Neutrino Factory –

– machine aspects

H. Haseroth, CERN

A Basic Concept for a Neutrino Factory

⇒Proton driver

⇒High-power proton beam onto a target

⇒System for collection of the produced pions and their decay products, the muons.

You may stop here for a Superbeam

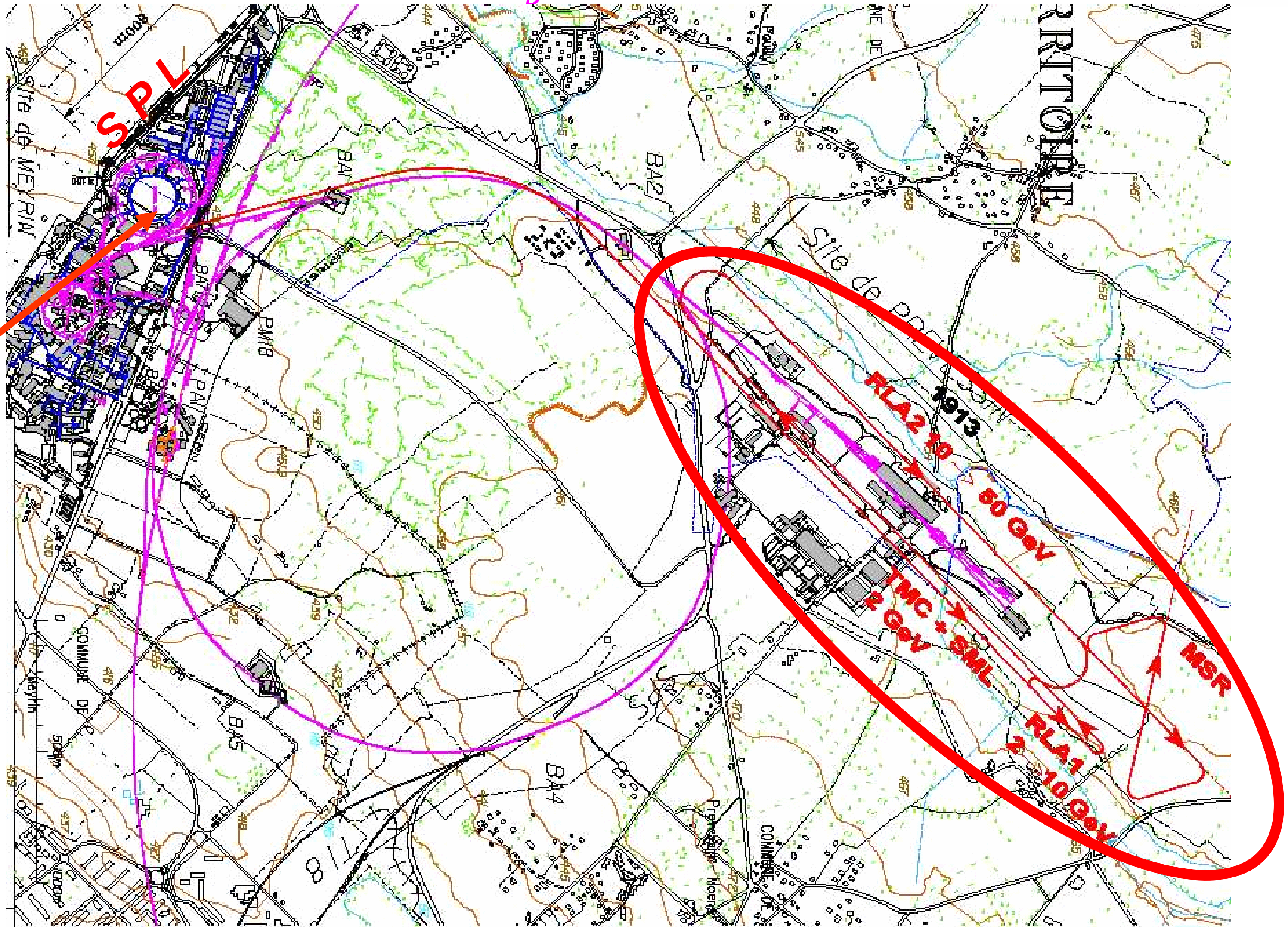
⇒Energy spread and transverse emittance may have to be reduced: “phase rotation” and ionisation cooling

⇒(Fast) acceleration of the muon beam with a linac and “RLAs” (Recirculating Linear Accelerators) or FFAGs (?)

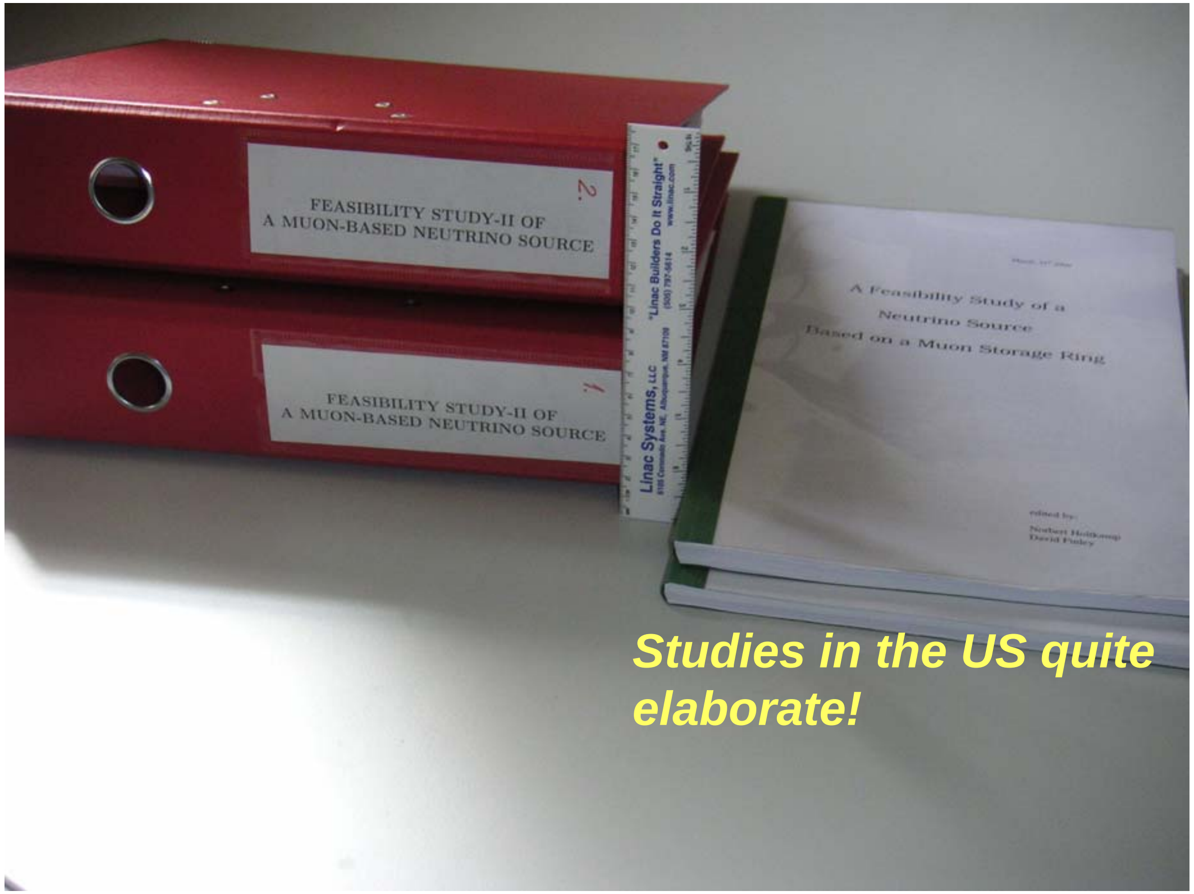
⇒Muons are injected into a storage ring (decay ring), where they decay in long straight sections in order to deliver the desired neutrino beams.

Preliminary Layout of a Neutrino Factory at CERN

Accumulator/ compressor ring (ex ISR)



American Studies I and II



http://www.fnal.gov/projects/muon_collider/nu/study/report/machine_report/

http://www.cap.bnl.gov/mumu/studyii/FS2-report.html

European (CERN) Study:

http://slap.web.cern.ch/slap/NuFact/NuFact/nf122.pdf

The Proton Driver

Technological challenges: **High power is a challenge in terms of beam losses, which can yield undesired activation of the machine components making hands-on maintenance impossible.**

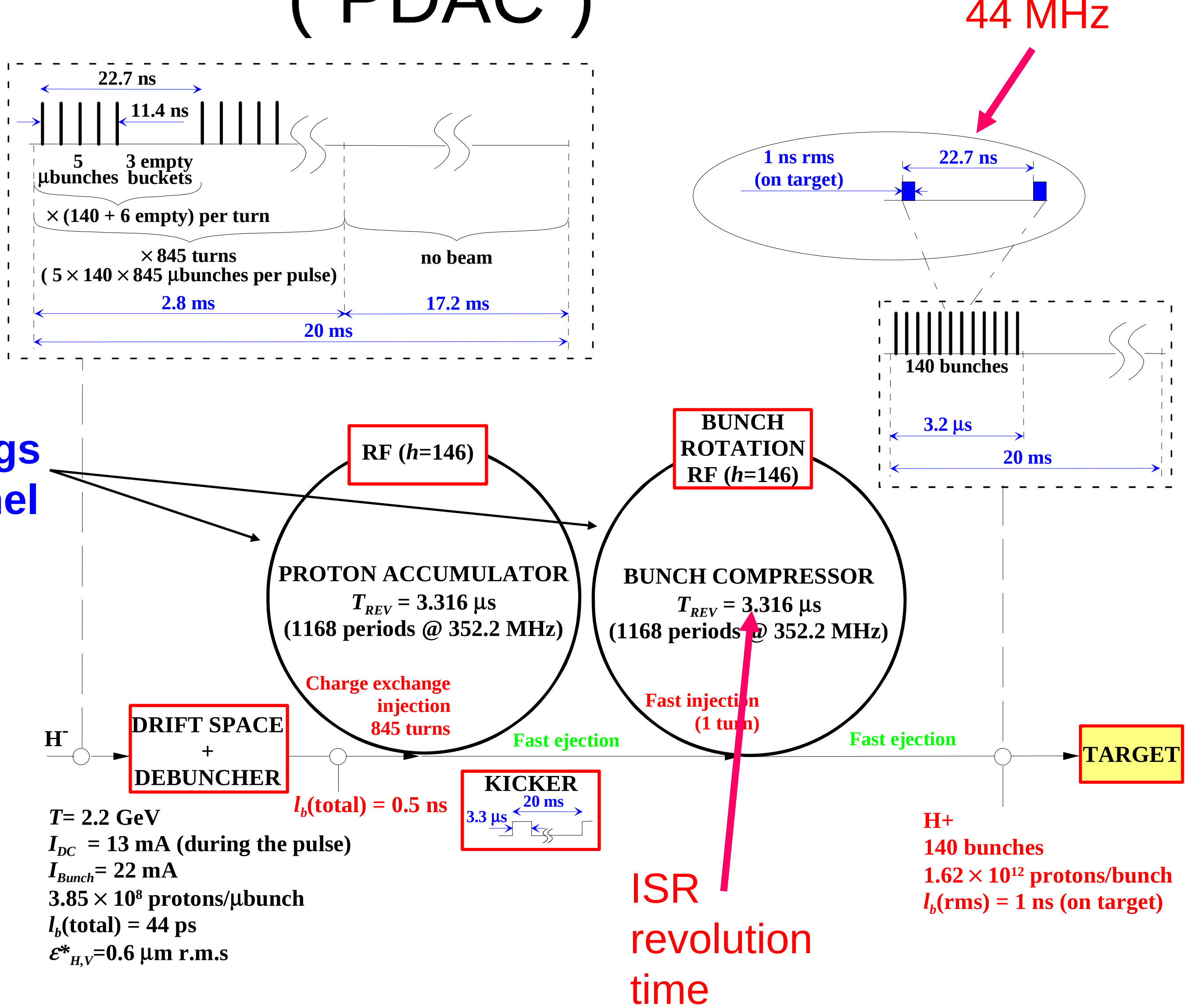
In the CERN scheme of an H- linac with charge exchange injection into an accumulator ring the stripping foil needs very close attention.

A common problem of all proton drivers is the production of very short bunches in order to reduce finally the energy spread of the muons with a scheme called "debunching" amongst linac experts ("phase rotation" for neutrino people)

Accumulator and Compressor Rings ("PDAC")

how to make out of 2.8 ms linac pulses a pulse of 3.3 μs with 140 bunches of 1 ns…

2 synchrotron rings in the ex-ISR tunnel



The target

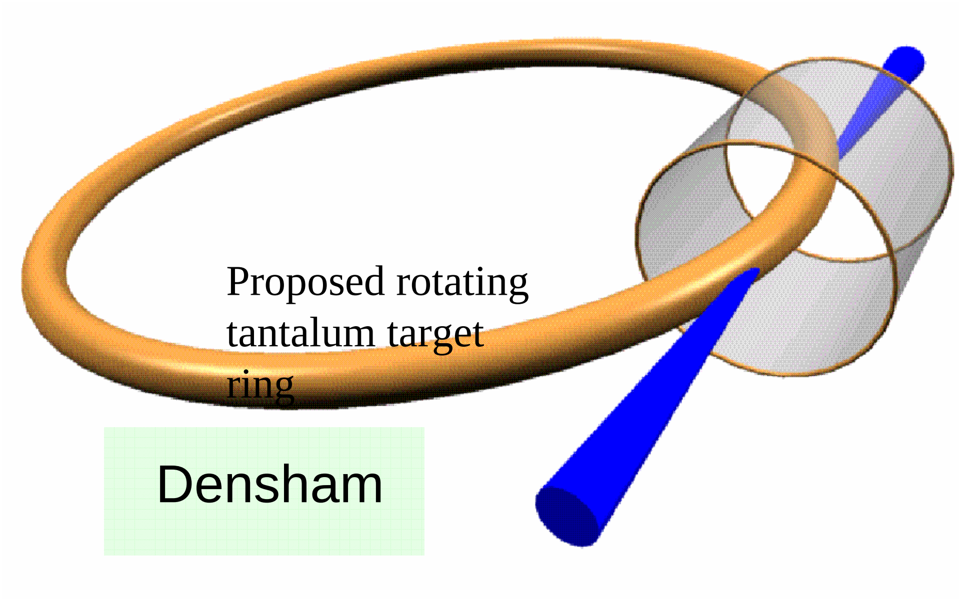
Many difficulties: enormous power density

⇒ lifetime problems

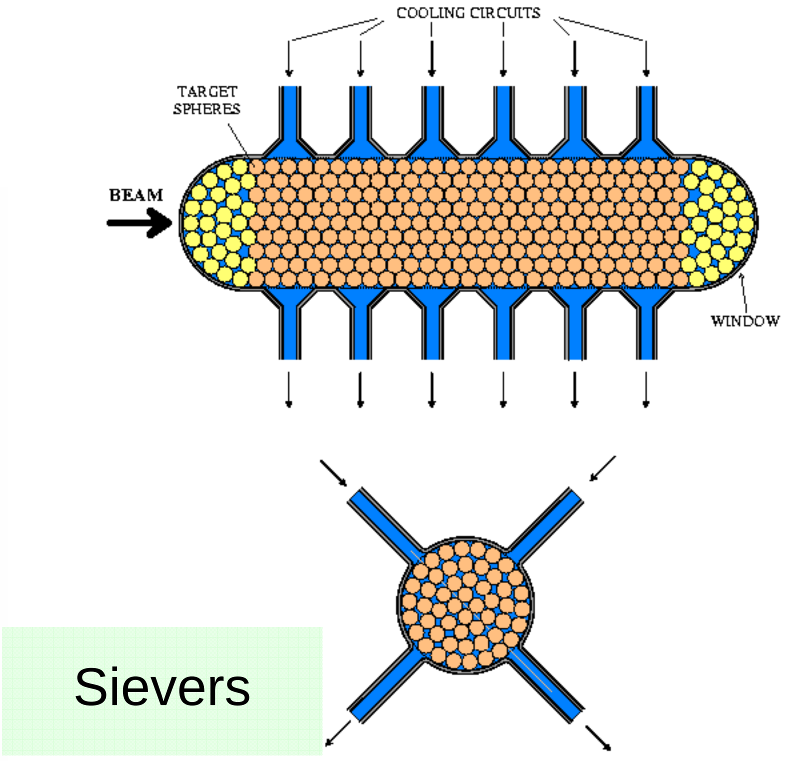
pion capture

Replace target between bunches:

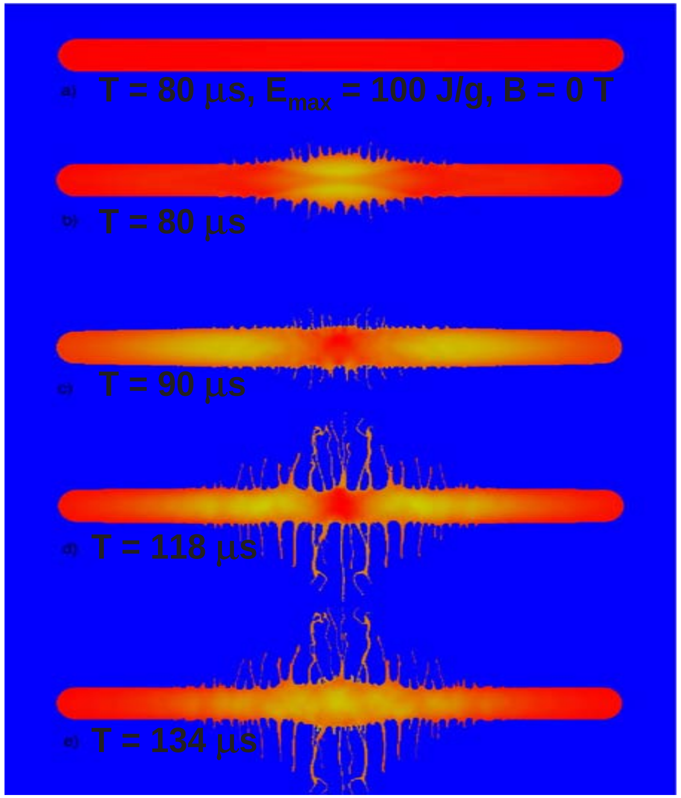
Liquid mercury jet or rotating solid target



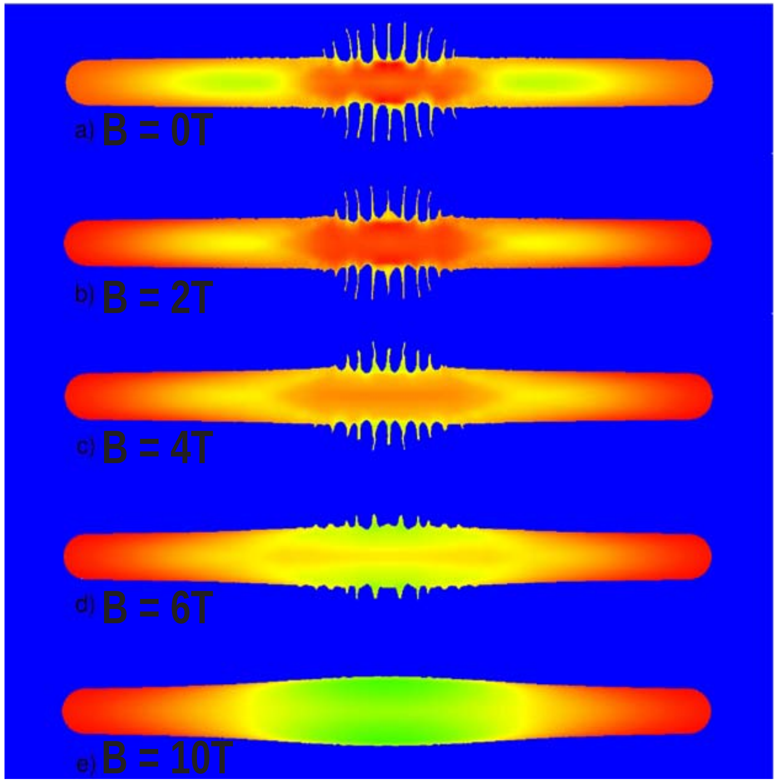
Stationary target:



Simulations of Hg target at BNL (Samulyak)

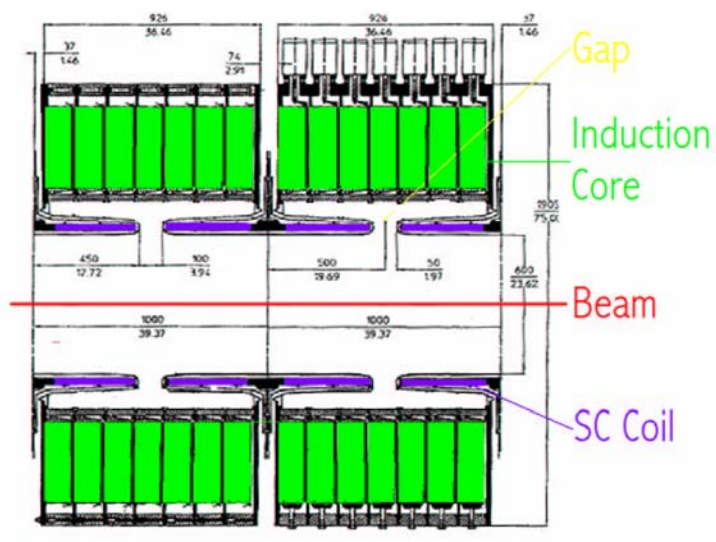


Gaussian energy deposition profile
Peaked at 100 J/g. Times run from
0 to 124 µs.

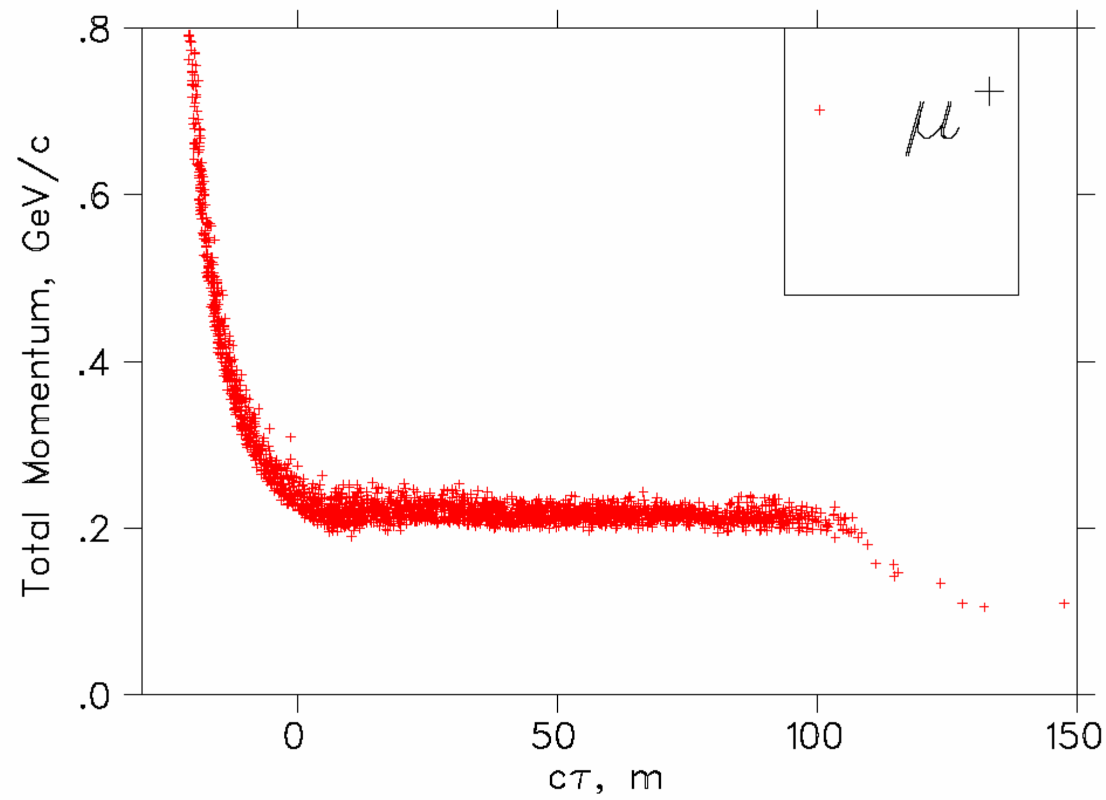


Jet dispersal at t=100 µs with magnetic
Field varying from B=0 to 10T

American Study 2, “phase rotation”

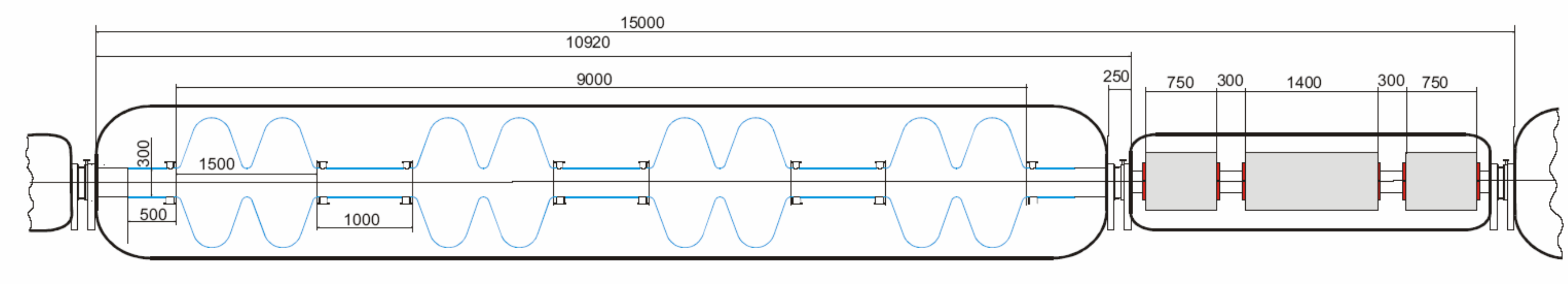


Induction linac

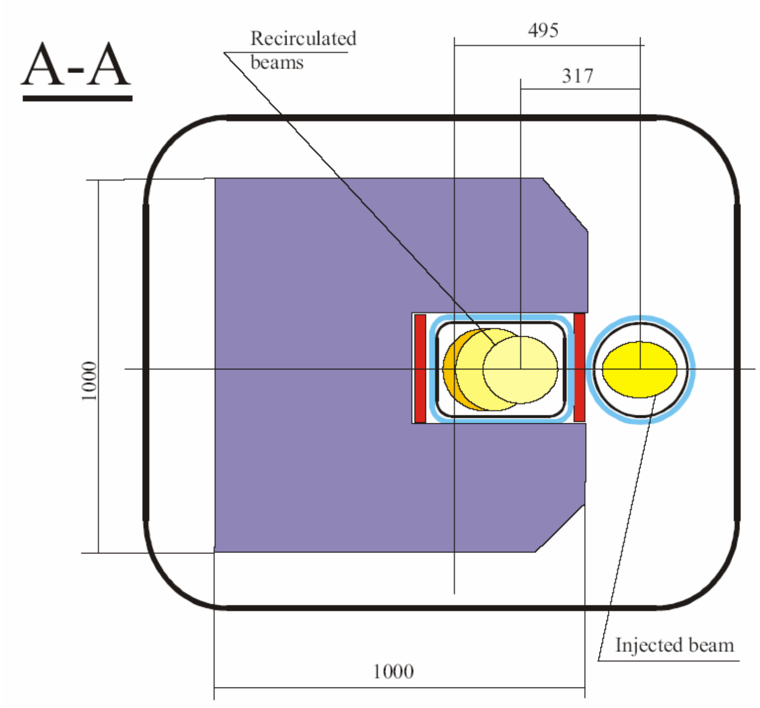


Beam longitudinal profile

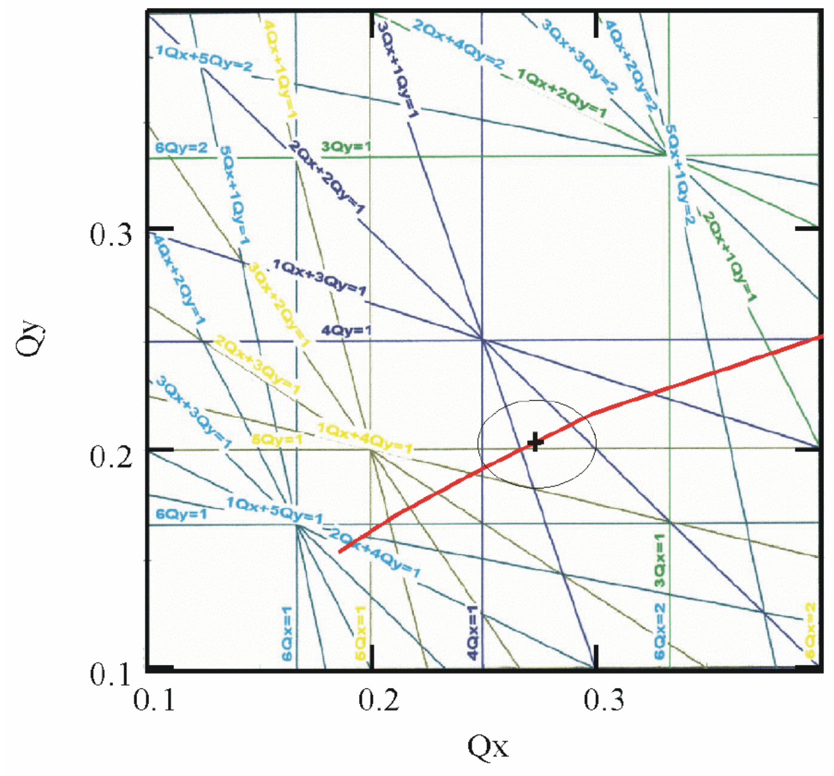
Study 2: RLAs



Layout of an RLA period

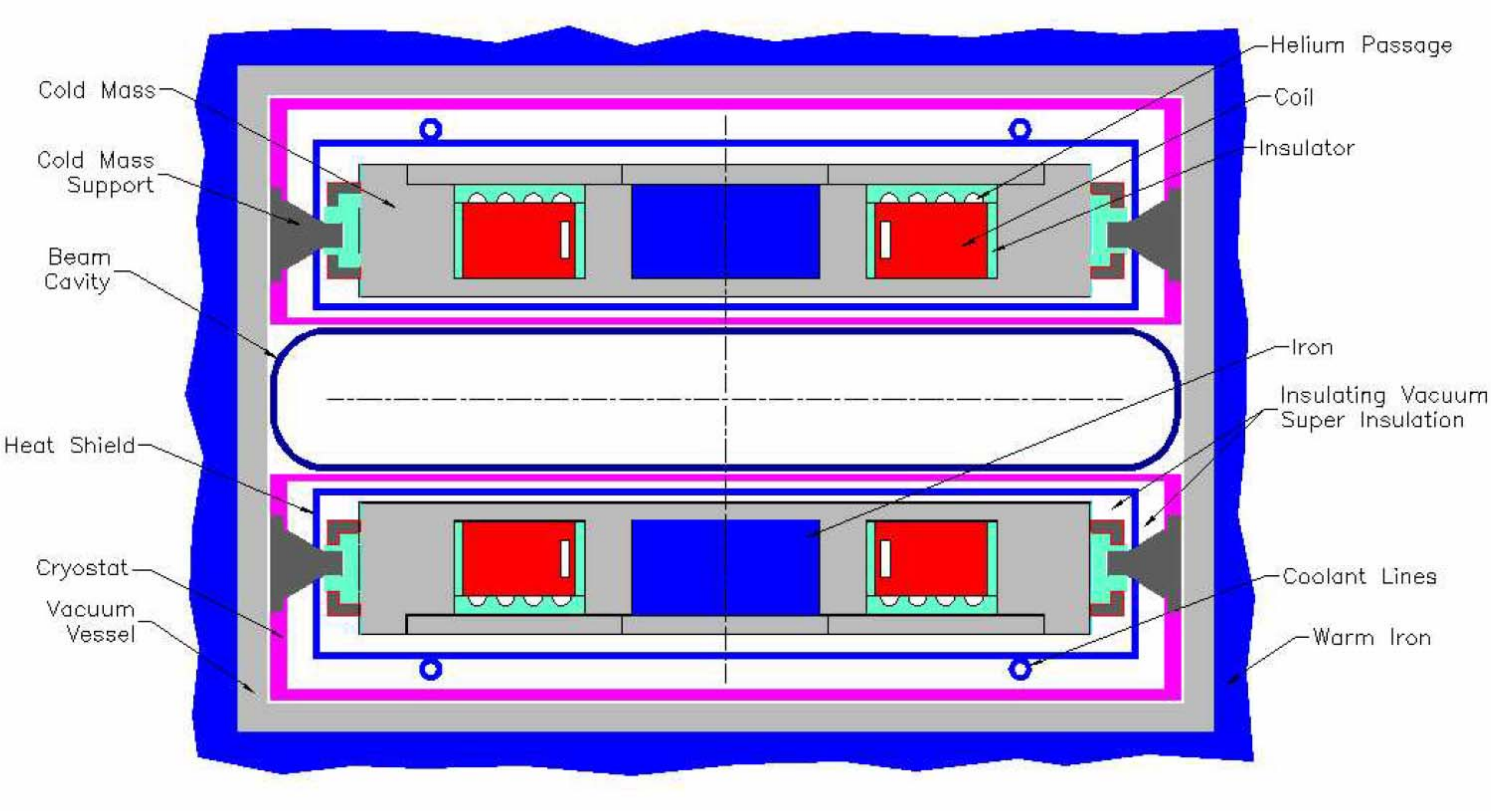


Injection chicane



Tune diagram

Storage (Decay) ring
(Study 2, magnet cross section)



Let me now go into some more details, of what has/could/should be done…

Targetry

(American word invention, my apologies to English language purists…)

Areas of application:

Neutrino physics

Studies of rare processes initiated by muons

Studies of materials with neutron beams from a spallation source

Accelerator production of tritium

Accelerator transmutation of waste

Accelerator test facilities for fusion reactor materials
etc…

Some of the problems:

Survival of components against melting/vaporization

Survival of components against beam-induced pressure waves, in the case of pulsed proton beams

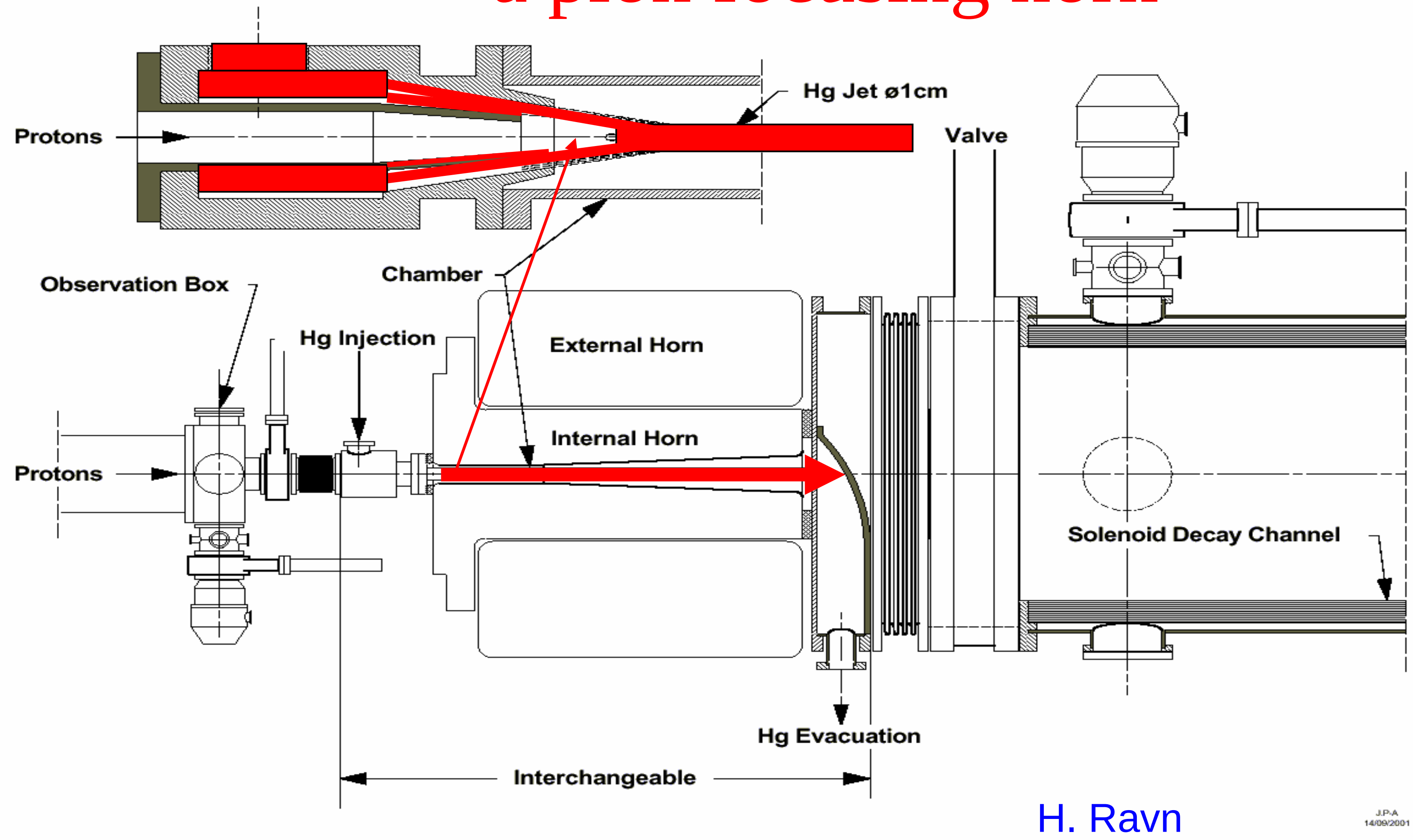
Survival of components against radiation damage

For beam power in excess of 1 MW passive solid targets (or rotating-wheel targets) become very problematic. This has led to consideration of flowing liquid targets: mercury, molten lead, molten Pb/Bi, *etc.*

Experience has shown that if a liquid target is confined inside a metal pipe in the region of the interaction with a pulsed proton beam, then the beam-induced pressure waves can cause pitting (associated with cavitation during the negative-pressure phases of the waves).

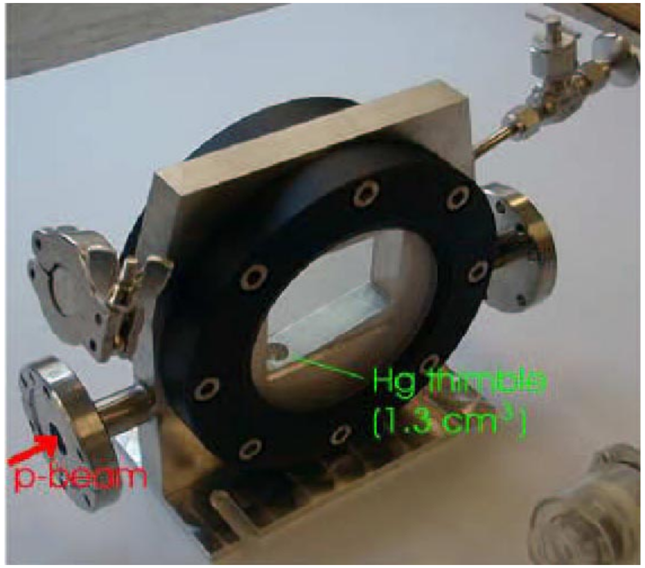
Such concerns indicate that it would be preferable to have a flowing liquid target in the form of a free jet, at least in the region of interaction with the proton beam.

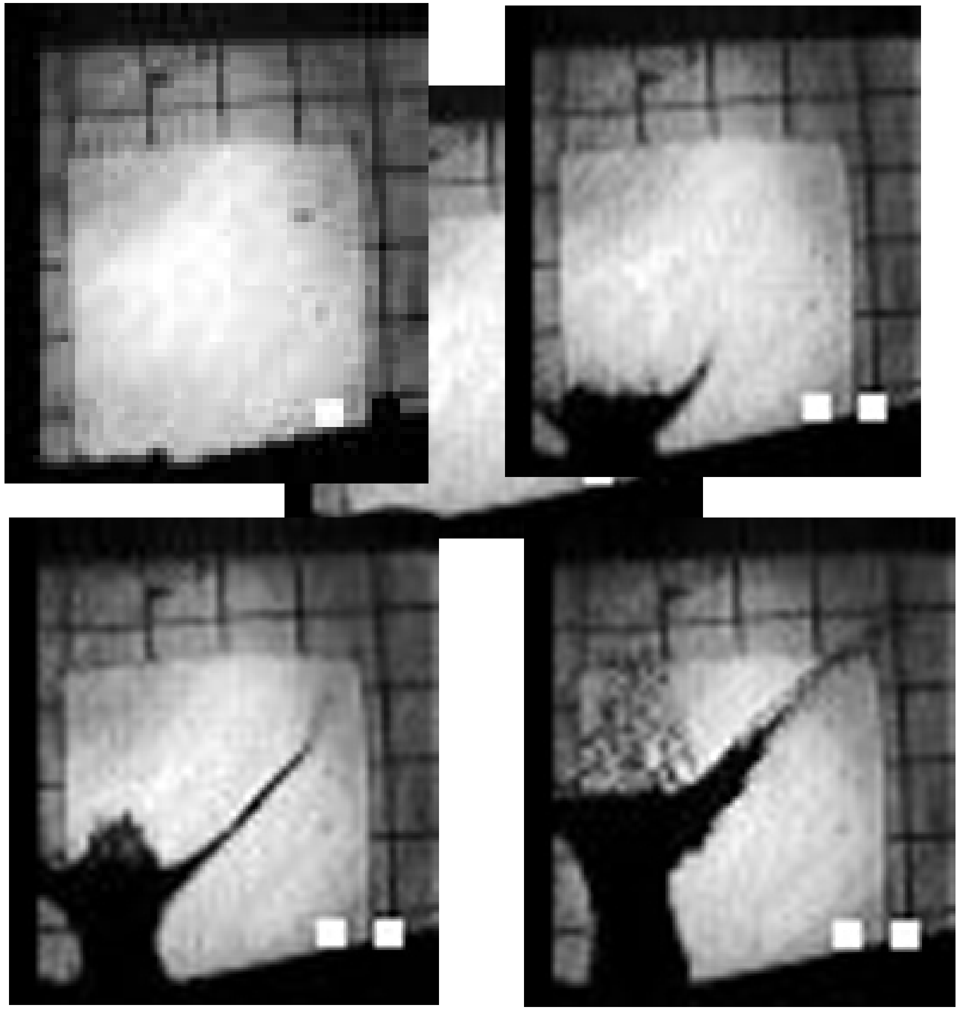
Hg-jet p-converter target with a pion focusing horn



H. Ravn

CERN Passive Hg Thimble Test

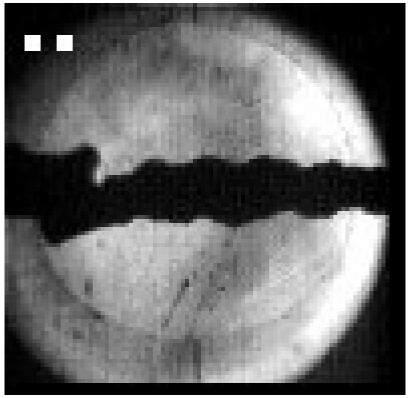




Exposures to a BNL AGS 24 GeV
2 TP beam. T=0, 0.5 , 1.6 and 3.4 ms.

Jet test at BNL E-951

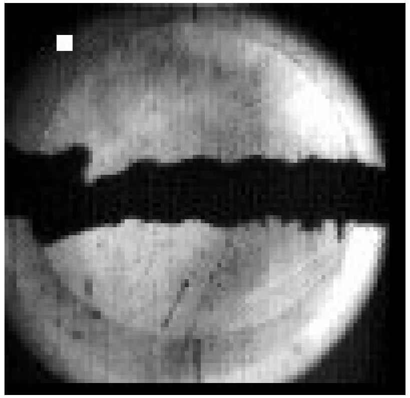
Harold G. Kirk



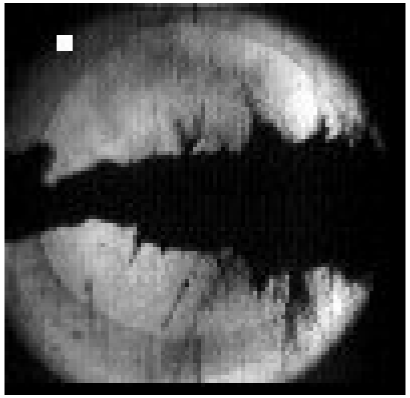
Event #11 25th April 2001

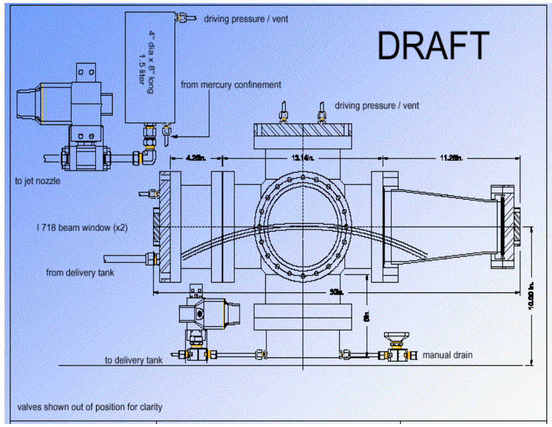
K. Mc Donald, H. Kirk, A. Fabich

Protons ←

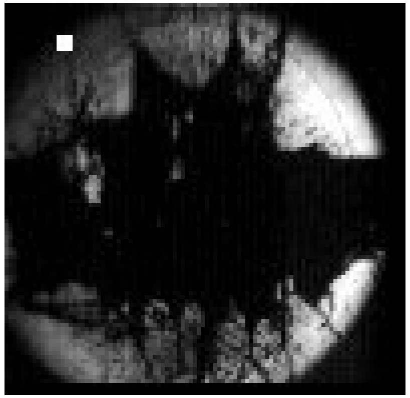


- **1cm diameter Hg Jet**
- **24 GeV 4 TP Proton Beam**
- **No Magnetic Field**





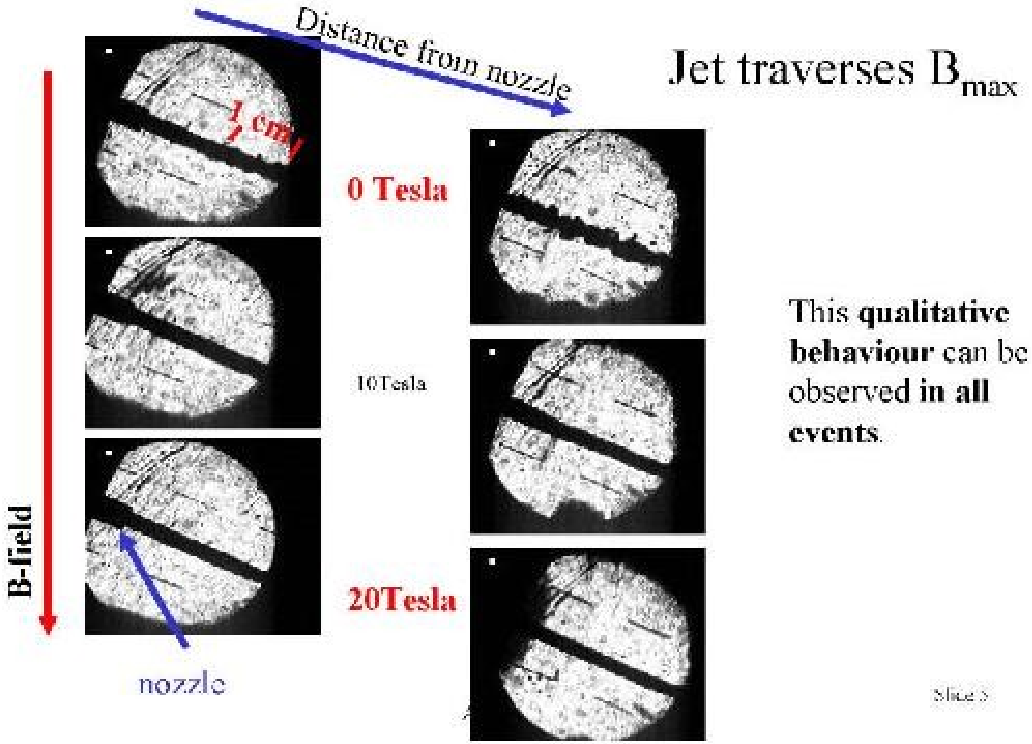
Picture timing [ms]
0.00
0.75
4.50
13.00



P-bunch: 2.7×10^{12} ppb
100 ns
t_o = ~ 0.45 ms

Hg- jet : diameter 1.2 cm
jet-velocity 2.5 m/s
perp. velocity ~ 5 m/s

CERN/Grenoble Hg Jet Tests



- **4 mm diameter Hg Jet**
- **v = 12 m/s**
- **0, 10, 20T Magnetic Field**
- **No Proton Beam**

A. Fabich, J. Lettry

Pion Capture

Pion Capture and decay channel

1. Solenoid, 10-20 Tesla

US consider they have a long life (>>1 year) design

2. Horn (CERN)

NEEDED for π^+ and π^- separation (Superbeam)

Problems with:

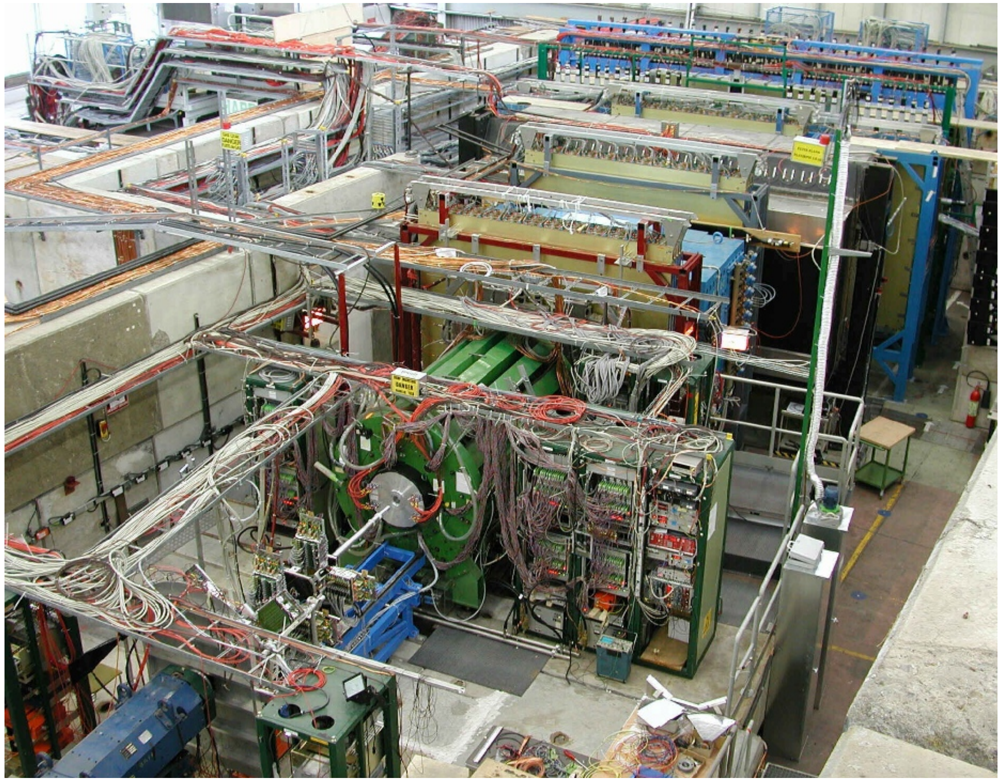
Heat dissipation, Radiation damage, Stress
Possible 6 week life
Studies will continue

The typical length of this channel is 30 m, to allow most of the pions to decay into muons.

We need the HARP results:

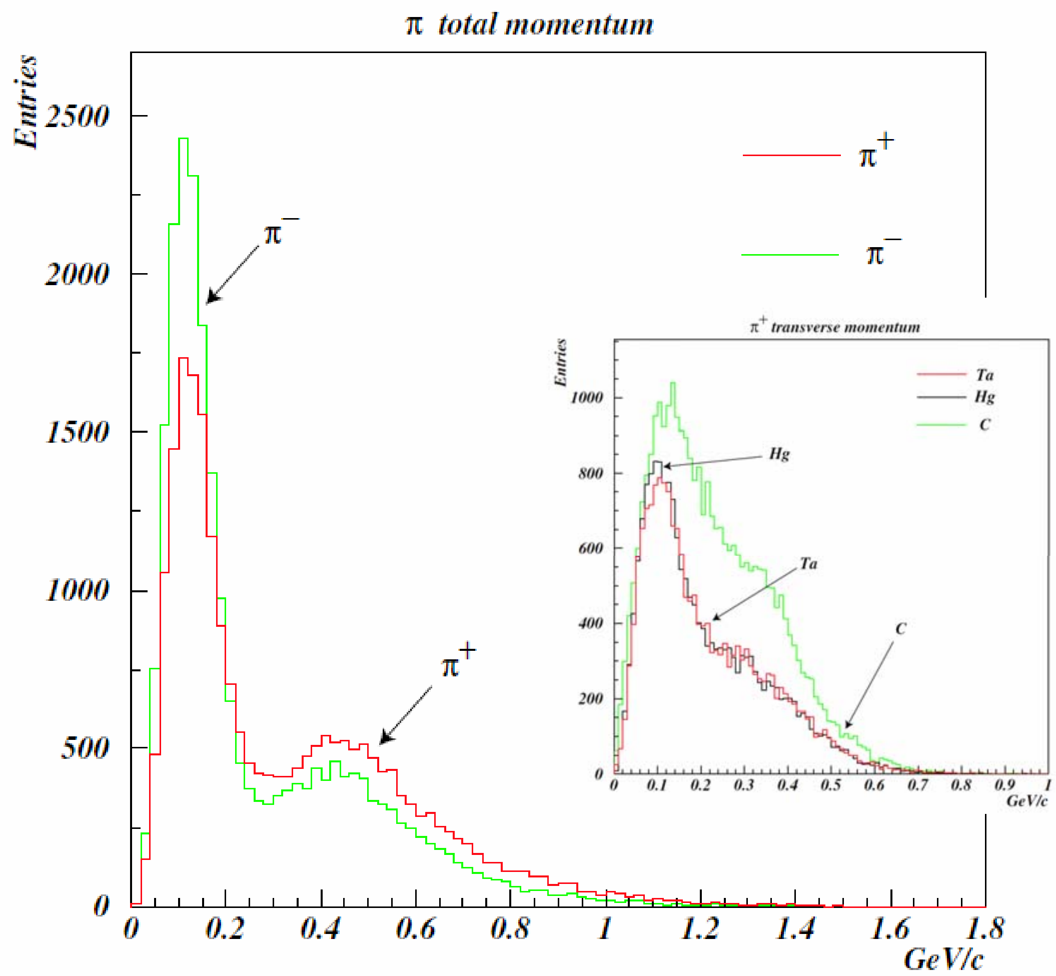
- ***For optimising the p-driver energy and the optimum focusing***

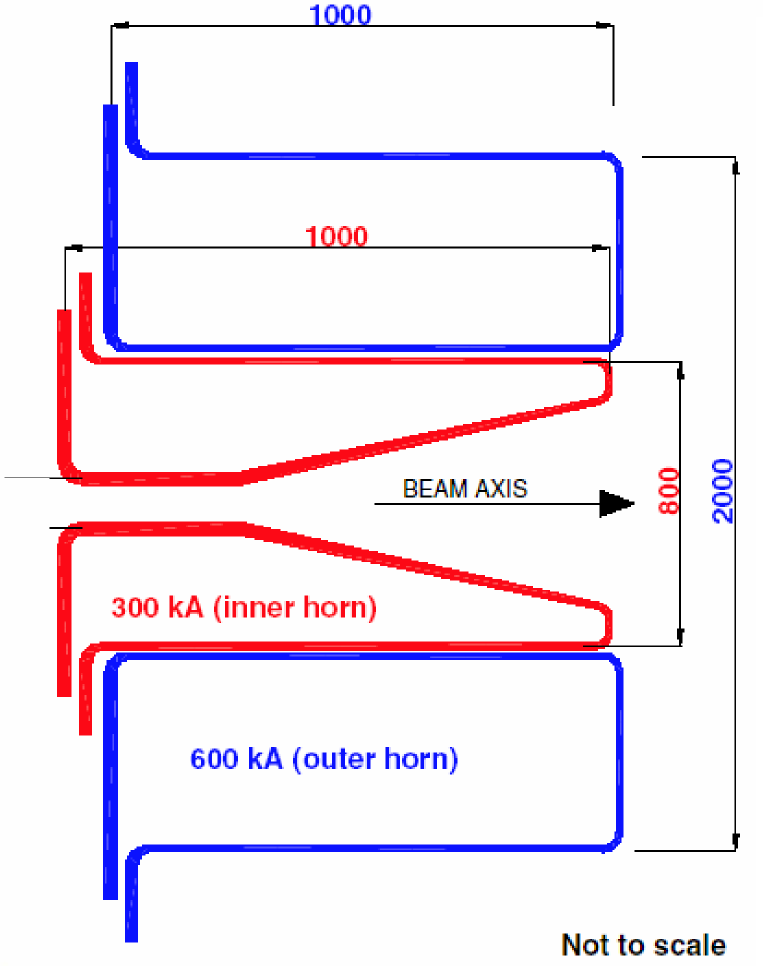
- ***In particular for the π^- production***



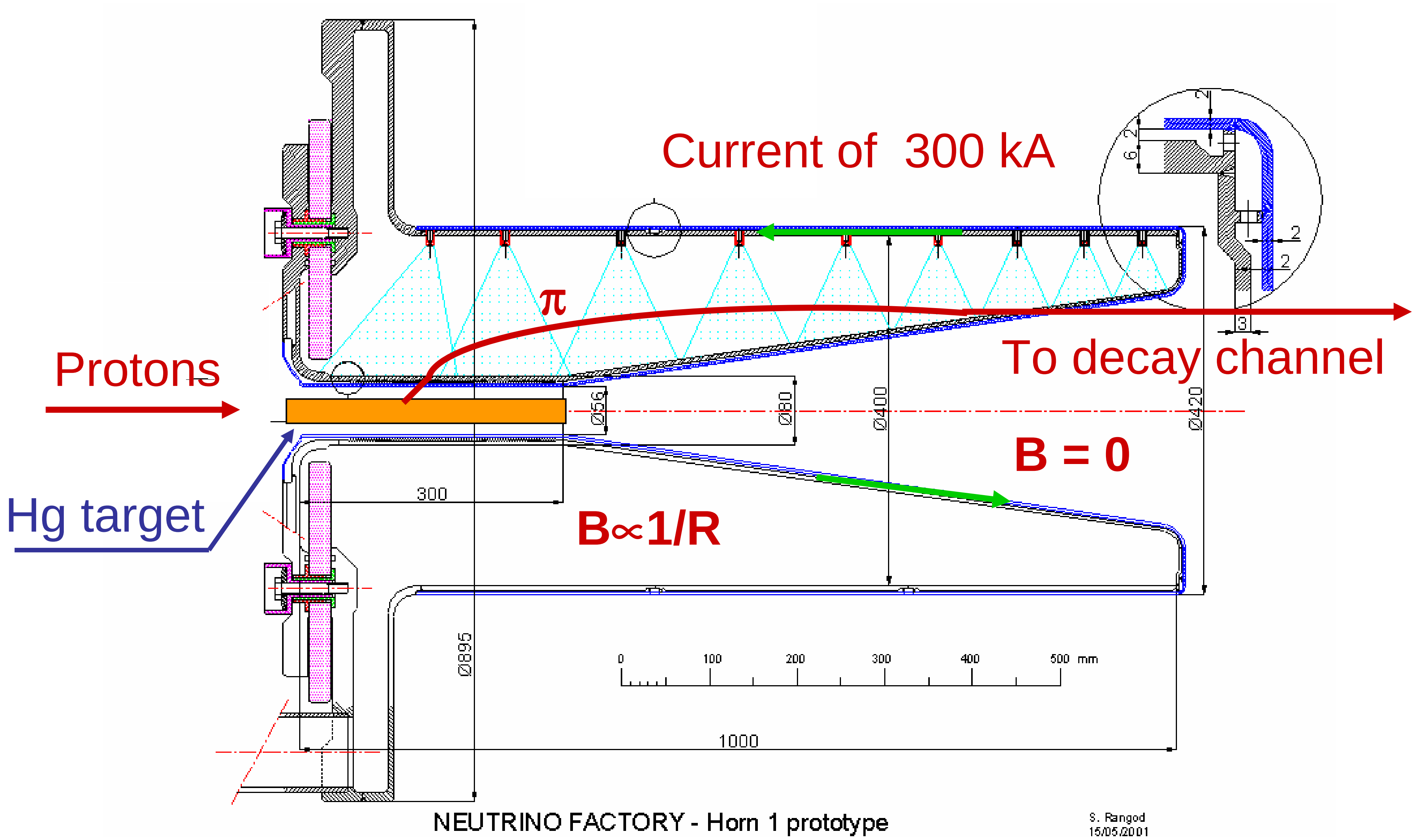
Proposed design (S. Gilardoni)

Particle at target

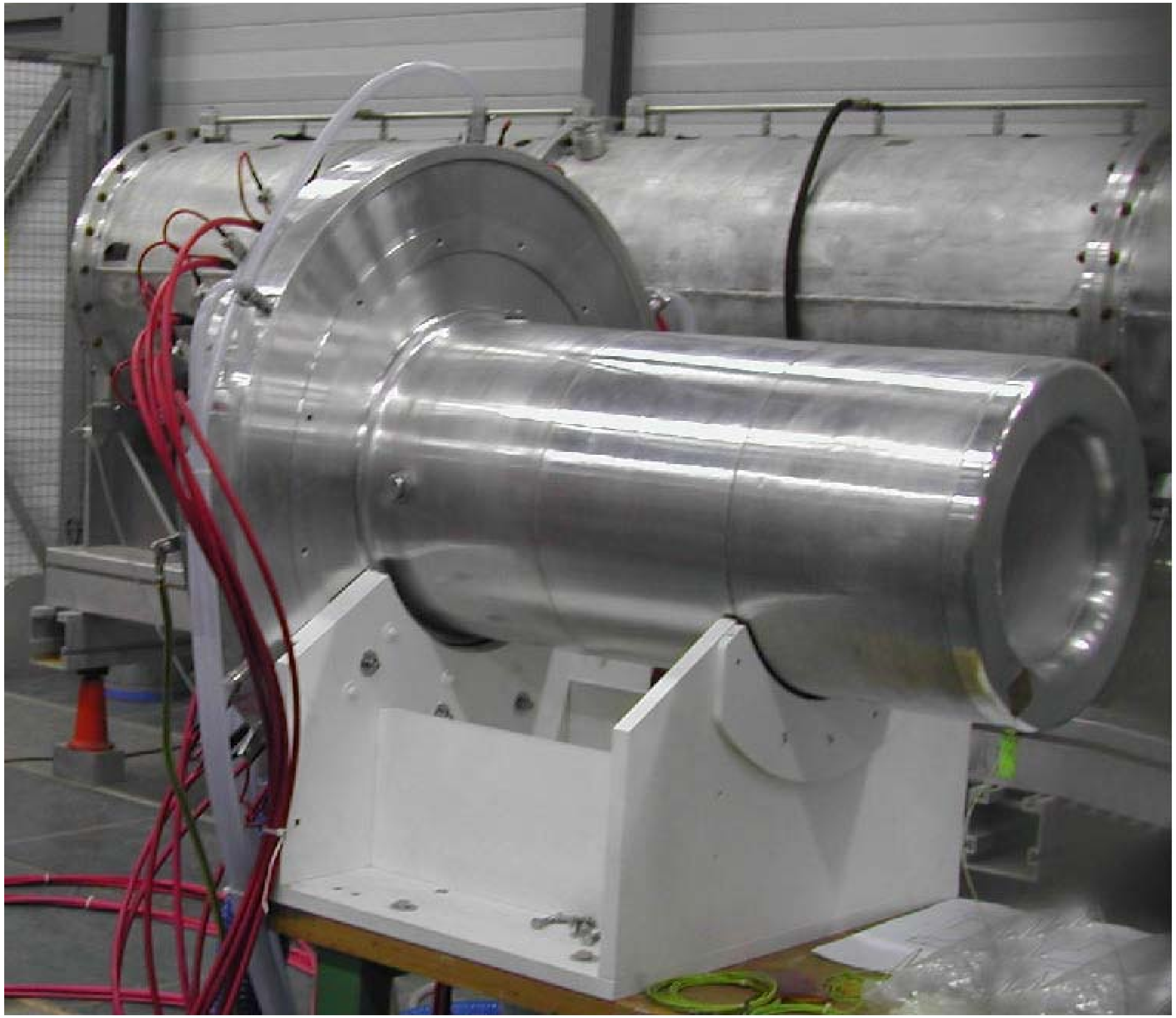




Horn focusing system (S. Gilardoni)



Horn prototype ready for tests (S. Gilardoni et al.)



Main horn parameters (S. Gilardoni)

•Radius of the waist	40 mm
•Peak current	300 kA
•Repetition rate	50 Hz
•Pulse length	93 μs
•Voltage on the horn	4200 V
•Total length	1030 mm
•Outer diameter	420 mm
•Max diameter (electrical connection flange)	895 mm
•Free waist aperture	56 mm
•Average waist wall thickness	6 mm
•Double skin thickness	2 mm

Done so far:

First “inner” horn 1:1 prototype

Power supply for Test One:

30 kA and 1 Hz, pulse 100 μs long

- ✓ *First mechanical measurements*
- ✓ *Test of cooling system*

Test Two: 100 kA and 0.5 Hz

Needed tests at:

Rep Rate 50 Hz **I = 300 kA**

Goal: Horn Life-Time 6 weeks (2*10^8 pulses)

Horn vs 20 T solenoid (S. Gilardoni)

Device	No Et cut	$0.2 < Et(GeV) < 0.8$	$0.3 < Et(GeV) < 0.6$
Horn	0.0015	0.0014	0.0013
Sol.	0.0045	0.0036	0.0015

Horn features:

- Same efficiency as 20 T solenoid for the NuFact interesting energy range
- Focus only one particle sign
  - no charge selection section in the machine (but only + or -…)
  - necessary for the SuperBeam
- Shape adjustable to capture only one selected pion energy range
- Low Cost (but life time shorter…)
  - Cost of the horn without the power supply: **200 kCHF**
  - Cost of the solenoid: **38 M$**

If target and horn seem too difficult…

Try funneling!

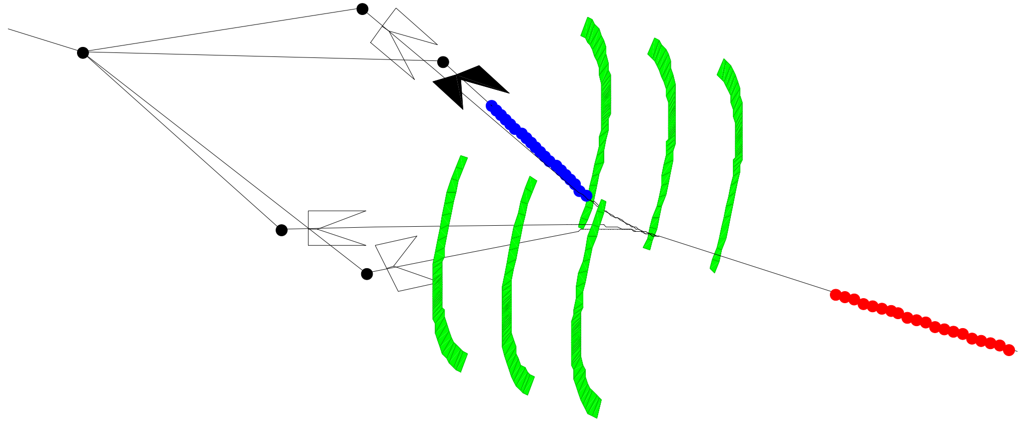
B. Autin, F. Meot, A. Verdier

What are the problems?

- Proton beam power: 4 MW
- Target to cope with high power
  (must be a high Z target because of the modest proton energy)
- Horn to be pulsed at: 50 Hz
  (Linac frequency)

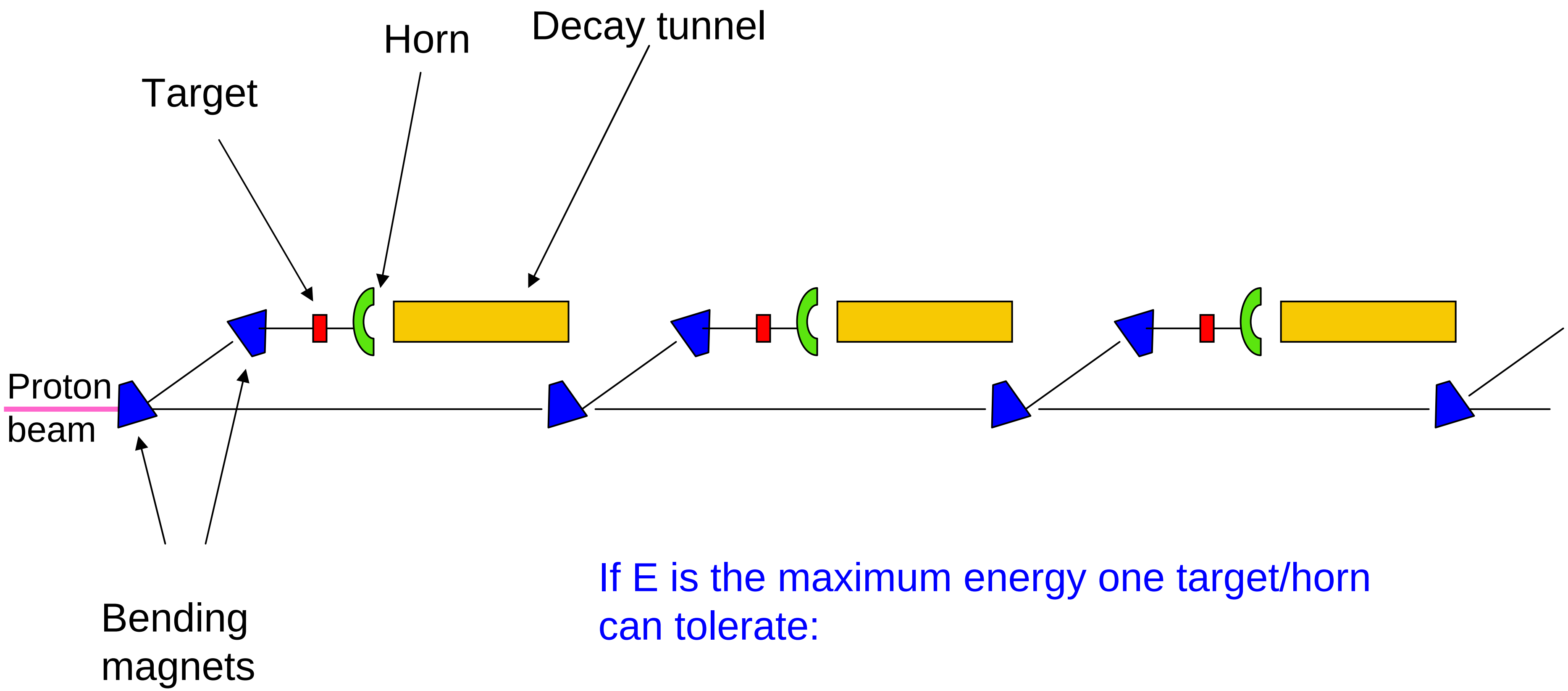
•It would be much simpler if we had only 1 MW and e.g. 12.5 Hz

Funneling step by step



Funneling maybe a nice idea for a Neutrino Factory, however, you do not need funneling for a superbeam…

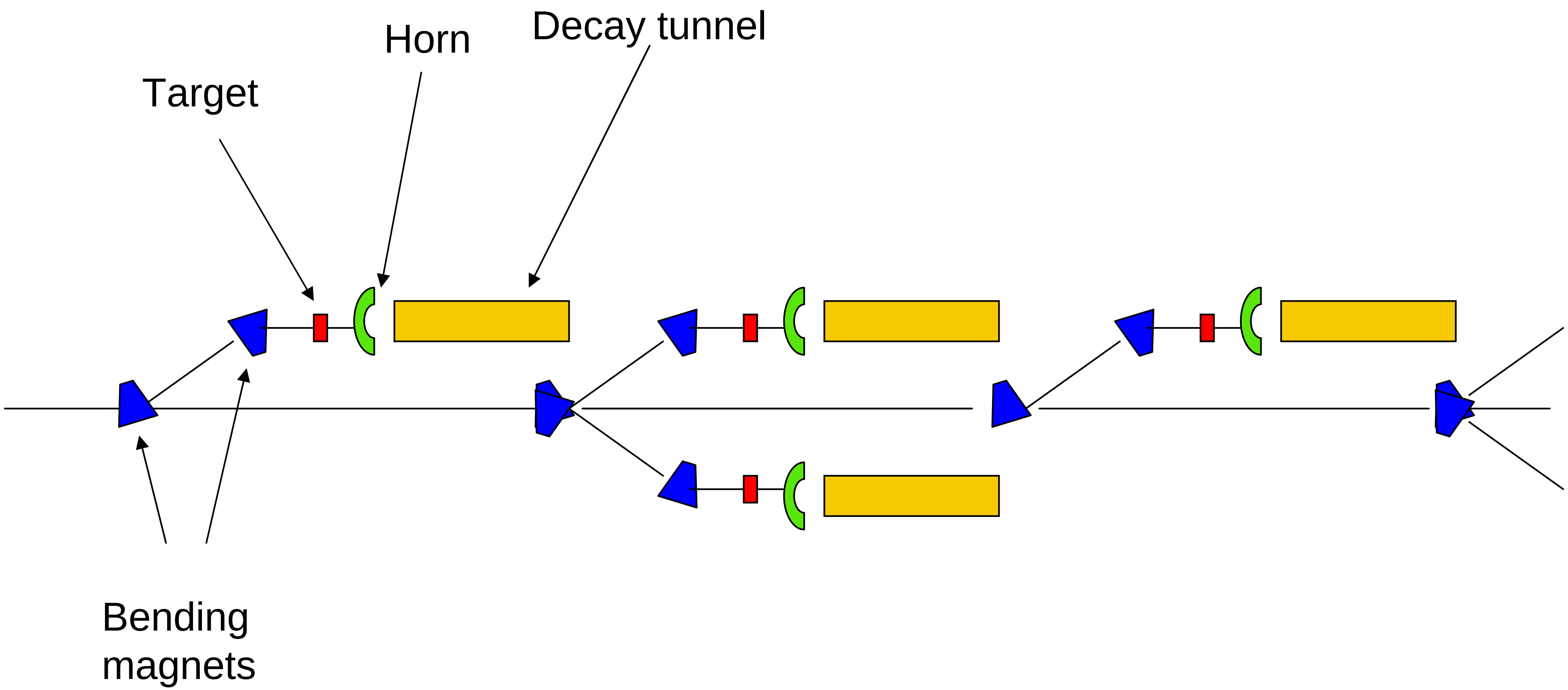
Schematic layout



If E is the maximum energy one target/horn can tolerate:

Do this n times to get n × E

Alternative layout



Of course

this means:

n targets,

n horns

n power supplies

n target stations with remote handling

but all are identical…

Acceleration with RLAs

(Rapid cycling Linear Accelerators)

After the cooling the muons have to be accelerated to energies between 20 and 50 GeV.

Normal synchrotrons are too slow and the decay losses of muons would not be tolerable (the muon's life time is only 2.2 μs). So-called recirculating linacs (RLA) are a good compromise between cost and speed.

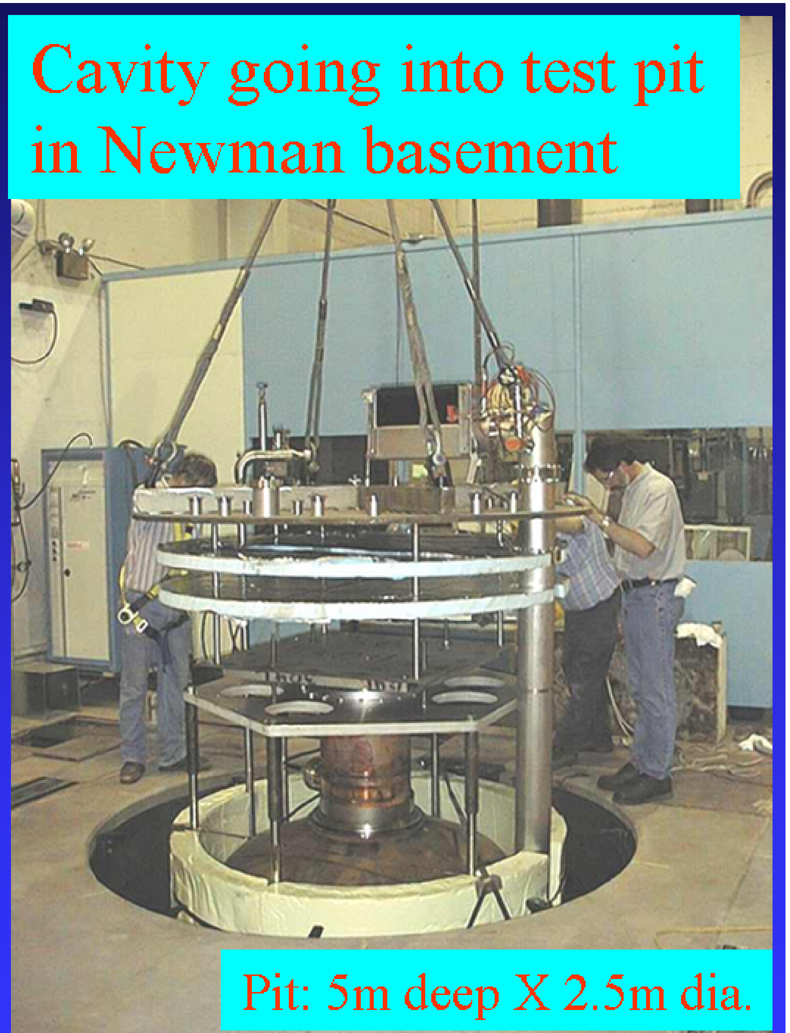
Sputtering at CERN

Electro-polished half cell

Magnetron Nb film (1-2 μm) sputtering

- DC voltage: 400-650 V
- Gas pressure: 2 mTorr
- Substrate T: 100 °C
- RRR = 11
- Tc = 9.5 K

RF test preparation at Cornell



Alternative: Acceleration with FFAGs!

(Fixed Field Alternating Gradient)

Large Acceptance

Both longitudinal and transverse

Fast acceleration due to fixed magnetic field

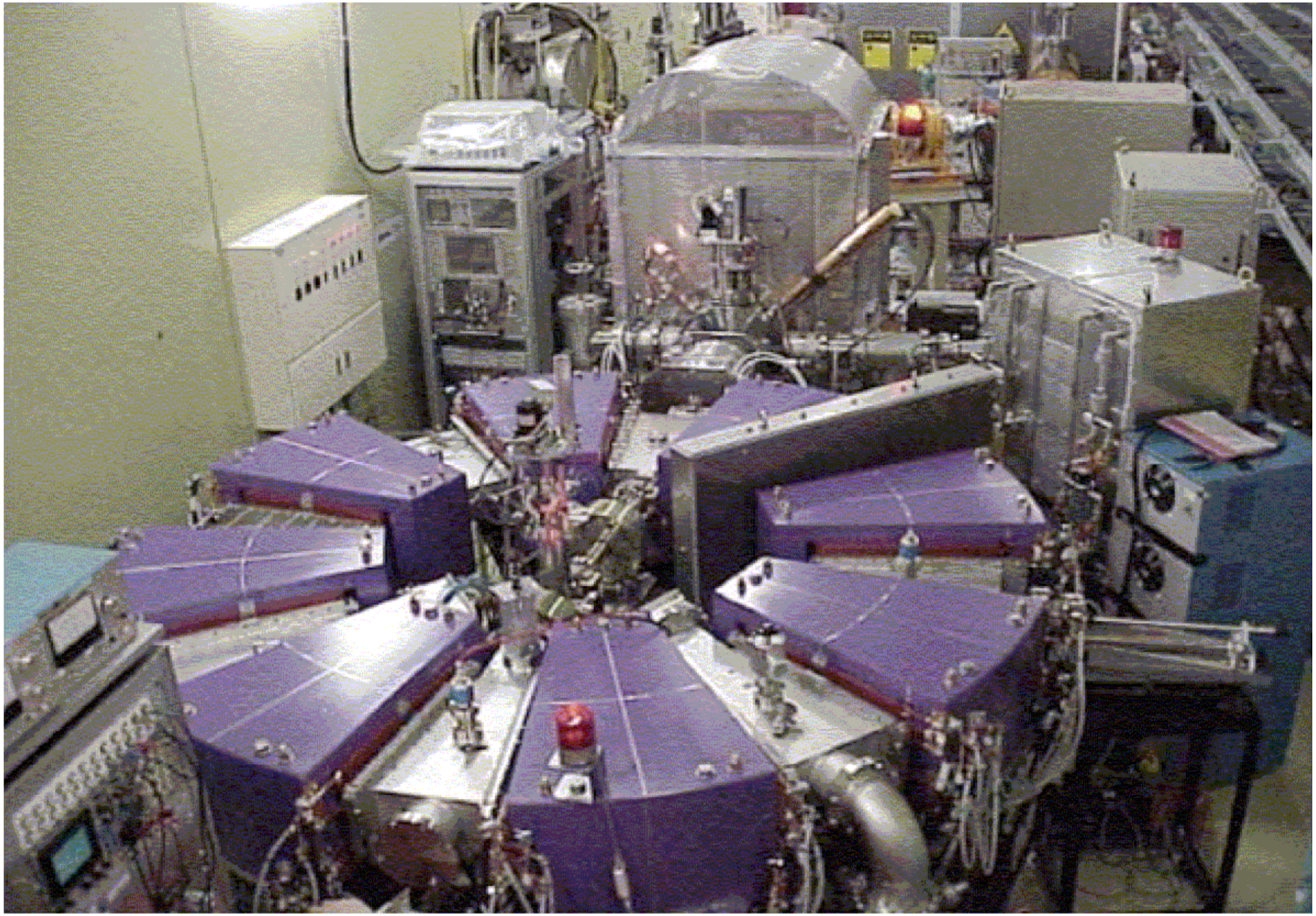
Suitable for Muon Acceleration

possibly without (but better with) cooling!

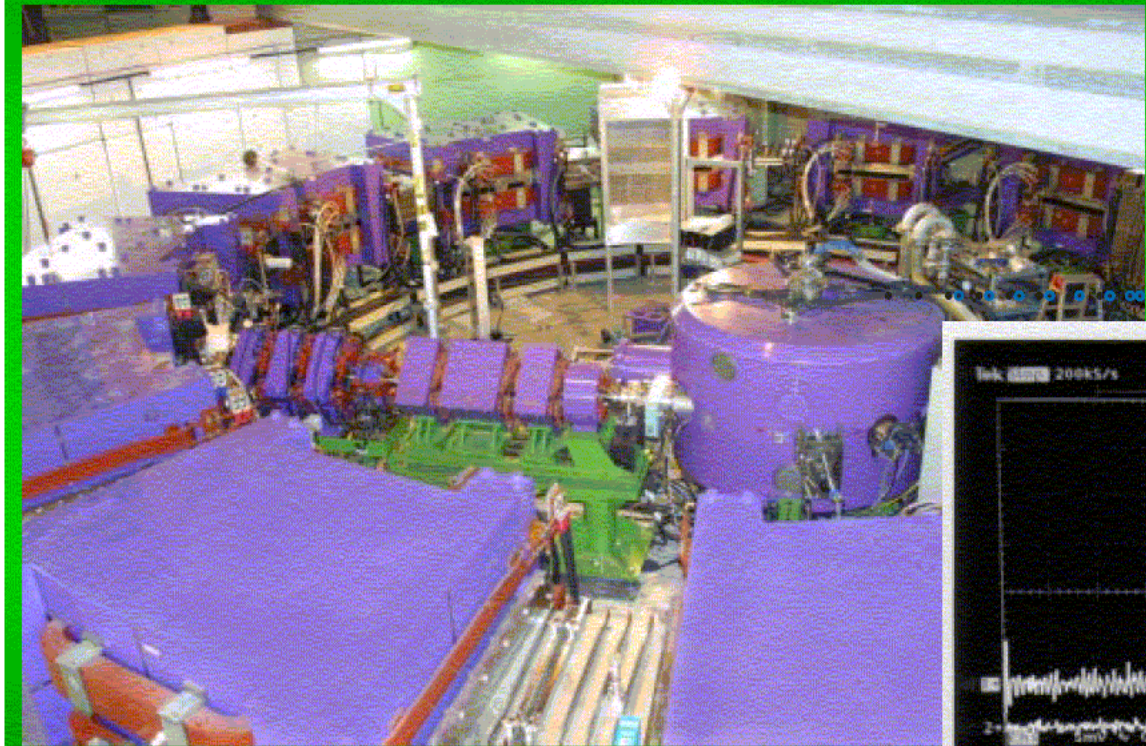
Built for protons in Japan:

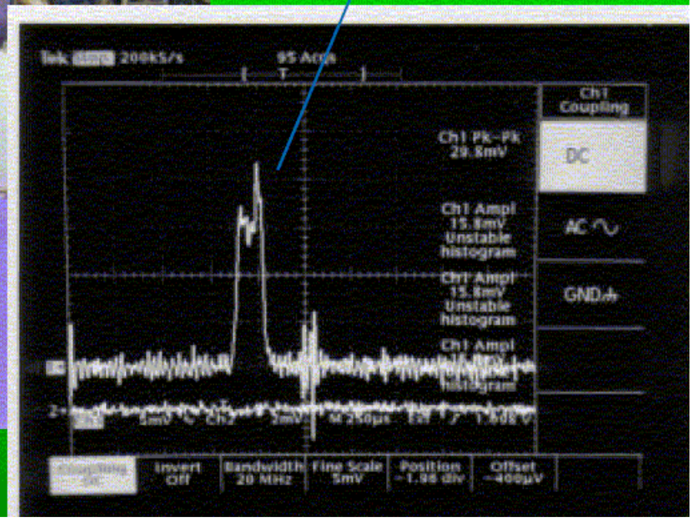
PoP FFAG: 50 keV to 500 keV, about 1 m radius

150 MeV is radius 5 m, rep rate 250 Hz

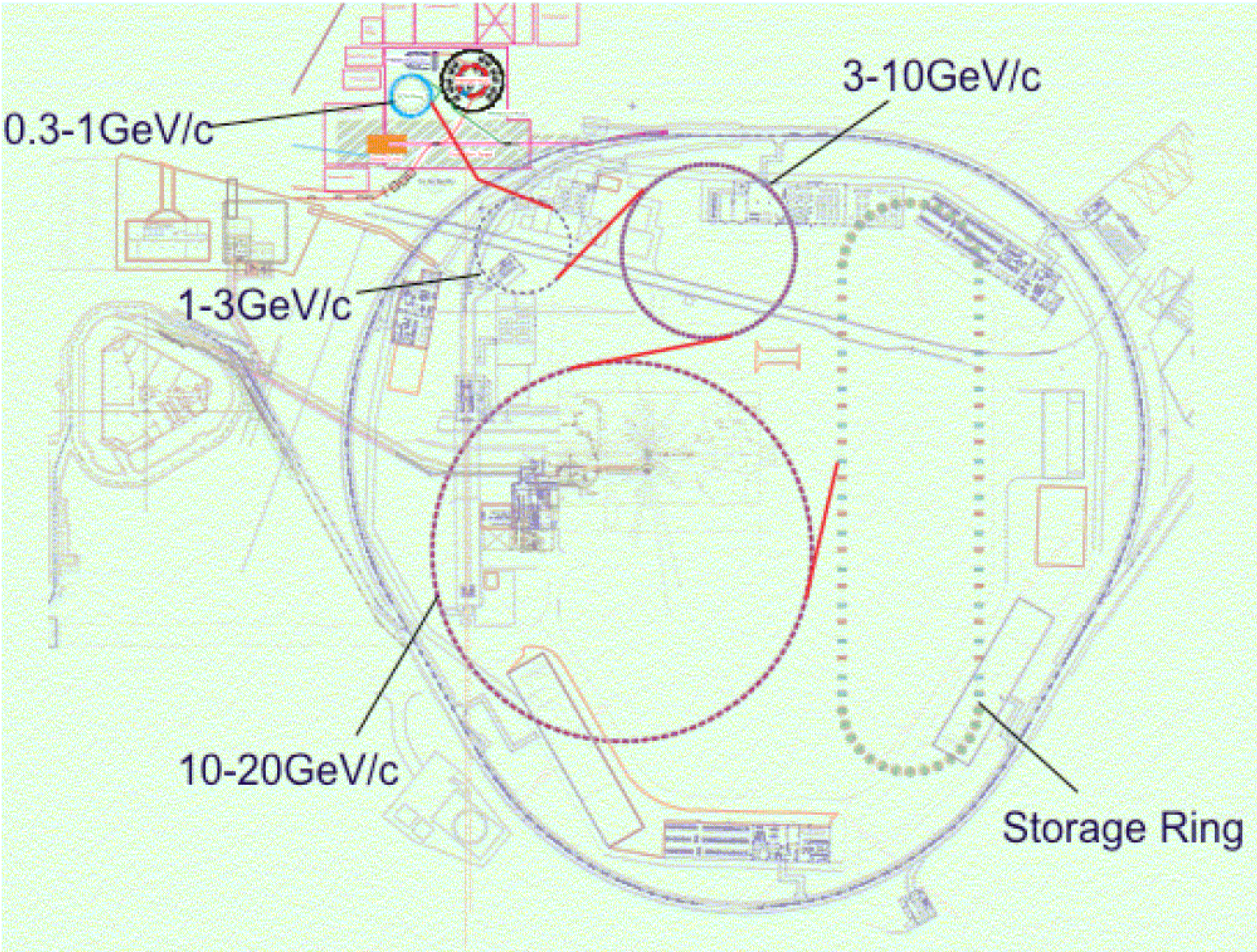


150-MeV FFAG




200kS/s
95 Acqs
Ch1 Coupling
DC
AC
GND
Ch1 Pk-Pk 29.8mV
Ch1 Ampl 15.8mV Unstable histogram
Invert Off
Bandwidth 20 MHz
Fine Scale 5mV
Position -1.98 div
Offset -400µV

Layout of Neutrino Factory at J-PARC



Muon Colliders

Some time ago regarded by some people as science fiction, it must be noted that the advances in cooling theory and technology are so impressive as to consider this type of machine as a real possibility in the future.

High Energy Frontier…

Cooling / Cooling Rings

To perform cooling, the beam is sent through (liquid hydrogen?) absorbers, reducing the transverse and longitudinal momenta.

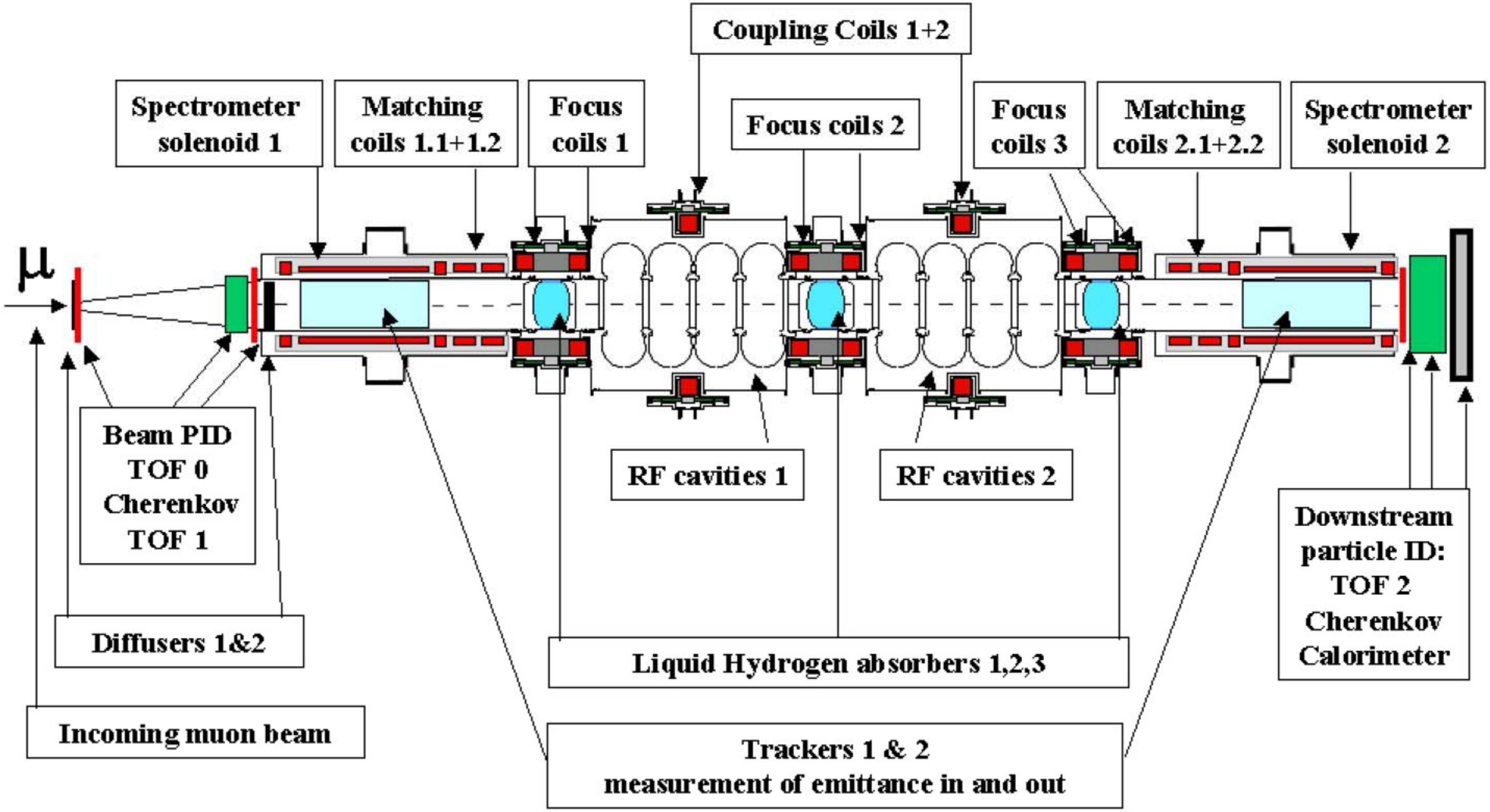
Subsequent reconstitution of the longitudinal momentum occurs with RF cavities.

Basically the cooling channel is a linear accelerator with (liquid hydrogen) absorbers.

The cooling channel will be fairly long and expensive, hence the interest in "ring coolers", where cooling is done over many revolutions.

Cooling: Muon Ionization Cooling Experiment

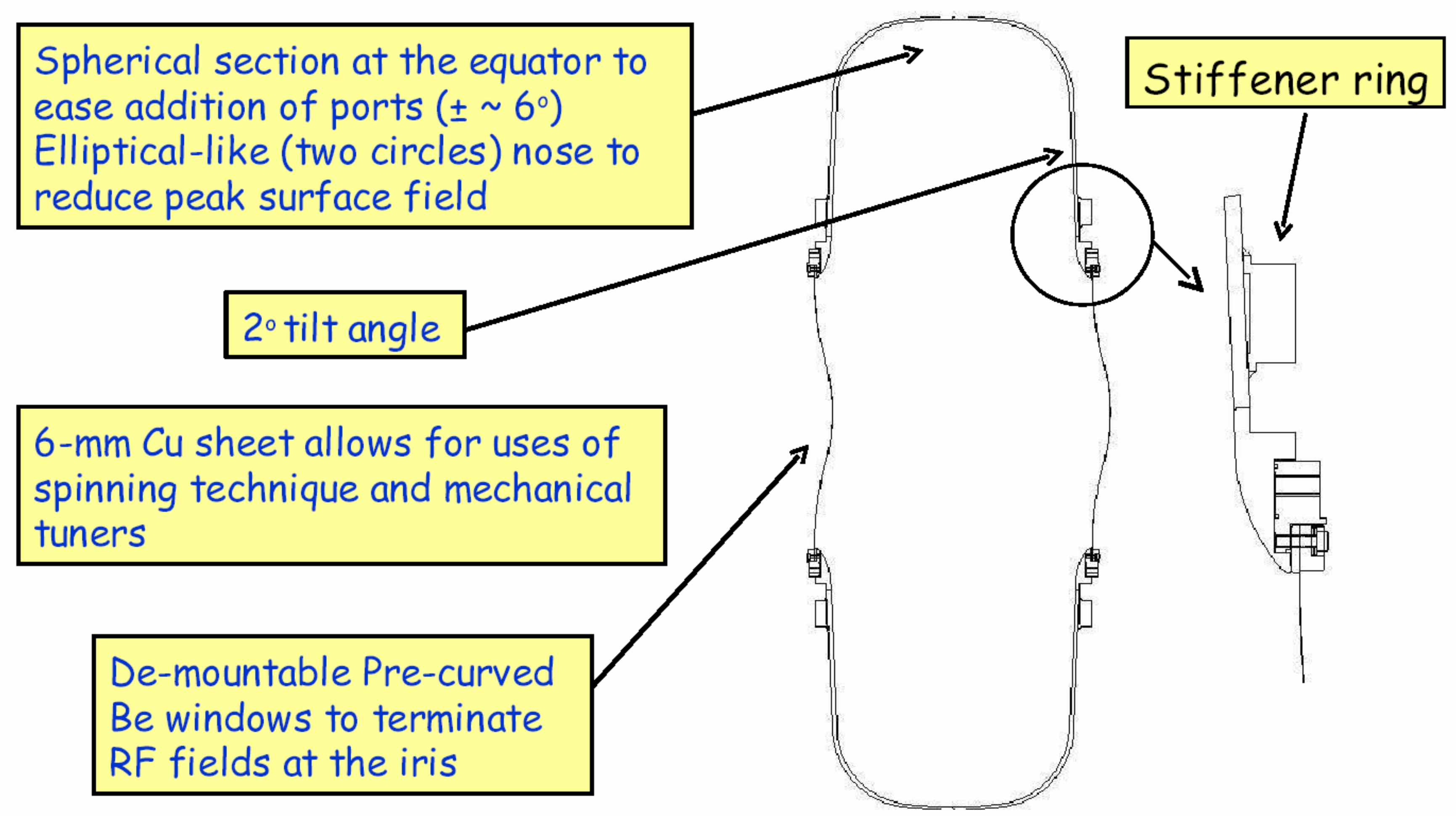
Planned and scientifically approved at RAL



200 MHz cavities (LBNL) as for MICE

Muon Ionisation Cooling Experiment

(Scientifically approved at RAL)

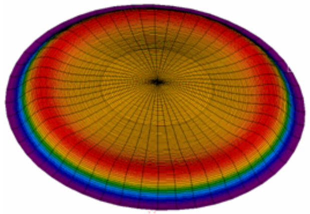


cavity production…

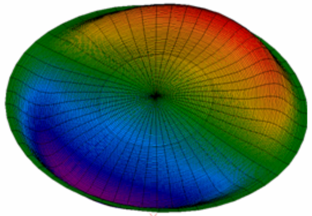
Mechanical cleaning of the cavity inner surface (right) after e-beam welding of the stiffener ring (above)

Real science in the Be windows simulations

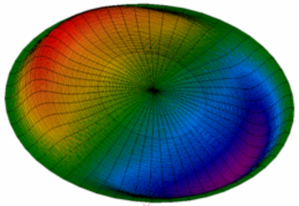
(Also for the LH2 absorber windows)



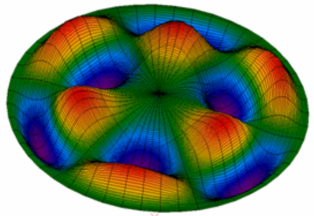
1st mode shape of the 3-D model



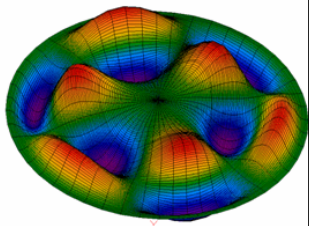
2nd mode shape of the 3-D model



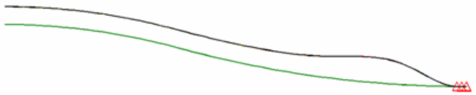
3rd mode shape of the 3-D model



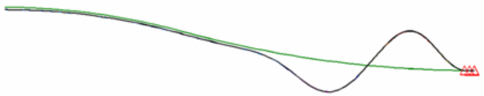
4th mode shape of the 3-D model



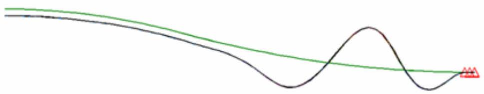
5th mode shape of the 3-D model



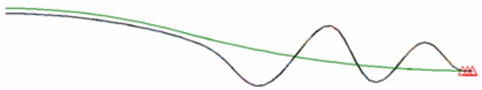
1st mode shape of the 2-D model



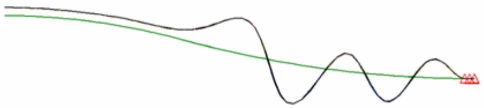
2nd mode shape of the 2-D model



3rd mode shape of the 2-D model



4th mode shape of the 2-D model

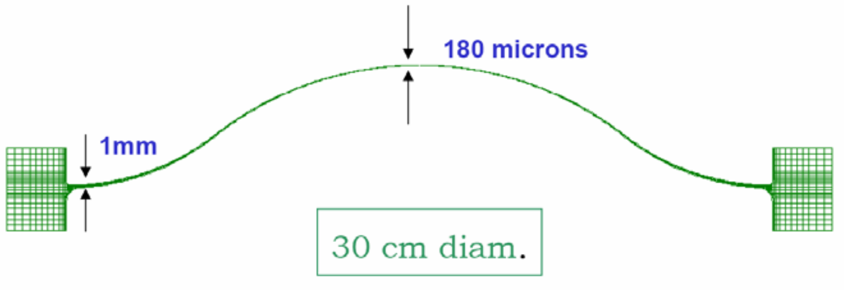


5th mode shape of the 2-D model

	0.25mm thk		0.38mm thk		0.5mm thk	
	2-D axisy model	3-D plate model	2-D axisy model	3-D plate model	2-D axisy model	3-D plate model
1st freq.	463 Hz.	482 Hz	559 Hz	582 Hz	635 Hz	660 Hz
2nd freq.	1878 Hz	586 Hz	2190 Hz	703 Hz	2449 Hz	793 Hz
3rd freq.	2343 Hz	586 Hz	2782 Hz	704 Hz	3140 Hz	793 Hz
4th freq.	3254 Hz	820 Hz	3890 Hz	1050 Hz	4423 Hz	1250 Hz
5th freq.	3849 Hz	820 Hz	4690 Hz	1050 Hz	5433 Hz	1250 Hz

Summary of the natural frequency runs

Liquid Hydrogen Absorbers



back to targetry:

a possible experiment at CERN

Letter of Intent-- Isolde and nToF Committee

CERN-INTC-2003-033
INTC-I-049
23 October 2003
Updated: 31 Oct 2003

A Letter of Intent to
the ISOLDE and Neutron Time-of-Flight
Experiments Committee

Studies of a Target System for
a 4-MW, 24-GeV Proton Beam

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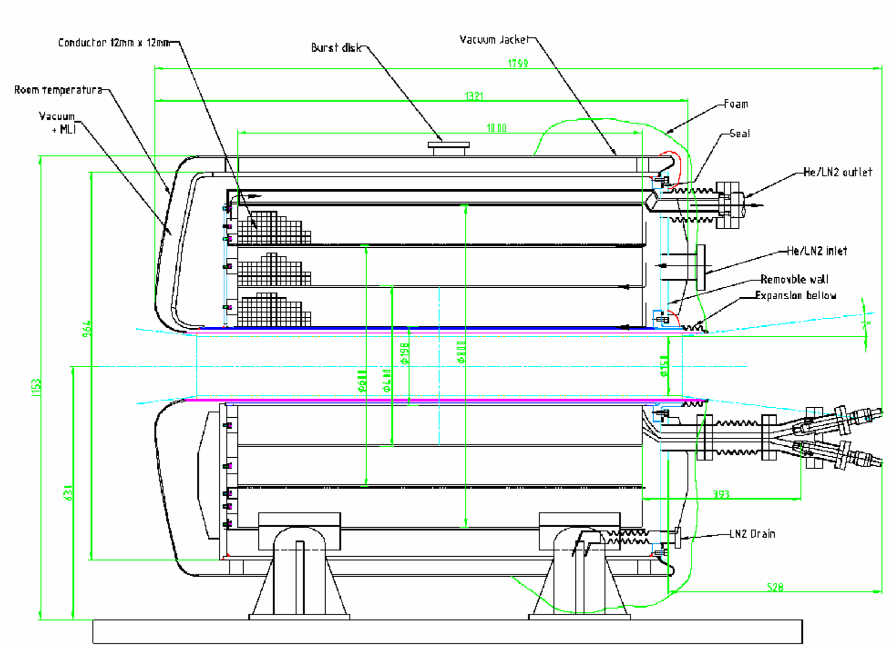
Spokespersons: H.G. Kirk, K.T. McDonald
Local Contact: H. Haseroth

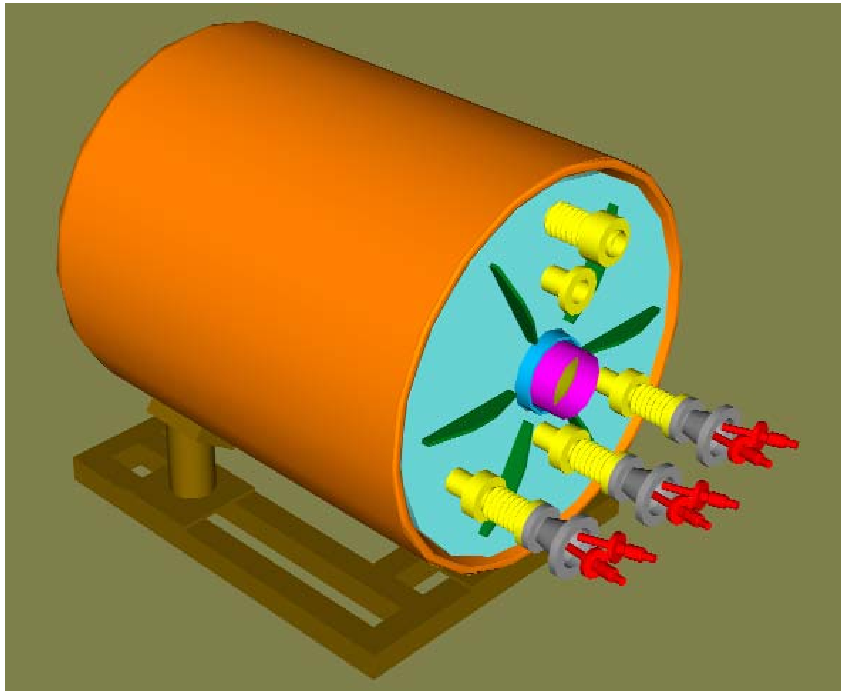
Participating Institutions

1) RAL
2) CERN
3) KEK
4) BNL
5) Princeton University

Harold G. Kirk

High Field Pulsed Solenoid
(being manufactured for $ 700 k)





- 70º K Operation
- 15 T with 4.5 MW Pulsed Power
- 15 cm warm bore
- 1 m long beam pipe

Peter Titus, MIT

CERN TT2a beam line towards nTOF

What can be achieved with such an experiment?

This is NOT an experiment of interest only to the Americans

It does NOT cover only the specific aspect of the beam target interaction in a magnetic field as stated on page 131 in SPSC-M-722

OF COURSE we shall run also without magnetic field!

Without magnetic field it will test the behavior of the target e.g. inside a magnetic horn (needed for a Superbeam)

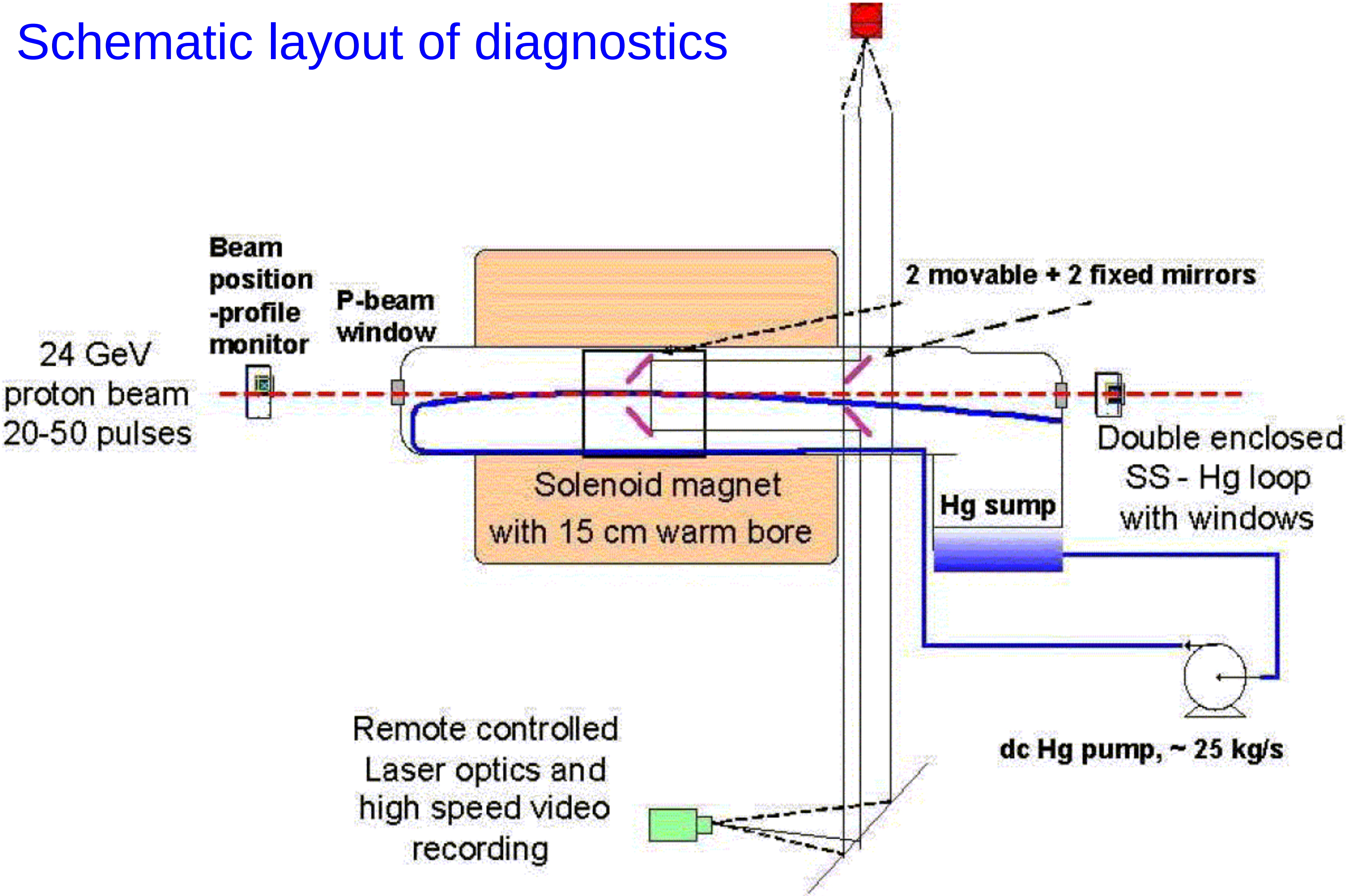
What can be achieved with such an experiment?

Machine	Energy [GeV]	Beam RMS radius [mm]	Protons/pulse [10^{12}]	Peak energy deposition [J/g]
AGS 1MW	28	1.5	17	103
CERN SPL	2.2	3.0	260	181
CERN PS	24	1.5	28	137

What this points to is that we could reach the SPL energy deposition level if we can get 28 TP protons/spill at 24 GeV and achieve a spot size radius of 1.3 mm.

Harold Kirk BNL

Schematic layout of diagnostics



and now there is a proposal…

Participating Institutions

1) RAL
2) CERN
3) KEK
4) BNL
5) Princeton University

and we have Oak Ridge on board

and radiation safety is no problem!

CERN-INTC-2004-016
INTC-P-186
26 April 2004

A Proposal to
the ISOLDE and Neutron Time-of-Flight Experiments Committee

Studies of a Target System for a 4-MW, 24-GeV Proton Beam

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Oak Ridge SNS layout

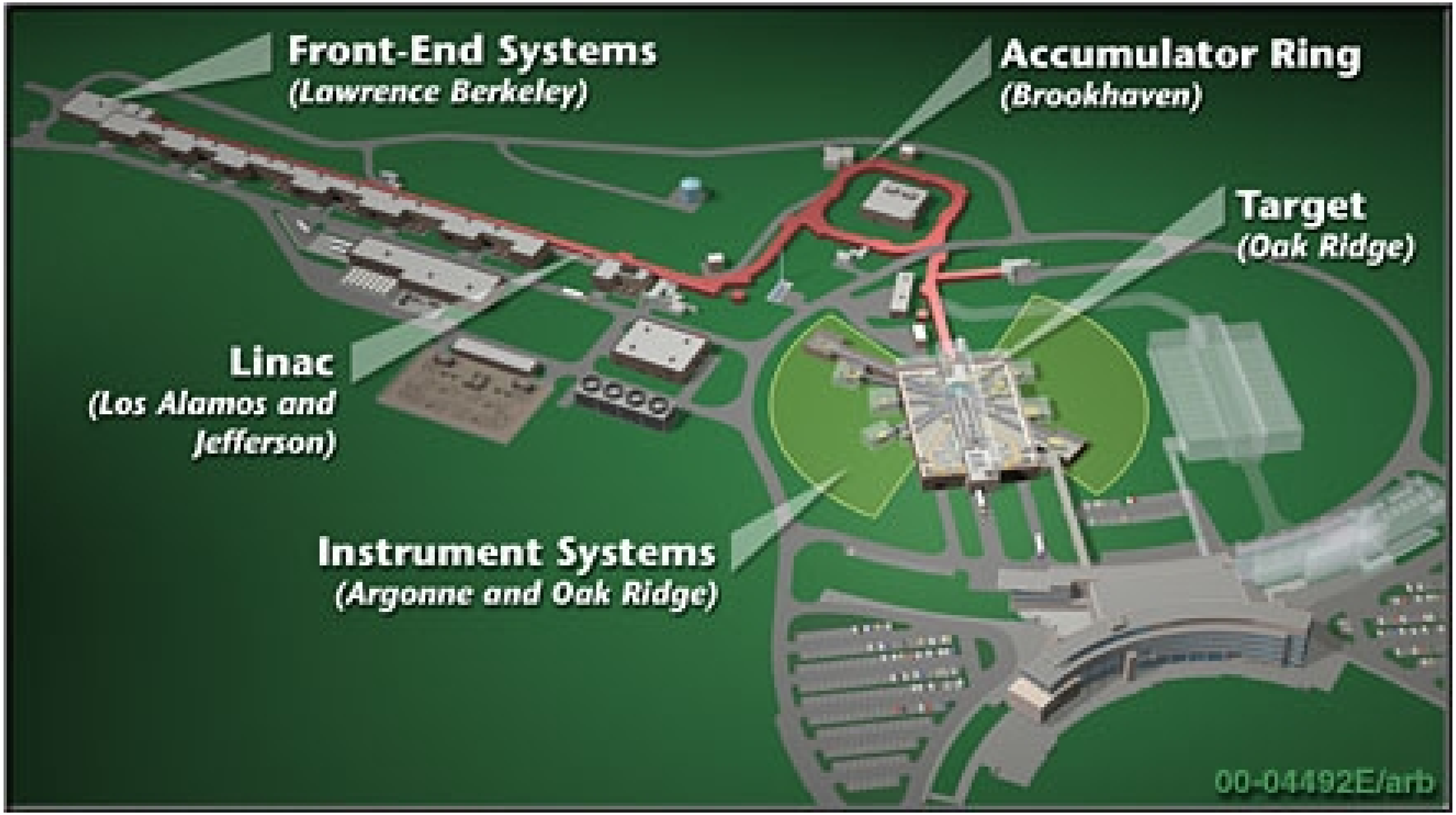


Photo courtesy of Oak Ridge National Laboratory

SNS *topview of linac tunnel*

Photo courtesy of Oak Ridge National Laboratory

SNS *target building*

Photo courtesy of Oak Ridge National Laboratory

SNS *target building*

Photo courtesy of Oak Ridge National Laboratory

SNS linac parameters and SPL

	SNS	SPL
Proton beam power on target	1.4 MW	4 MW
Proton beam kinetic energy on target	1.0 GeV	2.2 GeV
Average beam current on target	1.4 mA	1.8 mA
Pulse repetition rate	60 Hz	50 Hz
Protons per pulse on target	$1.5x10^{14}$ protons	2.3 e14
Charge per pulse on target	24 μC	
Energy per pulse on target	24 kJ	
Proton pulse length on target	695 ns	
Ion type (Front end, Linac, HEBT)	H minus	
Average linac macropulse H- current	26 mA	
Linac beam macropulse duty factor	6 %	
Front end length	7.5 m	
Linac length	331 m	
HEBT length	170 m	

American Study 2A ***"unloaded costs"***

Neutrino Factory - Cost Savings

- *Feasibility "Study 2A": Done for the APS Study, incorporating ideas that have accumulated since Study 2 a couple of years ago. Not a bottom-up costing (which is eventually needed) … but costs scaled from Study 2.*
  - *we have done well with the major cost items, but possible cost savings for the lesser items are not yet exploited*

i.e. for $M 1250 or $M 920 respectively you are in business…

	All ($M)	No PD ($M)	No PD & Tgt. ($M)
FS2	1832	1641	1538
FS2a-scaled (%)	67	63	60

The quoted costs are "unloaded". In US accounting, where you have to include all costs (including internal effort and laboratory overheads), the full cost would be expected to be something like a factor of two more. In CERN accounting, where internal effort and overhead is not included in the "full cost", the quoted cost is probably not far from the full cost.

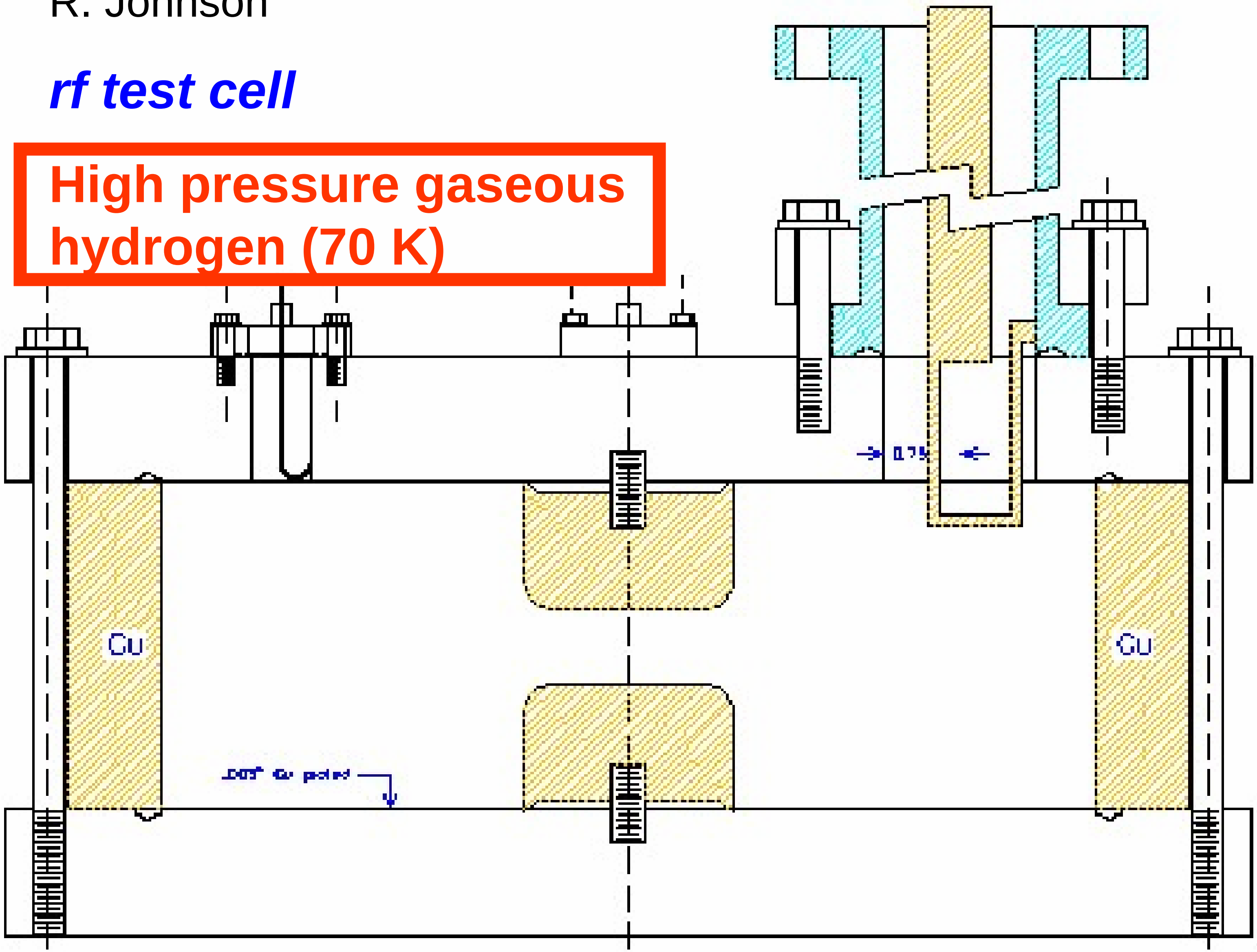

Thank you

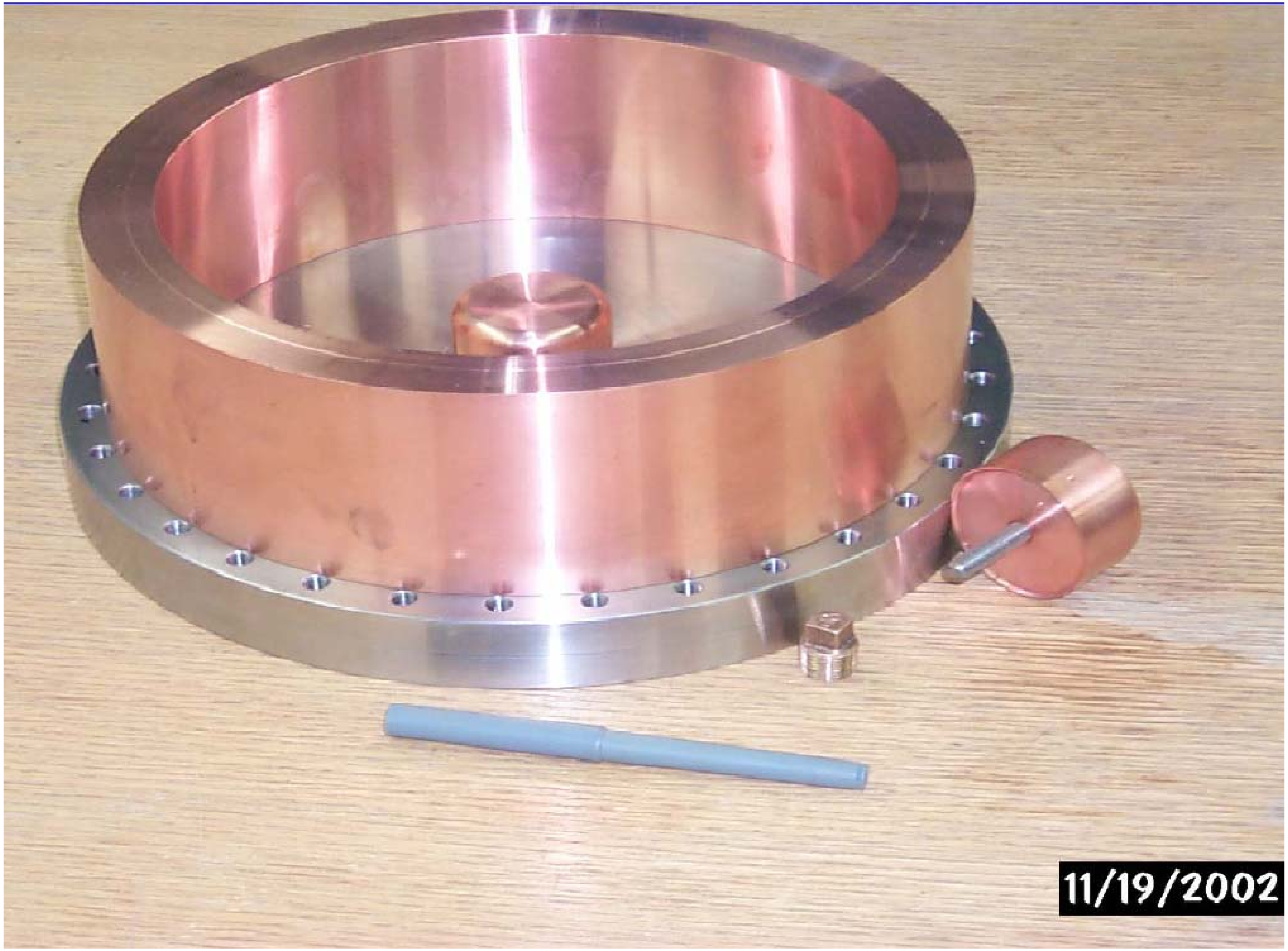
- *Some exotic ideas*

R. Johnson

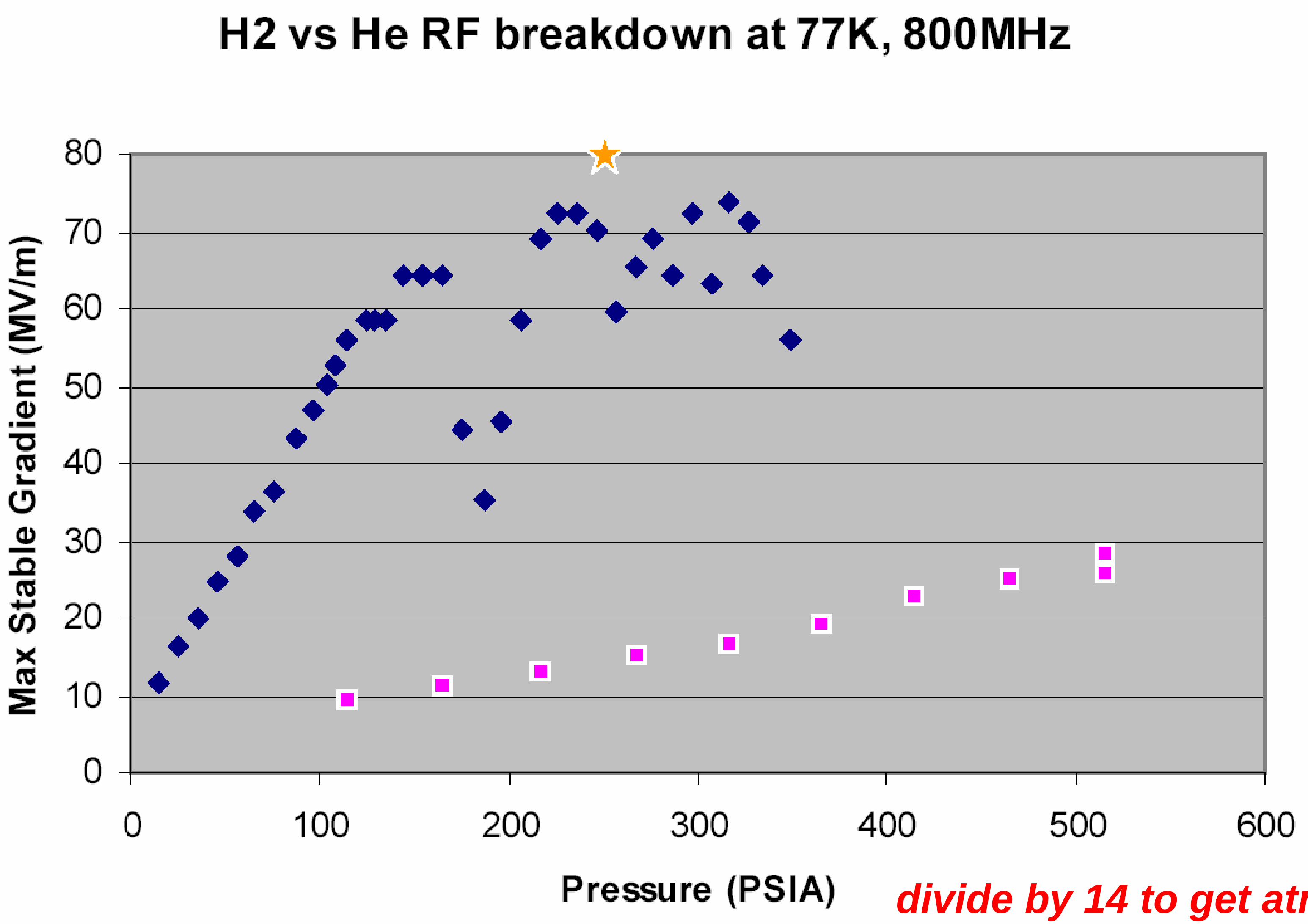
rf test cell

High pressure gaseous hydrogen (70 K)




11/19/2002

11/19/03 Lab G Results, Molybdenum Electrodes



divide by 14 to get atm !

Estimated parameters of a helical 6D cooling channel

Parameter	*Unit*	*Initial*	*Middle* ****)	*Final*
Beam momentum,	**MeV/c**	**100**	**100**	**100**
Solenoid field	**T**	**3.5**	**8**	**14**
Helix period	**m**	**1**	**0.44**	**0.22**
Transverse field at beam	**T**	**0.7**	**1.6**	**3.0**
Helix orbit radius	**cm**	**15**	**6**	**3**
Dispersion	**cm**	**37**	**15**	**7.5**
Accelerating RF field	**MV/m**	**40**	**40**	**40**
Frequency	**GHz**	**0.2**	**0.8**	**1.6**
Absorber energy loss rate	**MeV/m**	**14**	**14**	**14**
Synchrotron emittance	**cm**	**1.5**	**0.15**	**3.10^{-2}**
Relative momentum spread	**%**	**7.5**	**3**	**2**
Bunch length	**cm**	**30**	**7.5**	**1.1**
Beam width	**cm**	**3**	**0.56**	**0.15**
Transverse emittances	**cm x rad**	**1.7/1.7**	**0.2/0.2**	**$(1/3)10^{-2}$**

The cooling effect in this calculation in terms of reduction of the 6D emittance is $5\text{x}10^5$. The total energy loss in absorber is about 1.12 GeV. For a channel of continuous dense hydrogen gas with 14 MeV/m of energy loss, this implies a 6D cooling channel length, $L = \frac{1.12}{.014} / \sqrt{1+\kappa^2} = 56$ m.

5 ⑨ 10^5 in 6D emittance in 56 m !

Frictional Cooling for a Muon Collider

A. Caldwell
MPI f. Physik/Columbia University

Muon Cooling is the signature challenge of a Muon Collider

Cooler beams would allow fewer muons for a given luminosity, thereby

- Reducing the experimental background
- Reducing the radiation from muon decays
- Reducing the radiation from neutrino interactions
- Allowing for smaller apertures in machine elements, and so driving the cost down

Frictional Cooling A. Caldwell

MPI f. Physik/Columbia University

- Bring muons to a kinetic energy (T) where dE/dx increases with T
- Constant E-field applied to muons resulting in equilibrium energy
- Big issue – how to maintain efficiency
- Similar idea first studied by Kottmann et al., PSI