shirakabe, KEK
M.	Ferrario, INFN-LNF	D.	Sprehn, SLAC
A.	Firestone, NSF	C.	Wang, ANL
Y.	Fukui, UCLA	E.	Wilson, CERN
J.	Gareyte, CERN	M.	Yoshii, KEK
R.	Garoby, CERN	M.	Zisman, LBNL
U.	Gastaldi, INFN-LNL (Legnaro)		
M.	Green, LBNL		
K.	Hanke, CERN		
G.	Hanson, Indiana U.		
N.	Holtkamp, FNAL		
K.	Hübner, CERN		
C.	Johnstone, FNAL		
S.	Kamada, KEK		
E.	Keil, CERN		
K.	Koba, KEK		
V.	Lebedev, Jlab		
K.	Makino, MSU		
M.	Martini, CERN		
J.	Monroe, FNAL		

Working Group 4 Agenda
May 22, 2000

Session A: Tuesday—May 23, 2000 11:00 a.m.-12:30 p.m.
Review of R&D Plans and Schedules (Joint with WG-5)
Chair: Y. Iwashita, KEK

R&D in the U.S. (M. Zisman, LBNL)	30 min
R&D in Japan (Y. Mori, KEK)	20 min
Panel Discussion of R&D in Japan, Europe, U.S. (Y. Mori, KEK; H. Haseroth, CERN; M. Zisman, LBNL))	15 min
Discussion	25 min

Session B: Tuesday—May 23, 2000 2:00 p.m.-3:30 p.m.
Views of Cooling Front Ends (Joint with WG-5)
Chair: M. Tigner, Cornell

View-I (R. Palmer, BNL)	25 min
View-II (P. Spentzouris, FNAL))	25 min
View-III (A. Lombardi, CERN)	25 min
Discussion	15 min

Session C: Tuesday—May 23, 2000 3:50 p.m.-5:30 p.m.
Target & Capture
Chair: N. Mokhov, FNAL

Solid Target Options (S. Childress, FNAL)	15 min
Liquid-jet Target Options (K. McDonald, Princeton)	15 min
RAL Target Studies (P. Drumm, RAL)	15 min
Target and Capture Simulations (T. Yokoi, KEK)	15 min
Solenoid Capture (H. Kirk, BNL)	10 min
Horn Capture (N. Vassilopoulos, CERN)	10 min
Discussion	20 min

Session D+E: Wednesday—May 24, 2000 9:00 a.m.-10:40 a.m.

Front End

Chair: R. Palmer, BNL

Induction Linac Approach (Y. Fukui, UCLA)	20 min
RF Approach (A. Lombardi, CERN)	20 min
Buncher Options (D. Neuffer, FNAL)	15 min
Alternating Solenoid and Single Field Flip Channels (J. Monroe, FNAL)	15 min
Ideas for Emittance Exchange (G. Hanson, IU)	15 min
Discussion	15 min

Session F: Wednesday—May 24, 2000 11:00 a.m.-12:30 p.m.

Contributed Papers

Chair: M. Zisman, LBNL

Fermilab Proton Driver Lattice Design (C. Johnstone, FNAL)	10 min
CERN Linac Driver Proposal (R. Garoby, CERN)	10 min
High-Brilliance Source for Muon Colliders (U.Gastaldi, INFN-LNL Legnaro)	10 min
ARC Optics Design & Optimization for RLA (A. Bogacz, JLAB)	10 min
Muon Capture & Acceleration Without Phase Rotation and Cooling (K. Hanke, CERN)	10 min
Zero-Energy Muon Cooling Methods (K. Nagamine, KEK/Riken) 20 min	
Discussion :	20 min

Session G: Thursday—May 25, 2000 10:00 a.m.-10:40 a.m.

Proton Driver Options

Chair: J. Gareyte, CERN

CERN Approach (H. Schonauer, CERN)	10 min
Neutrino Factory Studies at RAL (C. Prior/G. Rees, RAL)	10 min
Japan Approach (M. Yoshii, KEK)	10 min
U.S. Approaches (W. Chou, FNAL)	10 min

Session H: Thursday—May 25, 2000 11:00 a.m.-12:30 p.m.

Acceleration

Chair: E. Keil, CERN

Initial Linac Longitudinal Acceptance (S. Berg, BNL)	10 min
Lattice Design Options for RLAs (V. Lebedev, Jlab)	15 min
Choice of Frequency for RLA-2 (J. Delayen, Jlab)	15 min
Other Acceleration Schemes (Y. Mori, KEK)	15 min
Beam Loading Effects During Acceleration (S. Berg, BNL)	10 min
High-Power RF Sources (D. Sprehn, SLAC)	10 min
Discussion	15 min

Session I: Thursday—May 25, 2000 2:00 p.m.-3:30 p.m.

Storage Ring

Chair: S. Kamada, KEK

Options for Polarization (A. Blondel, U. Geneva)	15 min
Error Sensitivity (M. Berz, MSU)	15 min
Feasibility of Single-Flip Cooling (J. Monroe, FNAL)	10 min
Lattice Design Options for Storage Ring (C. Johnstone, FNAL)	20 min
Large Acceptance Fixed-Field Acceleration (C. Johnstone, FNAL)	10 min
Discussion	20 min

Session J1: Thursday—May 25, 2000 3:50 p.m.-5:00 p.m.

Theory & Simulations

Chair: D. Neuffer, FNAL

Simulation Tools Available (Japan.) (S. Kamada, KEK)	10 min
Simulation Tools Available (Europe) (A. Lombardi, CERN)	10 min
Simulation Tools Available (U.S.) (R. Fernow, BNL)	10 min
Beam Dynamics Analysis of Ionization Cooling (K-J Kim, ANL)	10 min
Emittance Blowup During Pion Decay (B. Autin, CERN)	10 min
Discussion	20 min

Session J2: : Thursday—May 25, 2000 5:00 p.m.-5:30 p.m.

Preparation of Summary Report

Chairs: J. Gareyte, CERN; S. Kamada, KEK; M. Zisman, LBNL

Discussion of what we conclude	30 min

DRIVERS

$$\begin{cases} P = 4\ \text{MW} \\ \sigma_t = 1\ \text{ns} \end{cases}$$

- rep. rate: no clear optimum $\begin{cases} 50\ \text{GeV}\ \nu\text{fact: up to } 1\ \text{kHz} \\ 3\ \text{TeV}\ \mu\text{coll: } \sim 30\ \text{Hz} \end{cases}$

  envisaged: (0.5) 15 → 75 Hz

- N_b bunches/train : not clear

- Energy : not clear

  envisaged : 2.2 → 50 GeV

+ existing hardware to reuse
+ variety of experiences/competences
+ multipurpose

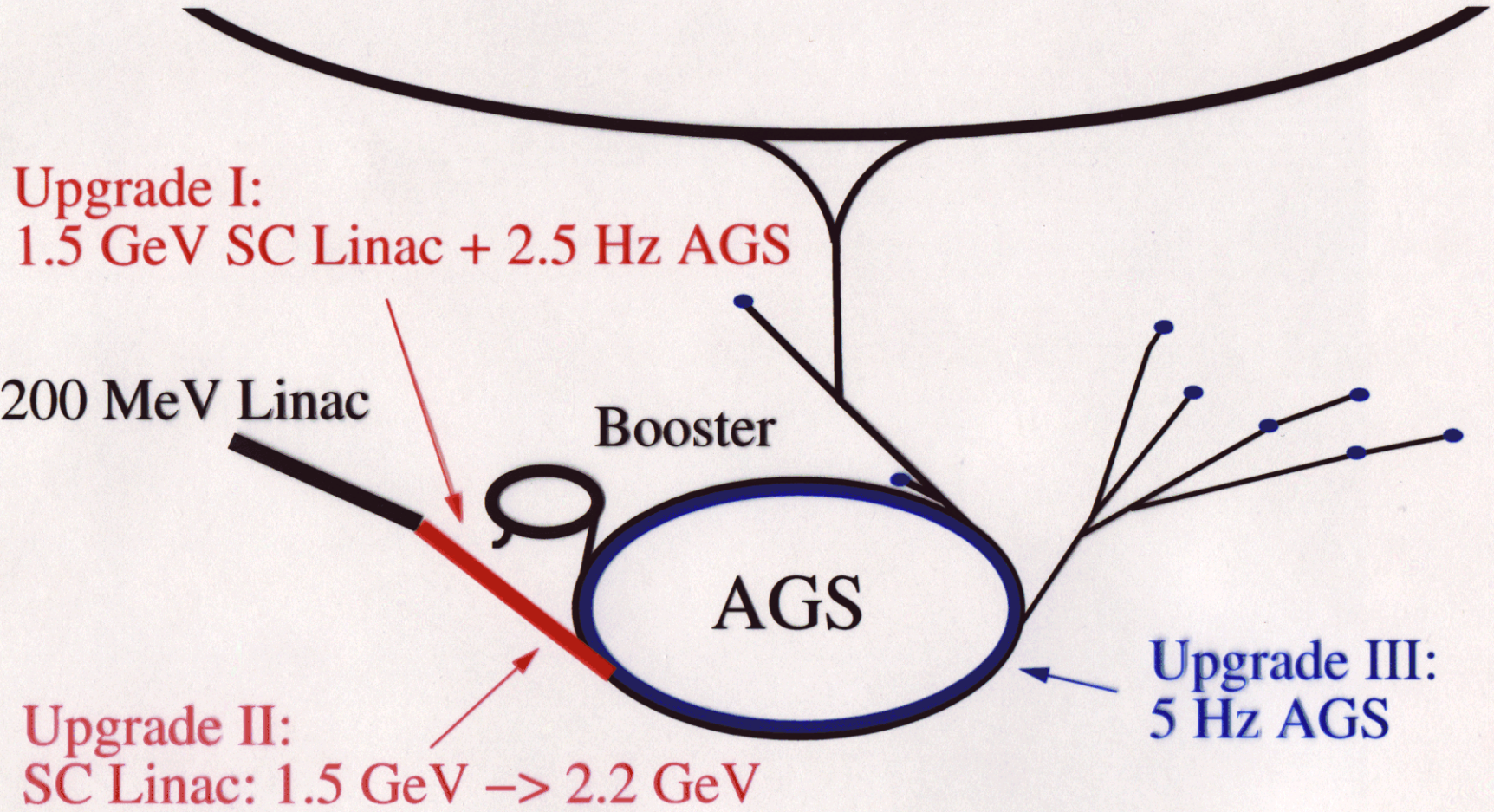
⇒ Diversity of solutions

* Goals are possible to achieve

Table 2: Proton Driver Parameters of Present, Phase I and Phase II (04/06/00)

	Present	Phase I (ν-factory)	Phase II ($\mu\mu$-collider)
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	1000
Peak current (mA)	40	60	80
Pulse length (μs)	25	90	200
H^- per pulse	6.3×10^{12}	3.4×10^{13}	1×10^{14}
Average beam current (μA)	15	81	240
Beam power (kW)	6	32	240
Pre-booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)			3
Protons per bunch			2.5×10^{13}
Number of bunches			4
Total number of protons			1×10^{14}
Normalized transverse emittance (mm-mrad)			200π
Longitudinal emittance (eV-s)			2
RF frequency (MHz)			7.5
Average beam current (μA)			240
Beam power (kW)			720
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	16	16
Protons per bunch	6×10^{10}	$7.5\,(1.7) \times 10^{12}$	2.5×10^{13}
Number of bunches	84	4 (18)	4
Total number of protons	5×10^{12}	3×10^{13}	1×10^{14}
Normalized transverse emittance (mm-mrad)	15π	60π	200π
Longitudinal emittance (eV-s)	0.1	2 (0.5)	2
RF frequency (MHz)	53	1.7 (7.5)	7.5
Extracted bunch length σ_t (ns)	0.2	3	1
Average beam current (μA)	12	72	240
Target beam power (kW)	100	1200	4000

AGS Proton Driver with SC Linac

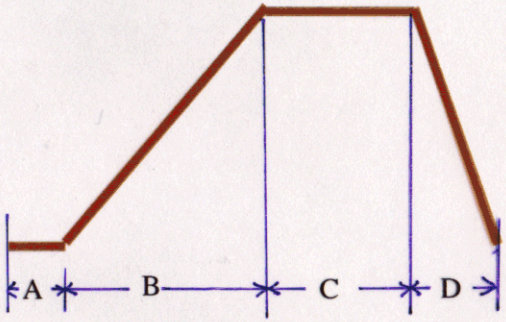


Parameters for AGS upgrades with SC Linac

	Upgrade I	Upgrade II	Upgrade III
200 MeV Linac intensity/pulse	12×10^{13}	24×10^{13}	24×10^{13}
200 MeV Linac rep. rate	2.5 Hz	2.5 Hz	5 Hz
Final energy	200 MeV	200 MeV	200 MeV
$\beta^2\gamma^3$	0.573	0.573	0.573
SC Linac intensity/pulse	12×10^{13}	24×10^{13}	24×10^{13}
SC Linac rep. rate	2.5 Hz	2.5 Hz	5 Hz
SC Linac extr. energy	1.5 GeV	2.2 GeV	2.2 GeV
$\beta^2\gamma^3$	14.9	34.1	34.1
AGS intensity/pulse	10×10^{13}	20×10^{13}	20×10^{13}
AGS rep. rate	2.5 Hz	2.5 Hz	5 Hz
Rf gradient	15 kV/m	15 kV/m	30 kV/m
AGS extr. energy	25 GeV	25 GeV	25 GeV
Beam power on target	1 MW	2 MW	4 MW

Upgrading - Beam intensity of the 50-GeV PS

Beam Intensity I=3.3 x 10^{14} ppp, i=20μA(fast ext.) Beam Power 1 MW



1) High repetition rate

0.3 Hz -----> 0.5 HZ

(B=1.9s,D=0.7s) (B=0.8s,D=0.35s)

2) Longitudinal barrier

free from harmonic number #of bunches: 8 bunches -----> 20 bunches

space charge tune shift $\Delta\nu$=-0.1 ------> -0.25

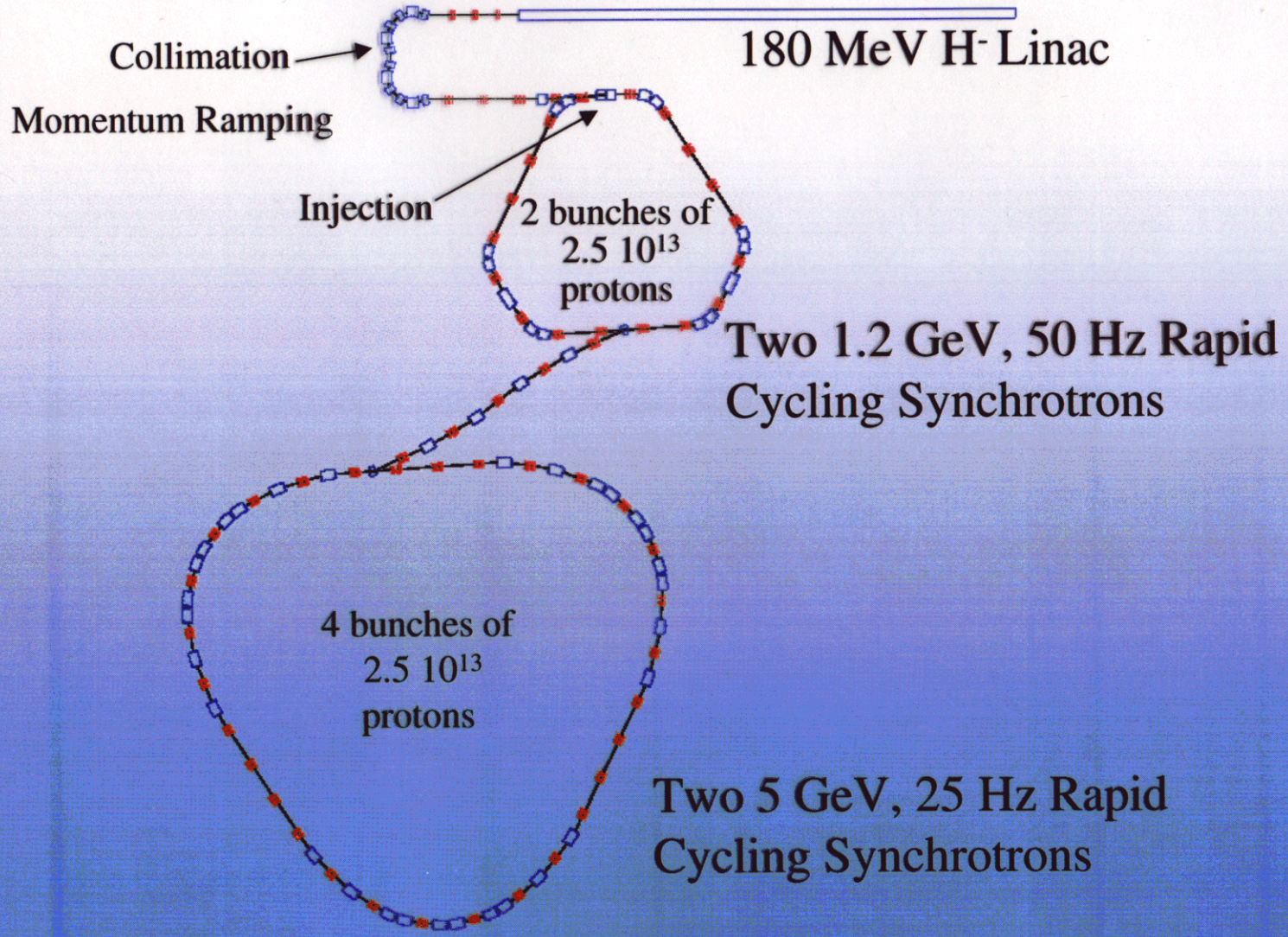
a) w/o barrier bucket I=3.3 x 10^{14} ppp

b) w barrier bucket I=8.2 x 10^{14} ppp

1) + 2) =

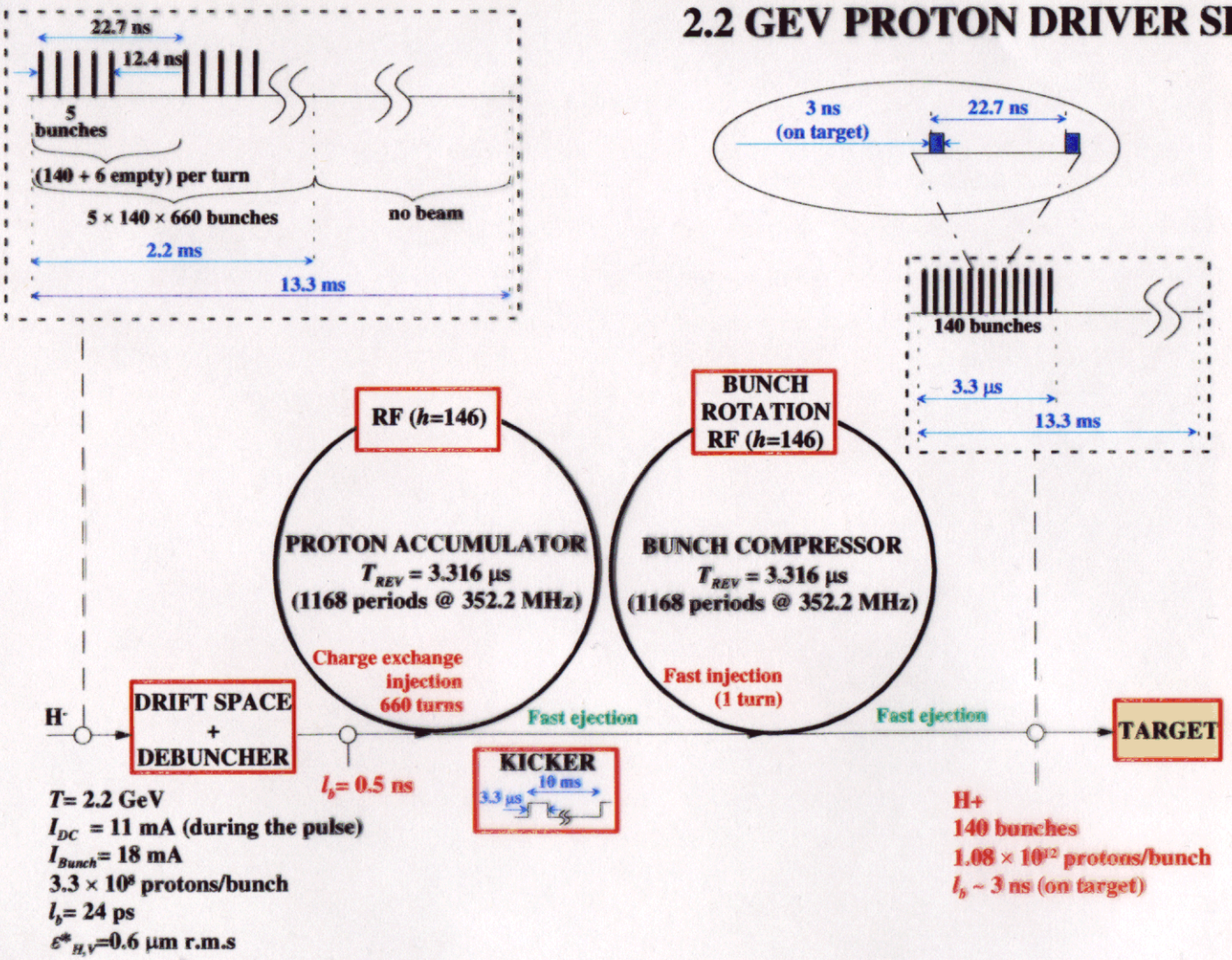
Beam Intensity I=8.2 x 10^{14} ppp, i=87 μA(fast ext.) Beam Power 4.4 MW

5GeV, 50 Hz Proton Driver



Accumulator-Compressor scheme for a Neutrino Factory: Case 2

2.2 GEV PROTON DRIVER SET-UP



75 Hz

Nu FACT '00

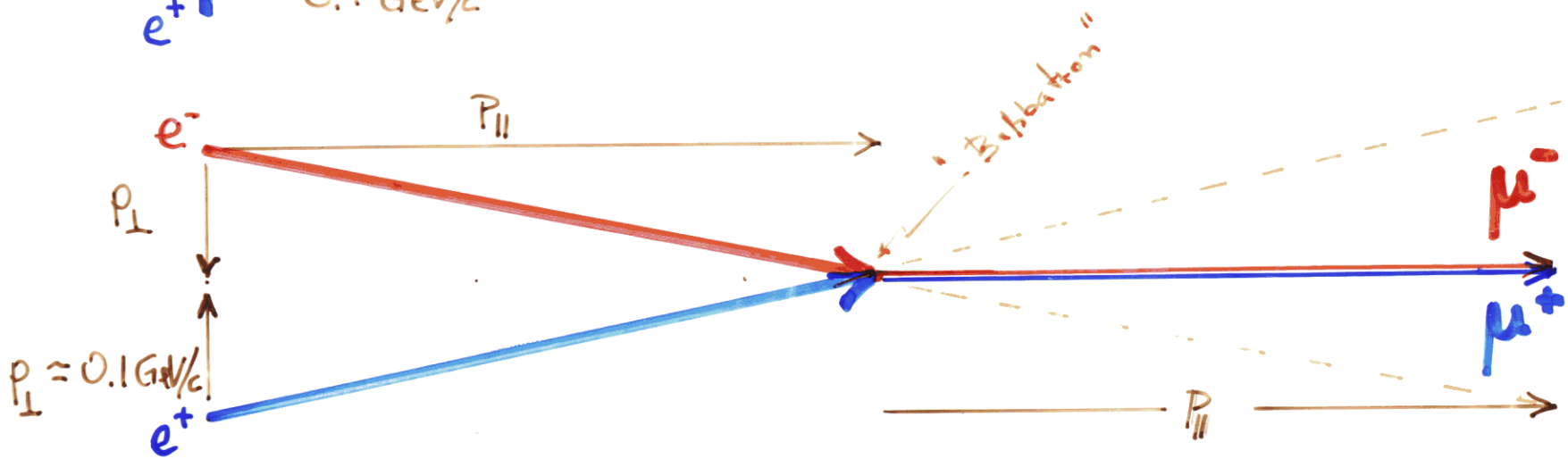
MONTEREY 24-V-2000

Ugo GASTALDI
INFN-LNL Legnaro

High brilliance $\mu^+ + \mu^-$ SOURCE for MUON COLLIDERS

$$E(e^+e^-)_{c.m.} \gtrsim 2\, m_\mu$$

$e^+e^- \to \mu^+\mu^-$ annihilation just above threshold (Bahba)



$$E(e^+e^-)_{Lab} = E_{e^+} + E_{e^-} = E_{\mu^+} + E_{\mu^-}$$

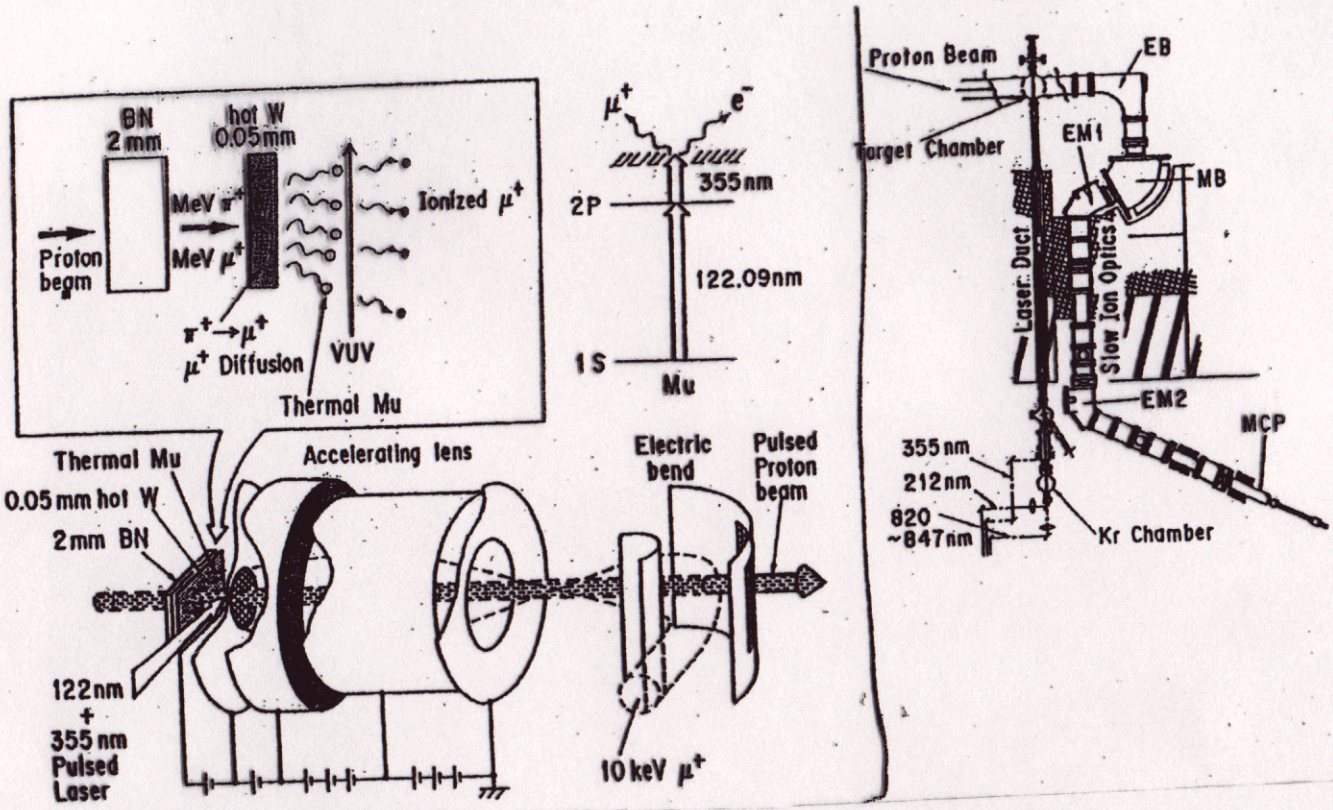
$$P(e^+e^-)_{Lab} = P_{\parallel e^+} + P_{\parallel e^-} = P_{\mu^+} + P_{\mu^-}$$

$\sigma = 3\,10^{-30}\ \beta\ cm^2$

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

$\boxed{\to 3\,10^3/s}$

Generation of cold (0.2 eV) μ^+s.



Prof. Nagamine.

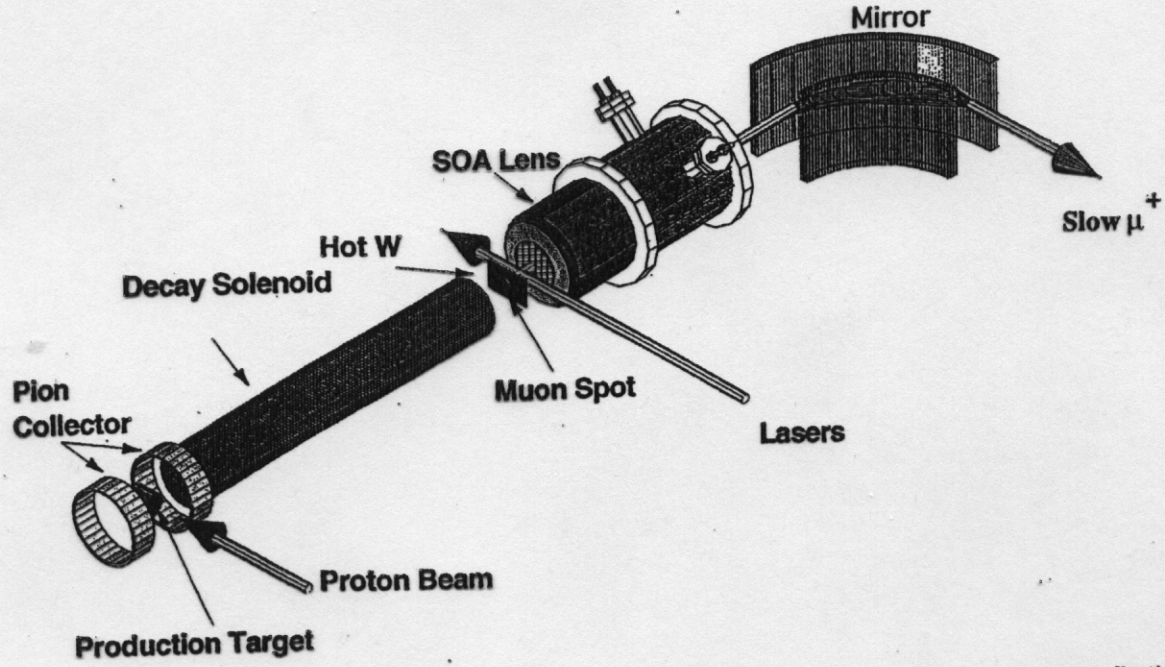


Fig. 2. Intense ultra-slow μ^+ production by employing the high-intensity muon production via a large acceptance pion collection.

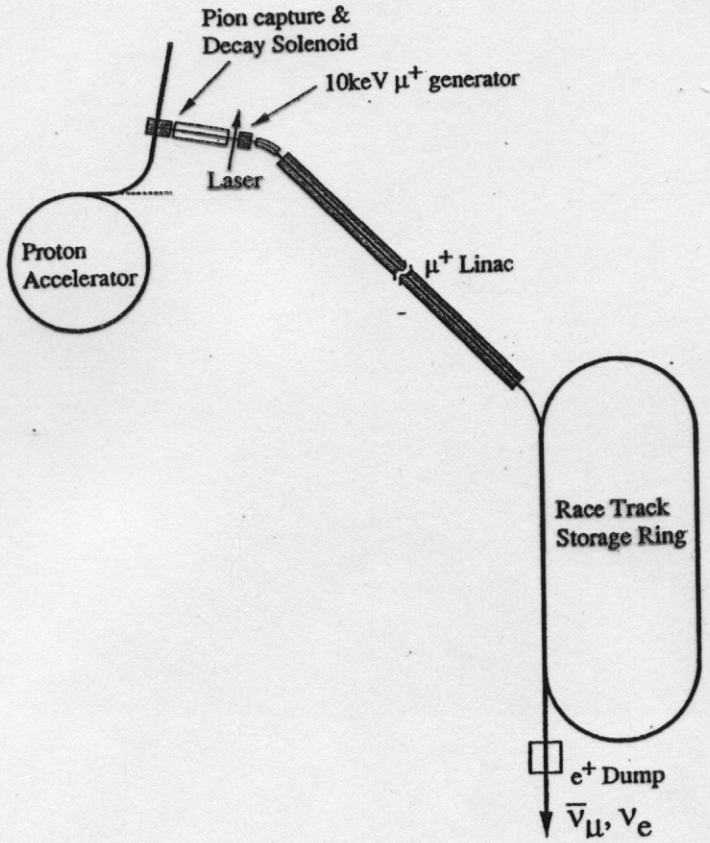


Fig. 3. Proposed scheme of the advanced generation of neutrino beam based upon a decay of the muons accelerated from the ultra-slow μ^+ ion-source.

Table I. Yield estimations for advanced neutrino source

	Expected numbers (s^{-1})	Conditions	Remarks
N_p	1.9×10^{18}	0.8 GeV × 300 μA	
$N_{\pi^+}^{tot}$	2.4×10^{18}	4 cm Carbon	$\sigma_{\pi^+}^{tot}$: 28 mb
N_{μ^+}	6.0×10^{11}	Pion Capture: 2.9 T, 20 cm bore × 1.5 m Muon Decay: 3.0 T, 25 cm bore × 10 m	Ref. (7) p_μ: 88 (42) MeV
N_μ^{stop}	2.9×10^{11}	20 × 100 μm W	
$N_{th.Mu}$	1.2×10^{10}	$\varepsilon_{th.Mu}$: 0.04	2000 K hot W
$N_{u.s.\mu^+}$	1.0×10^{10}	ε_{ion}: 0.8	Laser Resonant Ionization
$N_{\mu^+}^{Acc}$(10 TeV)	10^{10}	$\varepsilon_{cap.}$: 1.0 $\varepsilon_{acc.}$: 1.0	
$N_{\bar{\nu}_\mu \nu_e}$	0.5×10^{10}	Full conversion in Race-Track Storage Ring	$E_\nu \approx 3.3$ TeV, $\theta_\nu \approx 10^{-6}$

$N_{\pi^+}^{tot}$: total π^+ at production target, N_{μ^+}: total μ^+ at the exit of decay solenoid, N_μ^{stopp}: μ^+ stopping number at thermal Mu producing material, $N_{th.Mu}$: thermal Mu yield, $N_{u.s.\mu^+}$: ultra-slow μ^+ yield after thermal Mu ionization.

WHAT DO WE CONCLUDE ?

- Progress since Lyon ? → • detailed work started
  - • sophistication introduced

- Time to introduce errors ?

- Do we have necessary tools ?
  - • simulation seems OK : good intern. coll.
  - • lack optimization routines
  - • <u>lack analytic approach</u> !

- Need for universal figure of merit (μ/pGev ?)

- Hope WGS considered • μ beam : to do what ?
  - • diagnostics in harsh environment

What do we expect at next meeting (in 1 year) ?

- components developed - capabilities assessed.
- better definition of goals for phased approach
- comparison R.F./I.L.

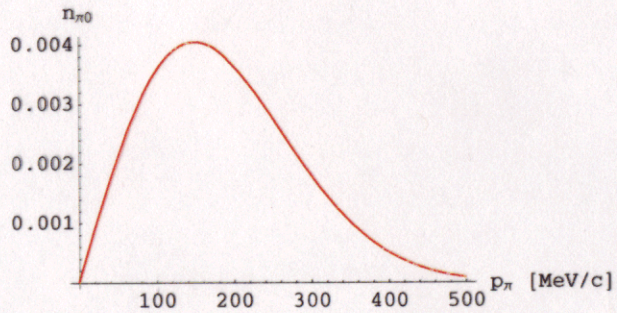
⋮

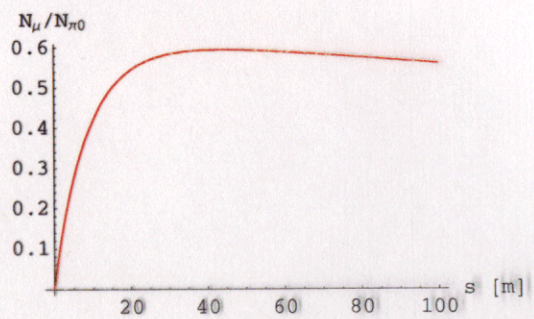
■ Phase portrait area

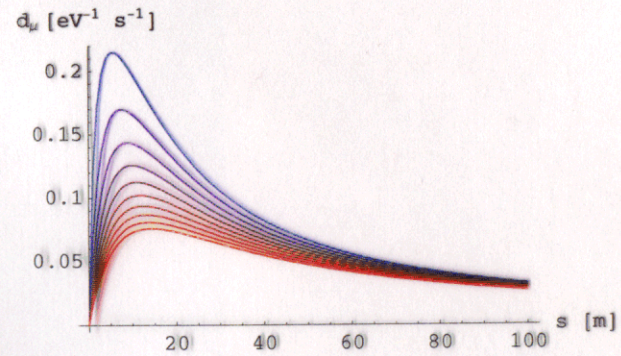
$$\frac{m_\pi^2-m_\mu^2}{m_\pi\, c\cos(v)}\,\mathrm{Log}\left(\frac{m_\pi+\sqrt{m_\pi^2+p_{\pi1}^2}}{m_\pi+\sqrt{m_\pi^2+p_{\pi2}^2}}\,\frac{p_{\pi2}}{p_{\pi1}}\right)s+\left(\frac{m_\pi^2-m_\mu^2}{m_\pi^2}\,p_{\pi1}+\frac{(m_\pi^2-m_\mu^2)(p_{\pi2}-p_{\pi1})+(m_\pi^2+m_\mu^2)(e_{\pi2}-e_{\pi1})}{2\,m_\pi^2}\right)t_p$$

■ Muon distribution along the decay channel

$$\frac{N_\mu(s)}{N_{\pi0}}=\int_{p_{\pi1}}^{p_{\pi2}} n_{\pi0}(p_\pi)\,N_\mu(s,\,p_\pi)\,d\,p_\pi$$







IDEAS FOR EMITTANCE EXCHANGE

Gail G. Hanson
NuFACT'00
May 24, 2000

INTRODUCTION

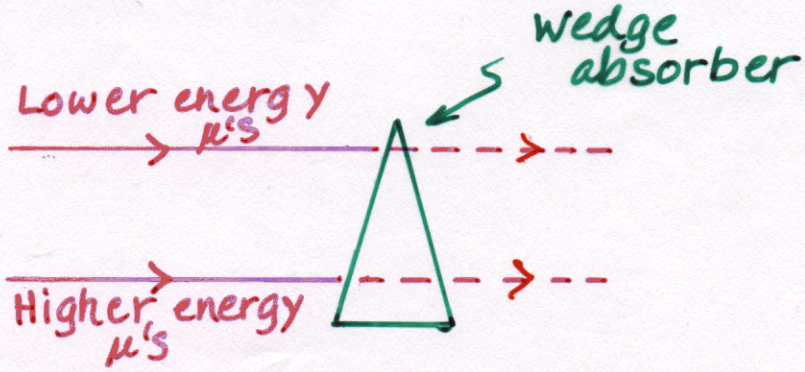
Transverse ionization cooling is produced by passing the muon beam through material (LH_2), which decreases both the transverse and longitudinal momenta. Longitudinal momentum is restored using rf cavities. Solenoidal magnets provide focusing.

The cooling channel in neutrino factory designs produces longitudinal heating. Longitudinal cooling would improve the performance for neutrino factories.

Longitudinal cooling is absolutely necessary for a muon collider.

Emittance exchange can transfer the cooling to longitudinal phase space. This can be achieved by producing a correlation between energy or time and transverse momentum or position.

Example:



Higher energy muons lose more energy than lower energy muons

Some emittance exchange schemes that have been proposed:

- Bent solenoid & wedge
- Dipoles & wedge
- RF cavities
- Ring cooler
- Correlation between energy and transverse position (β function)
- Bunch stacking
- 3D ionization cooling along a spiral orbit in a solenoid
- Others? Lithium lens, plasma lens, ...

So far, none of these has been proven to be successful in a full simulation.

Emittance Exchange Workshop at BNL

September 11-29, 2000

Registration form has been sent around.
Organizers: Gail Hanson & Rick Fernow

Would like to have some simulation efforts started beforehand. Who?

G. Hanson - attempt simulation of spiral cooling in ICOOL

R. Palmer - β effect

Y. Fukui - stacking

[(R. Bennett) - acceleration of "slowed" muons]

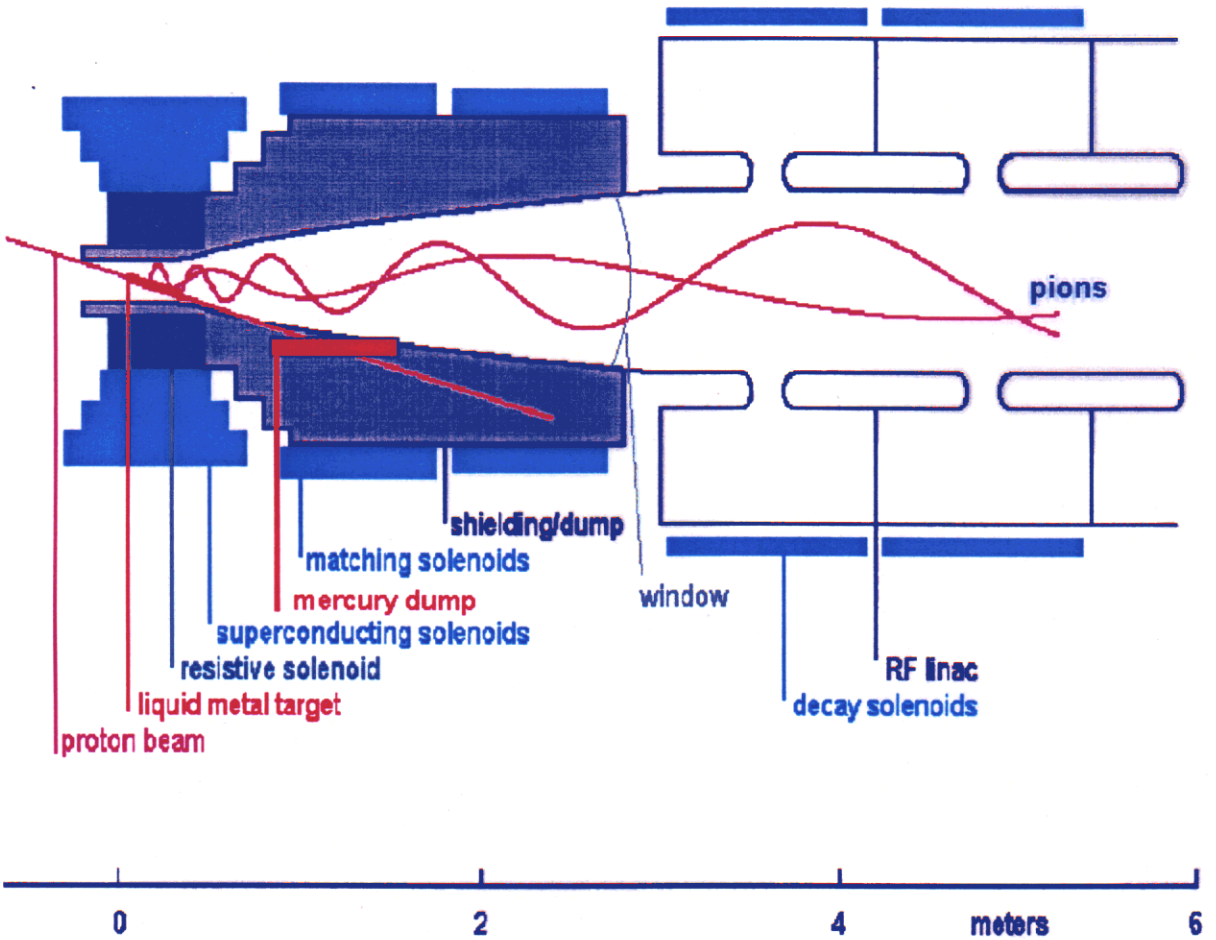
Will put new link on Emittance Exchange Web Page to list these. Talk with me here or send e-mail to gail@indiana.edu.

Solenoid Capture

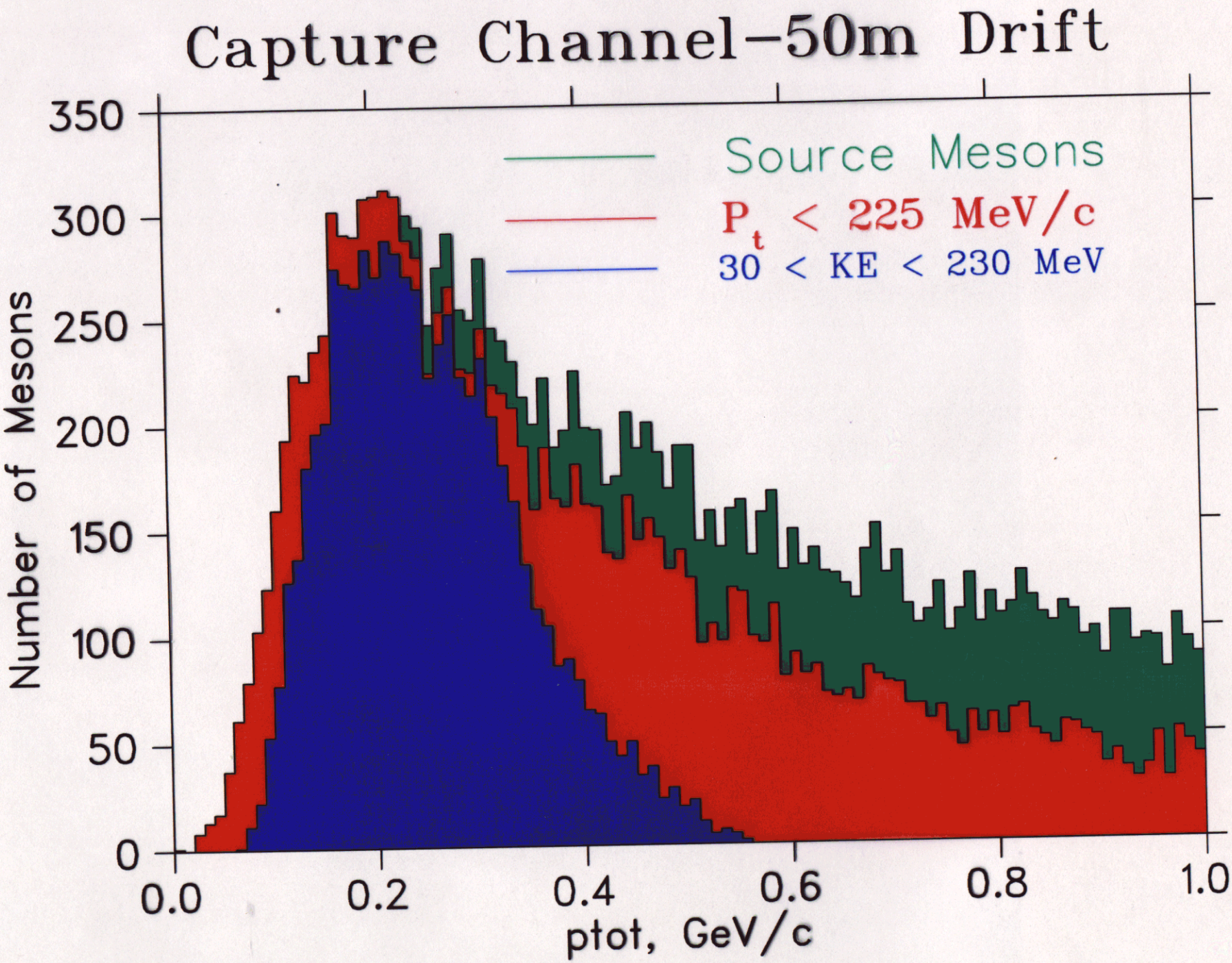
Harold G. Kirk
Brookhaven National Laboratory

NuFACT'00
Monterey, California
May 22-26, 2000

TARGET, CAPTURE & DECAY



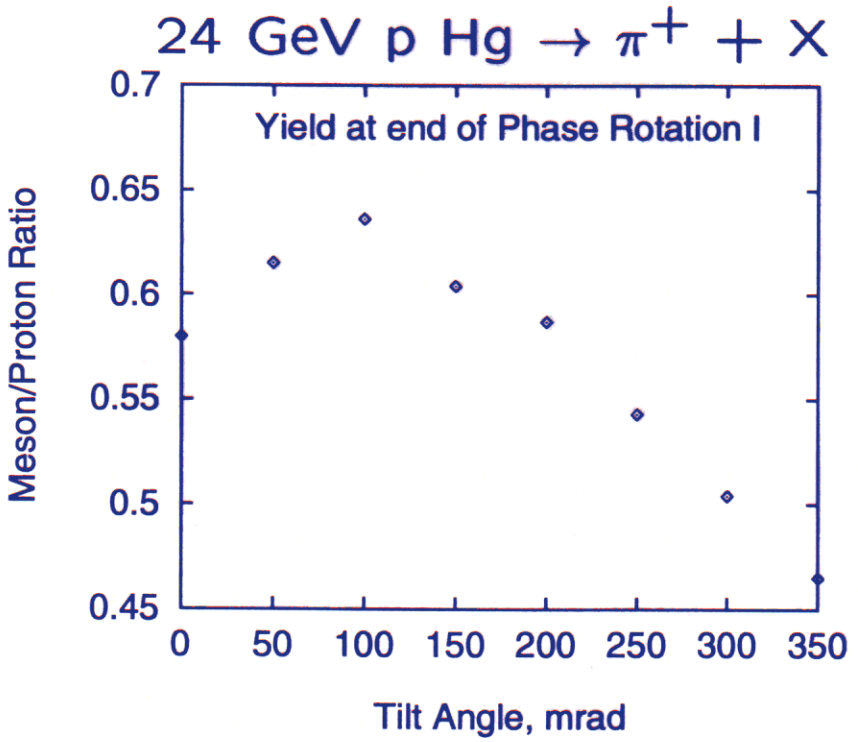
- TARGET:Liquid Metal Jet
- CAPTURE:20 T Solenoid
- BEAM DUMP
- MATCHING
- DECAY & PHASE ROT:1.25 T


Capture Channel–50m Drift
Source Mesons
P_t < 225 MeV/c
30 < KE < 230 MeV
Number of Mesons
ptot, GeV/c
0
50
100
150
200
250
300
350
0.0
0.2
0.4
0.6
0.8
1.0

Variation of target tilt angle

- 1.0cm diameter target
- proton beam $\sigma_x = \sigma_y = 0.15$ cm
- proton beam KE = 24 GeV

Results at end of Phase Rotation I



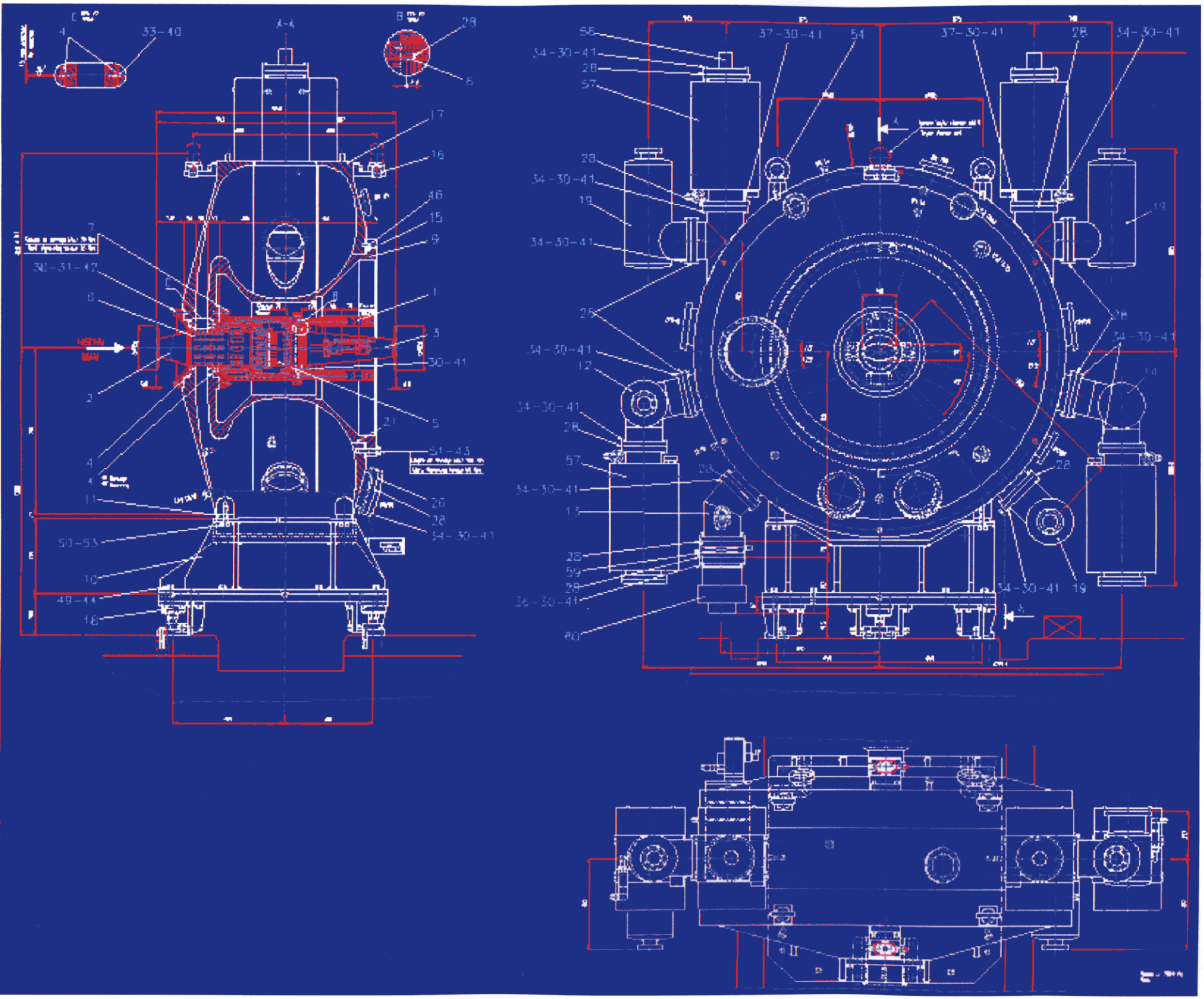
Pion Production/Capture

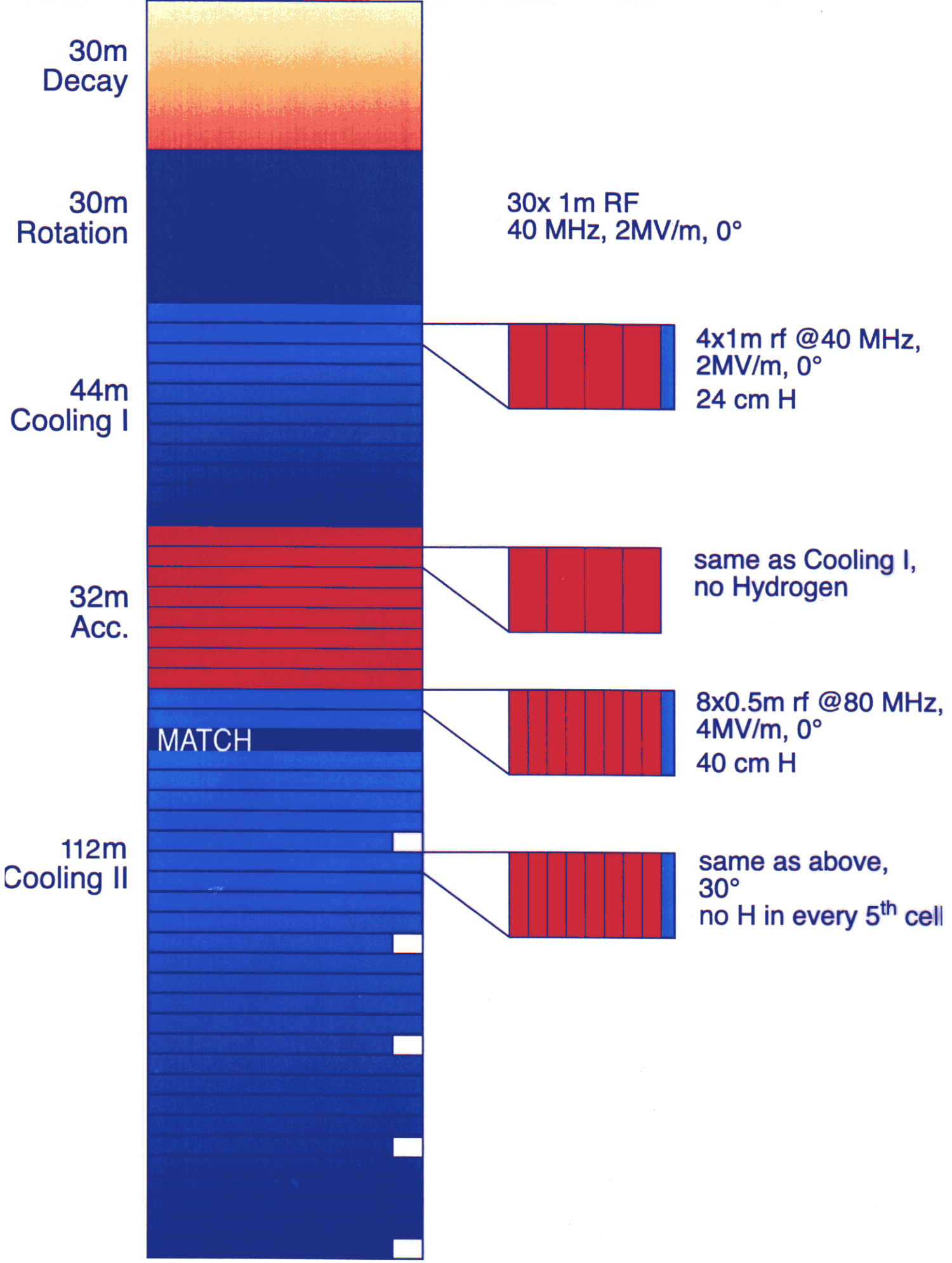
	Meson/Proton Yield	
16 GeV Protons	Carbon	Mercury
π^+ (30 <KE<230MeV)	.182	.309
π^- (30 <KE<230MeV)	.153	.315
24 GeV Protons		
π^+ (30 <KE<230MeV)		.469
π^+ (190 <P<390MeV/c)		.636

RF approach to front end

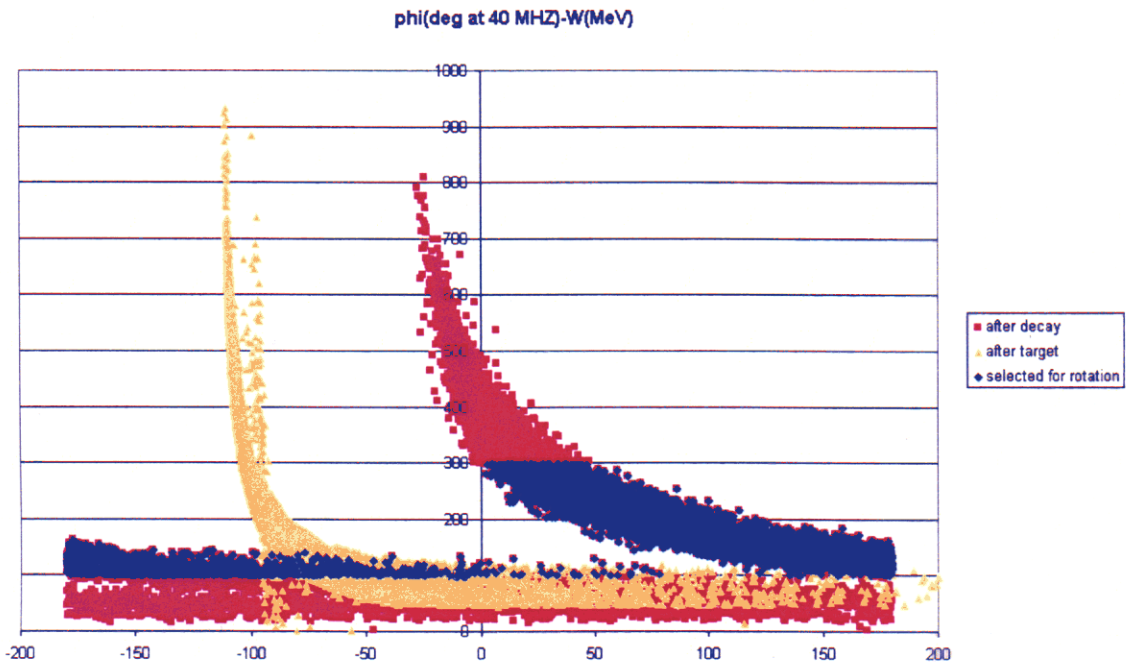
- the overall system
- beam dynamics for each section
- the pros and cons, the technical challenges…
- future work
- feedback

Alessandra Lombardi


A-A
33-40
17
16
46
15
9
7
36-31-42
8
1
3
30-41
2
5
21
4
51-43
11
26
28
34-30-41
50-53
10
49-44
18
56
54
37-30-41
57
19
12
59
60


30m
Decay
30m
Rotation
30x 1m RF
40 MHz, 2MV/m, 0°
44m
Cooling I
4x1m rf @40 MHz,
2MV/m, 0°
24 cm H
32m
Acc.
same as Cooling I,
no Hydrogen
MATCH
8x0.5m rf @80 MHz,
4MV/m, 0°
40 cm H
112m
Cooling II
same as above,
30°
no H in every 5th cell

END OF DECAY

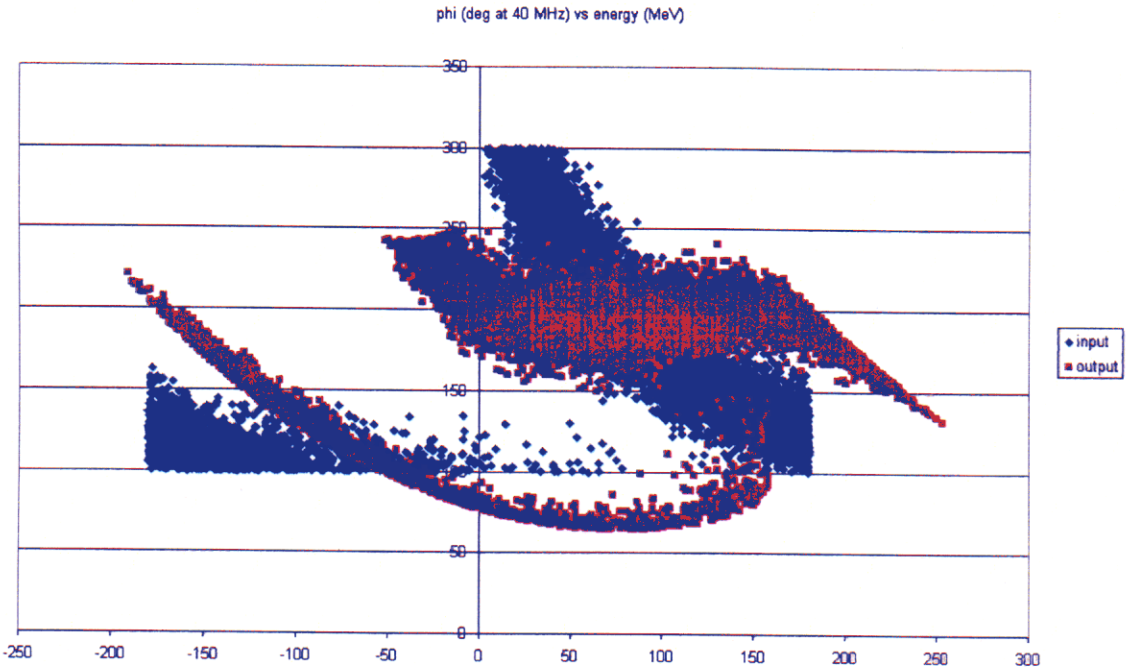


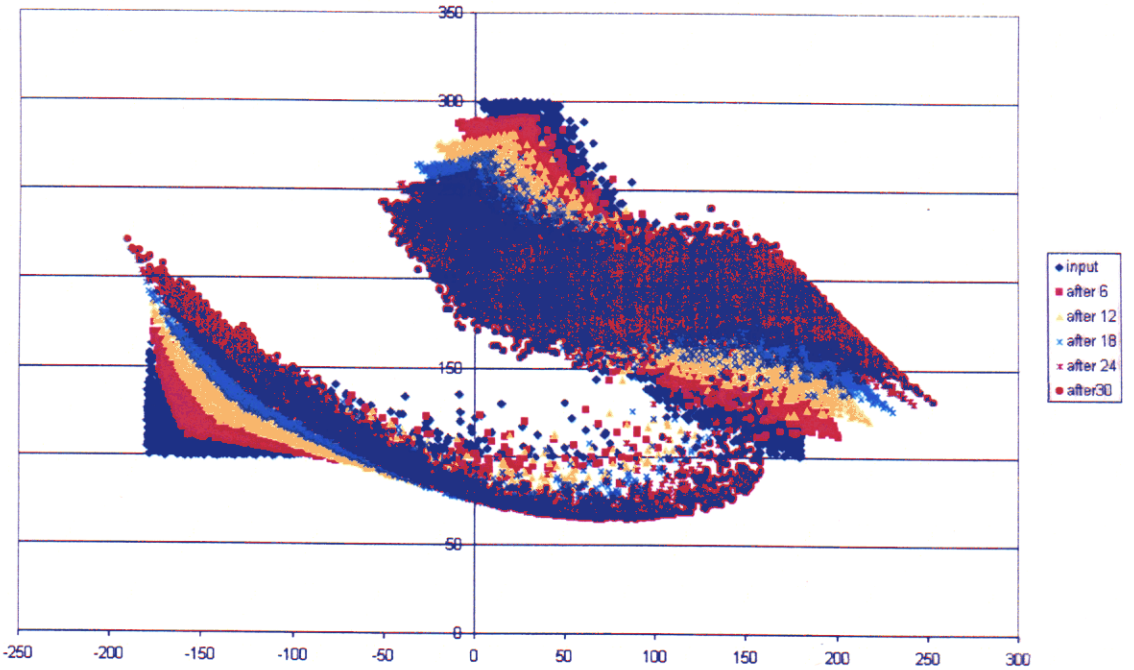
≈ 50 % of the muons are selected

there is no improvement of the decay channel that can increase this number

ROTATION

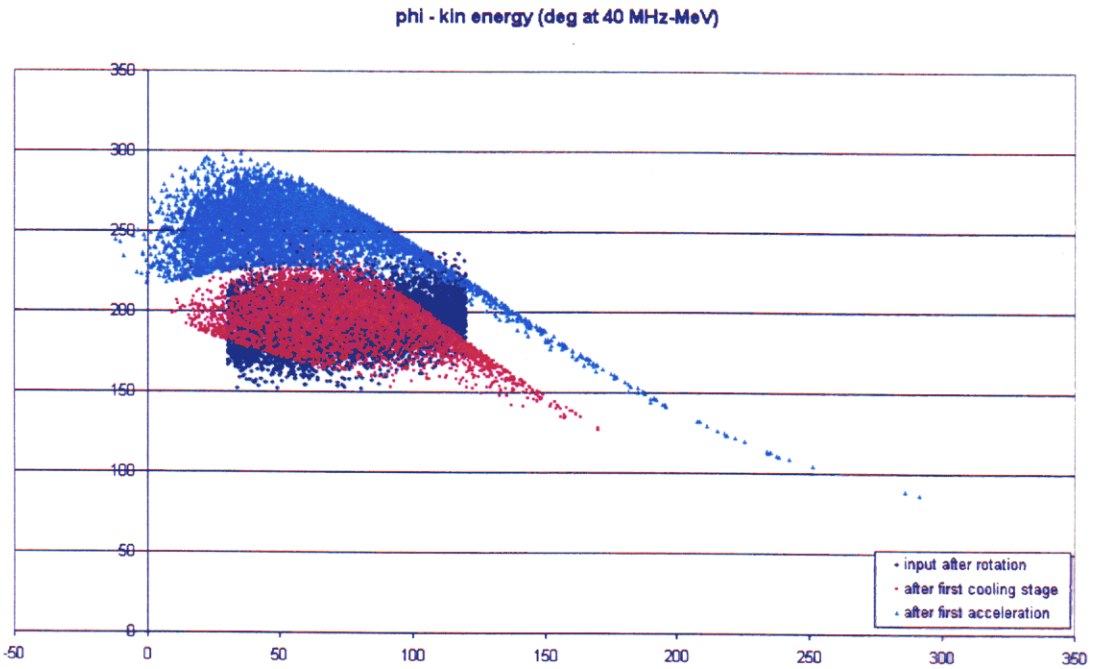
30 cavities , 1 m long, 40 MHz, 2MV/m, 1.8 Tesla solenoid around (or adjacent)

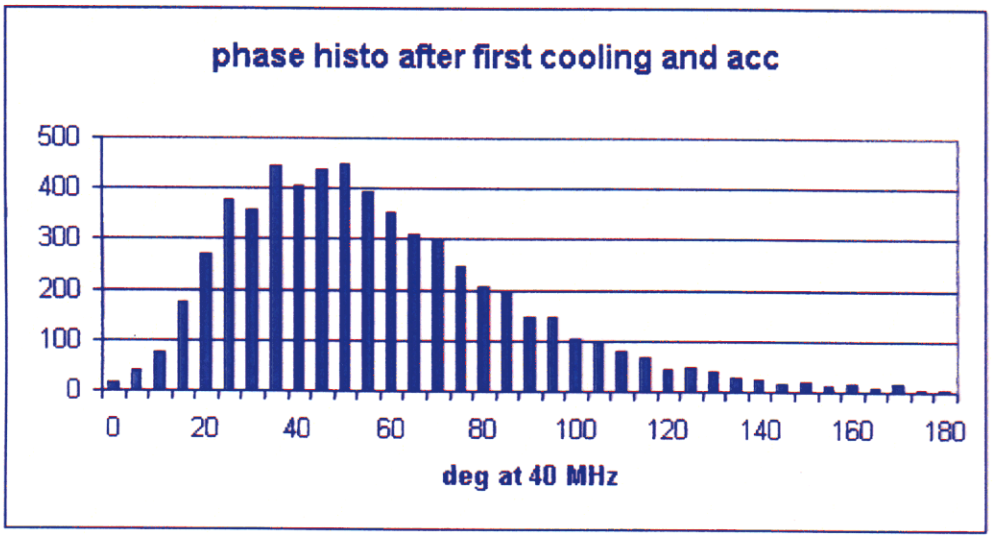




rotation : 3 deg / cell , rf defocusing small

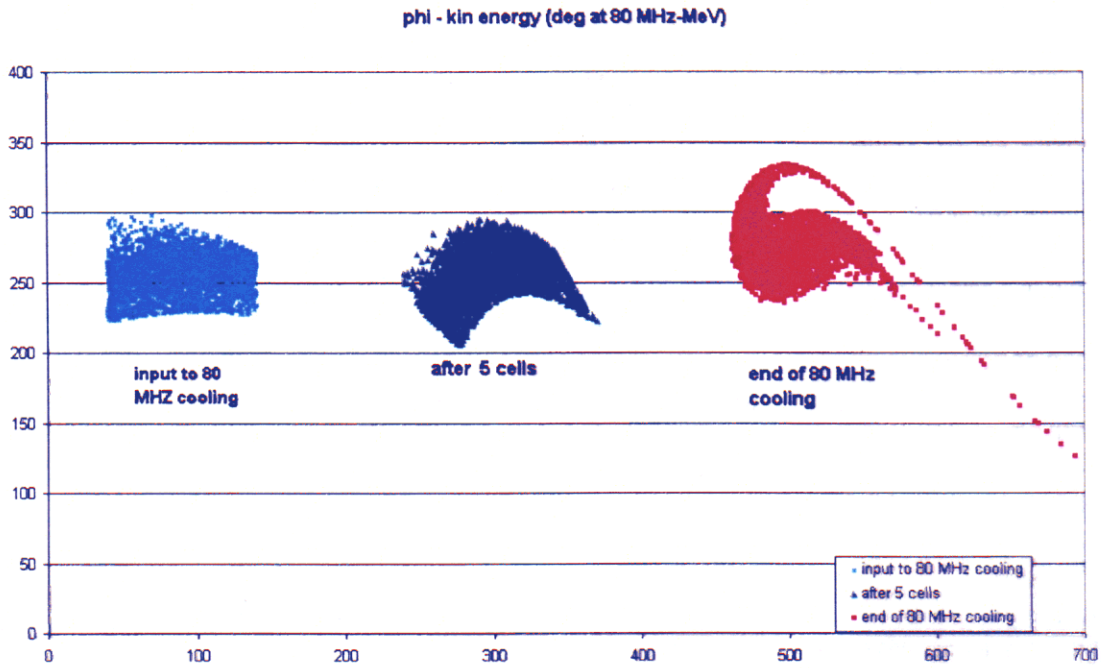
COOLING-40MHz



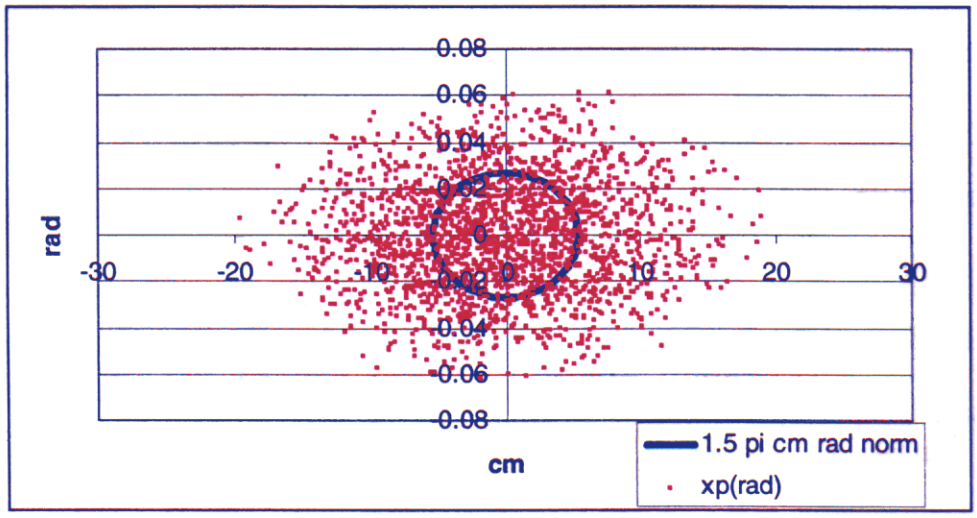


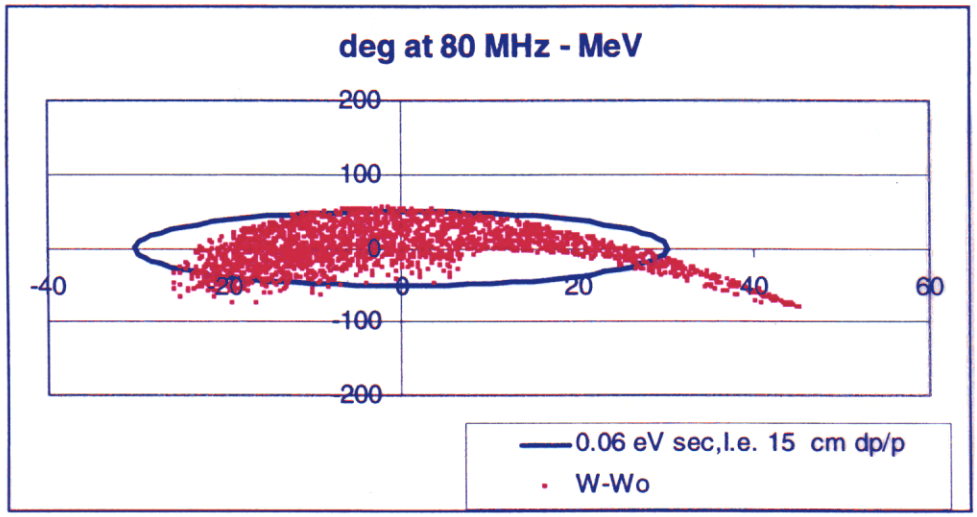
65%of the particle are in 90deg at 80 MHz

COOLING-80MHz



40-80 MHz scheme at 1 GeV

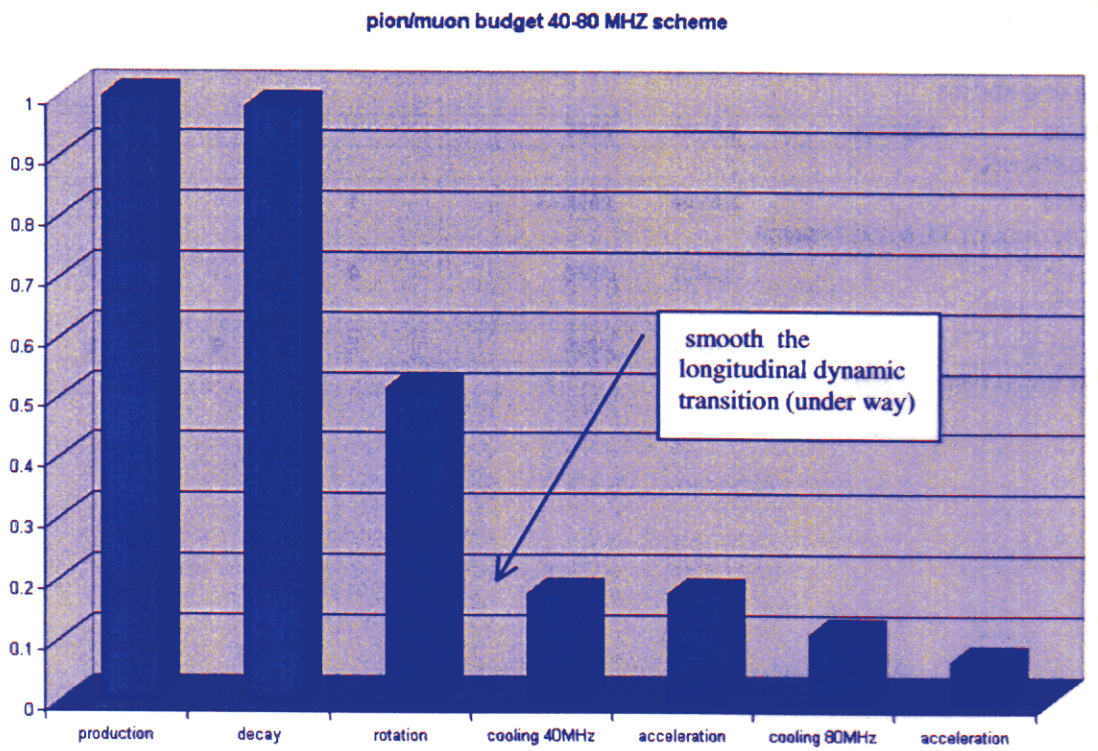




PARTICLE BUDGET

At the moment :

0.012 μ/proton i.e. 1.2 10^{21} μ/year of which half are in the re-circulator acceptance (1.5 pi cm rad, 15 pi cm dp/p)



Magnetic Horn Study for the NuFact

By:

Alan Ball

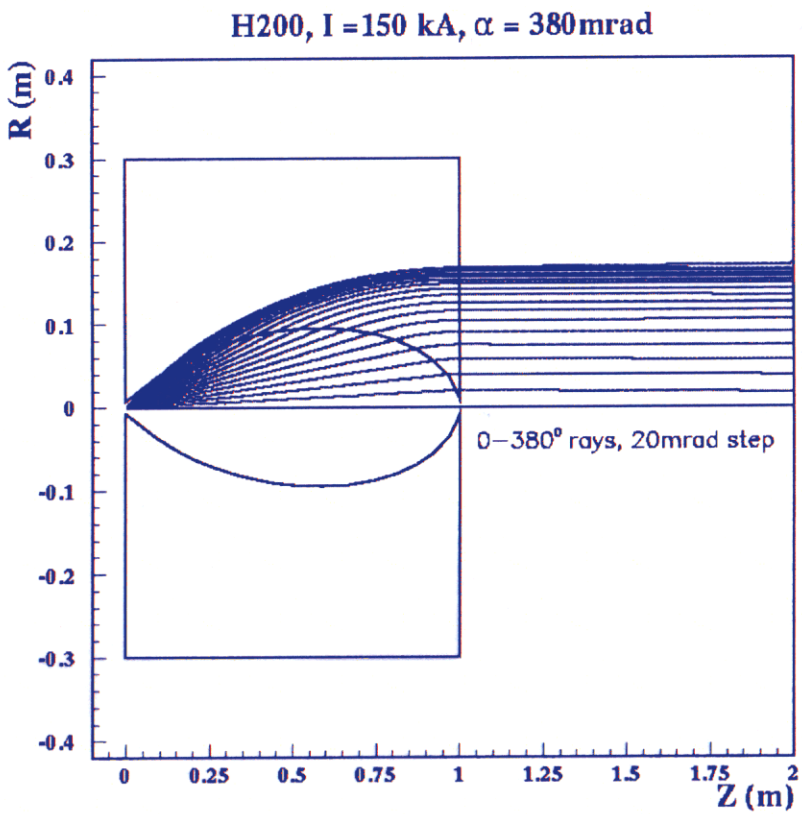
Alain Blondel

Simone Gilardoni

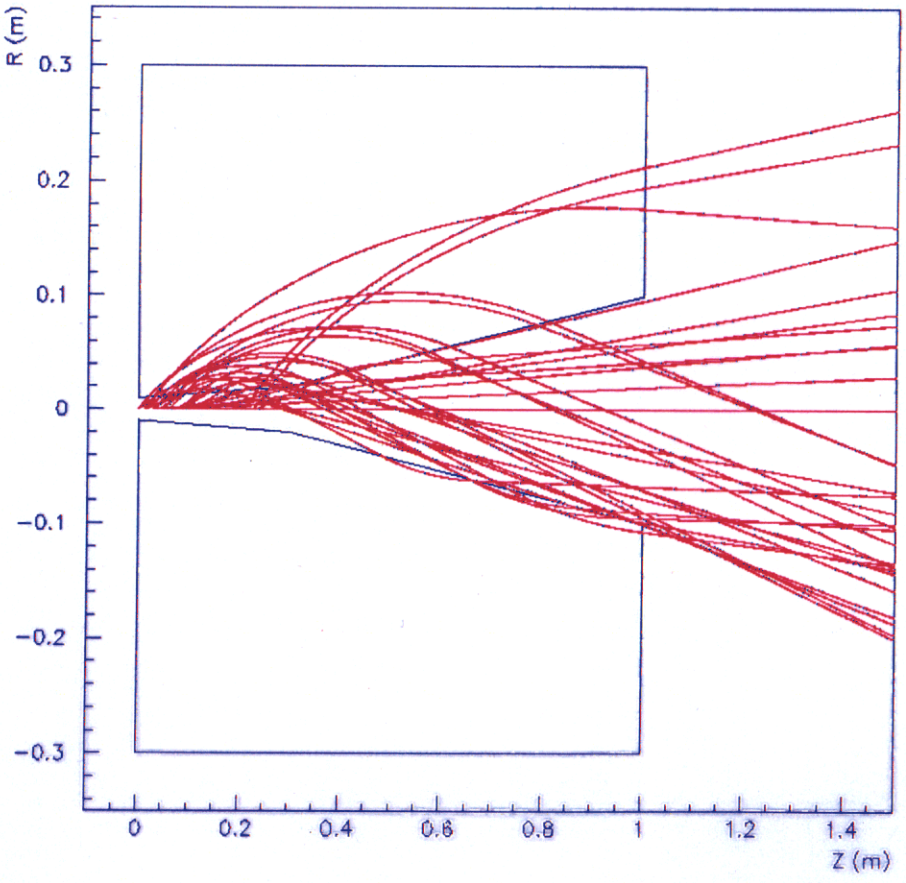
Nikolaos Vassilopoulos

ν-factory 2000

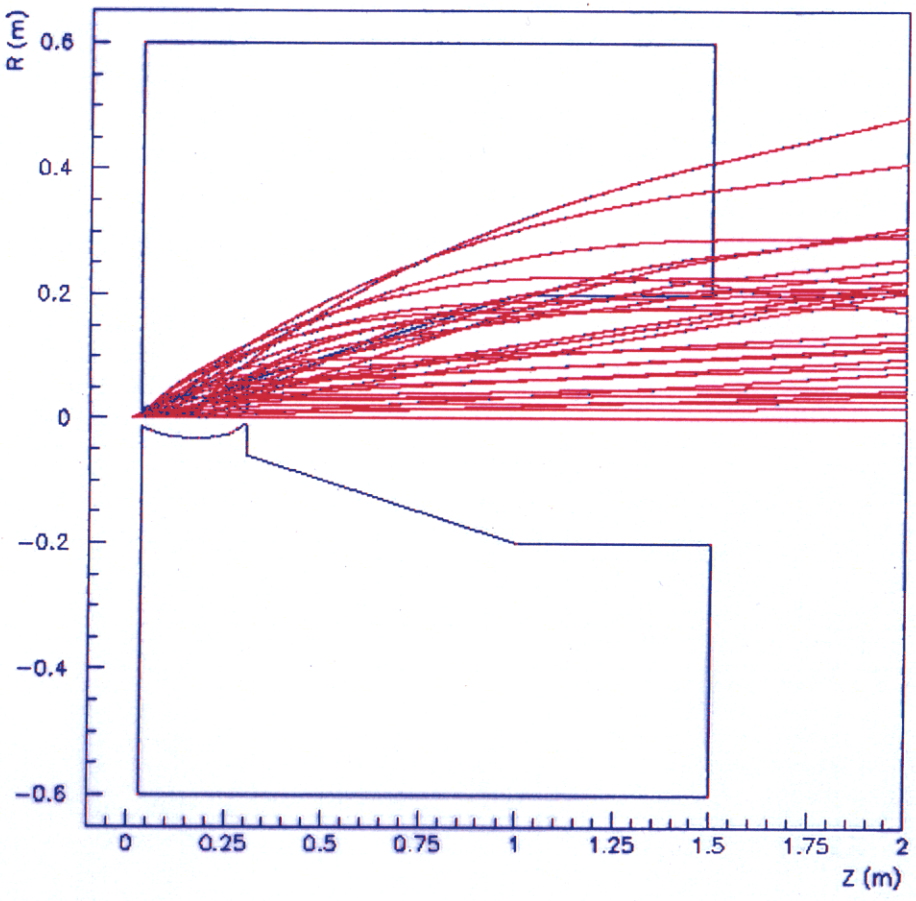
The Horn: vote for it!!!



New horns



Triangular 300 kA



S 300kA

Conclusions

Number of π^+ for 2 GeV proton per 2 λ_i

Radius < 30 cm Y > 1	[redacted] Arbitrary Units		
	S 300	T 300	Solenoid
After match	9.6	11.5	8.6
After 1 m	7.2	9.9	7.3

Future works includes C targets, material simulation

200 MHz Buncher Section

David Neuffer

Fermilab

with R. Palmer, V. Balbekov, A. Van Ginneken, C. Kim,
G. Penn, ...

Buncher Section

Purpose:

- Split long bunch from rf rotation section (induction linac) into string of 200 (0r 175) MHz bunches for cooling section
- Transverse match from induction linac (B=1.25 T) Into cooling channel

Baseline Beam parameters from rf rotation

$P_{\mu,central} \cong$ 200 MeV/c
(Kinetic energy $\cong$ 120 MeV)

Longitudinal
$L_{total} \cong$ 100 m ($\sigma_z \cong$ 16m)
$\sigma_P \cong$ 8 to 10 MeV/c (PJK ~ 4MeV/c)

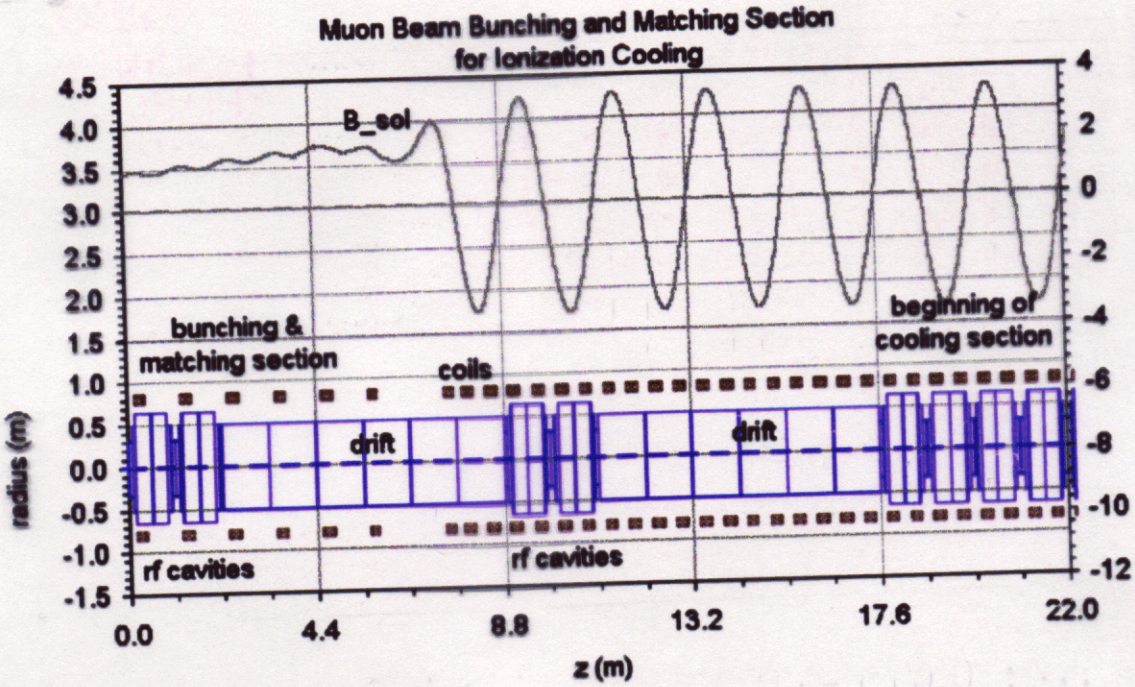
Transverse:
$\varepsilon_{T,N} \cong$ 0.015 m ($\sigma_x \cong$ 8cm)

Cooling Channel beam parameters:

$\sigma_z \cong$ 10cm; $\sigma_p \cong$ 15 MeV/c
$\beta_\perp \cong$ 0.3m ($\sigma_x \cong$ 5cm)

Possible Configuration

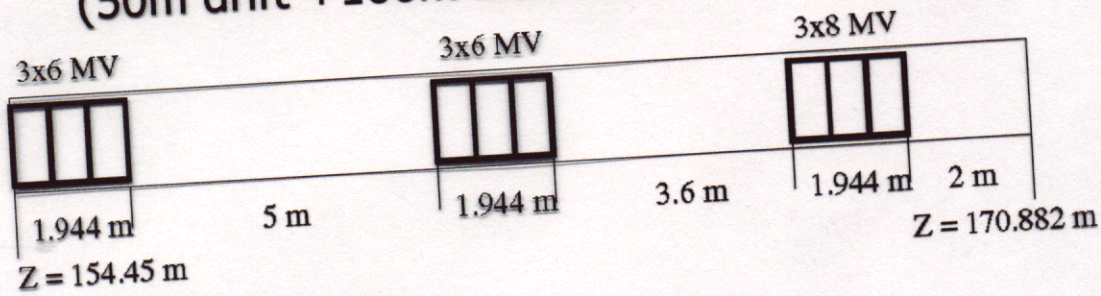
(C. Kim - 2-step buncher, 1.1m cells):



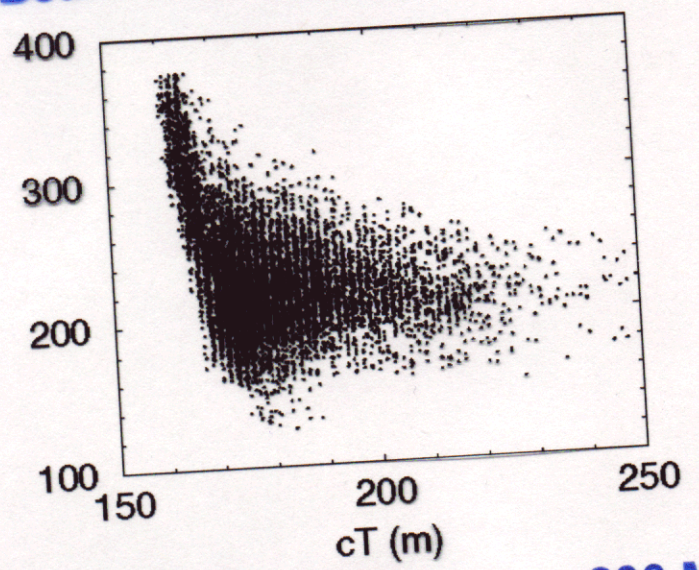
Case includes transverse matching solenoids

Feasibility study buncher:

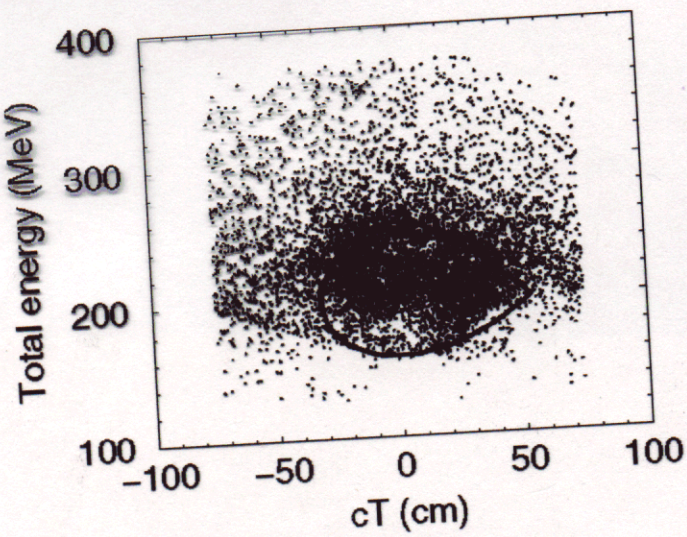
(50m drift +100m induction linac + "minicool")



Beam after Buncher:



Distribution folded over 200 MHz periodicity:



R&D to do:

Optimize/ improve scenarios

Rf capture ⇒ Cooling

Need more 6-D, integrated simulations

At output of induction linac, **ΔE is too large**

⇒ Output of buncher has ε_L **is too large**

(overfills rf cooling bucket)

⇒ Large losses in buncher and cooling channel

⇒ **Need energy cooling**

⇒Emittance exchange workshop (July at BNL)

Correlations –

δp-A^2 correlation has not been matched.

Study effects and optimization possibilities.