# RF Systems

## *Challenges*

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# 1) RF requirements for "conventional accelerators"

Examples for the layout of present machines: power, frequencies etc

# 2) RF requirements for Neutrino Factories

i) Proton driver

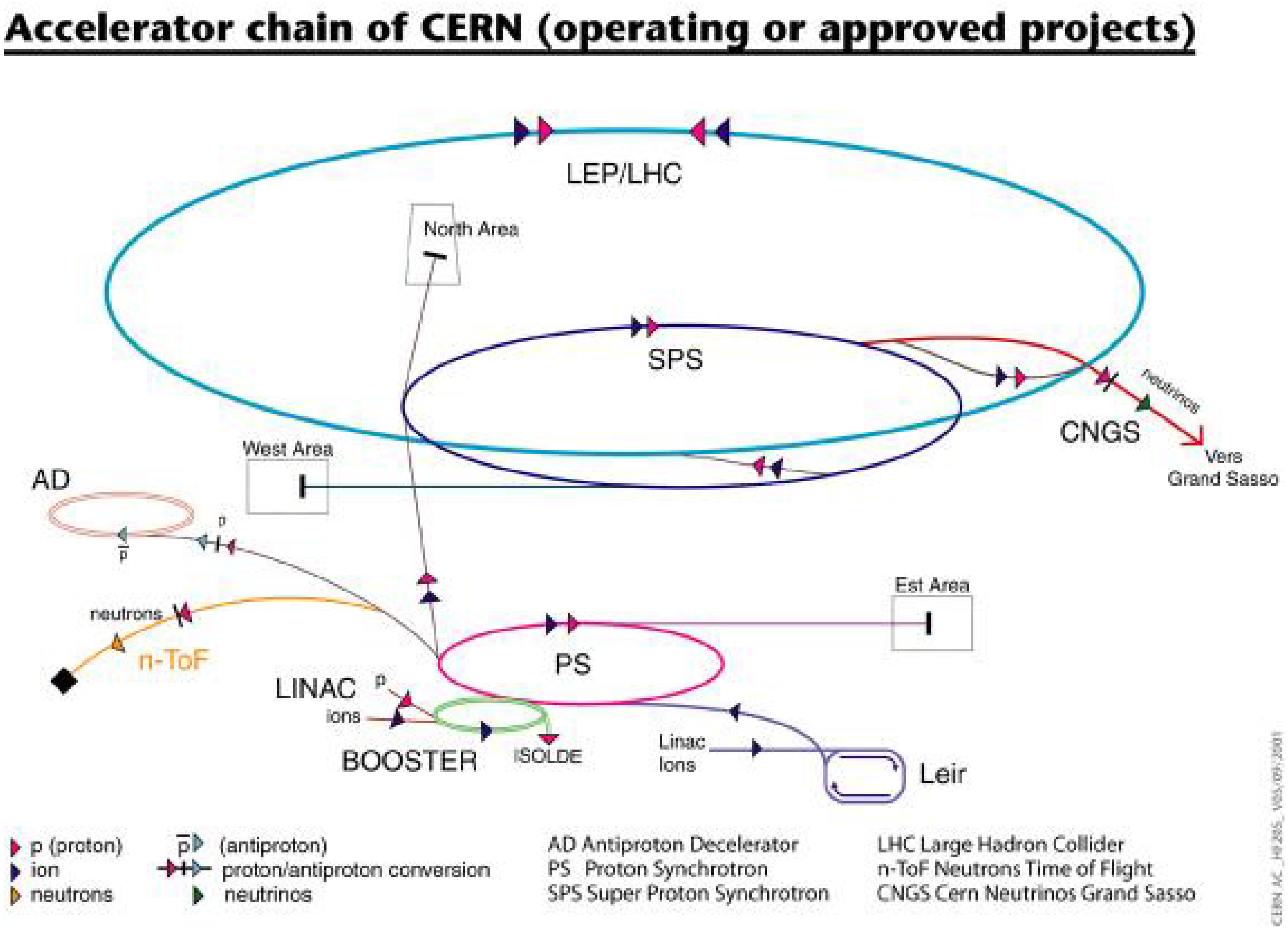
- a) CERN layout
- b) American layout (similar to RAL)
- c) Japanese scheme

ii) muon - acceleration:

- Cooling (power, frequency in American/European scheme)
- Dave Neuffer scheme
- Ring coolers
- Linac up to 2-3 GeV, RLAs.
- Fast cycling synchrotron

# 1) RF requirements for "conventional accelerators"

## *Example of CERN*



# LINAC 2 (Proton LINAC)

Started: ~ 1978
Output energy (protons): 50 MeV (kinetic)
Beam current: ~ 150 mA / 100 µs
Repetition period: 1.2 s

| TYPE OF STRUCTURE | FREQUENCY | ENERGY GAIN (per structure) | RF INPUT POWER (per structure | QUANTITY |
|---|---|---|---|---|
| RFQ | 202 MHz | 750 keV | ~ 500 kW | 1 |
| Alvarez | 202 MHz | < 20 MeV | < 3 MW | 3 |

## LINAC 3 (Lead Ions LINAC)

Started: ~ 1994
Output energy ($Pb^{27+}$): 4.2 MeV/u (kinetic)
Beam current: ~ 30 µA of $Pb^{53+}$ (after stripping) / 600 µs
Repetition period: 1.2 s {100 ms foreseen}

| TYPE OF STRUCTURE | FREQUENCY | ENERGY GAIN (per structure) | RF INPUT POWER (per structure | QUANTITY |
|---|---|---|---|---|
| RFQ | 101 MHz | 250 keV/u | ~ 300 kW | 1 |
| IH | 101 (1) & 202 (2) MHz | ~ 1.3 MeV/u | ~ 400 kW | 3 |

## PSB (4 rings) (Proton Synchrotron Booster)

Started: ~ 1972
Output energy (protons): 1 GeV (kinetic) {1.4 GeV in 1999}
Beam current: up to 3.2 $10^{13}$ protons per pulse
Repetition period: 1.2 s

| TYPE OF STRUCTURE | FREQUENCY | VOLTAGE (per cavity) | RF INPUT POWER (per structure | QUANTITY |
|---|---|---|---|---|
| Ferrite loaded cavities | 3 to 8.5 MHz | 14 kV | ~ 20 kW | 4 |
| Ferrite loaded cavities | 6 to 16 MHz | 8 kV | ~ 10 kW | 4 |
| *Ferrite loaded cavities* | *0.6 to 1.8 MHz* | *8 kV* | *~ 30 kW* | *4* * |
| *Ferrite loaded cavities* | *1.2 to 3.6 MHz* | *8 kV* | *~ 30 kW* | *4* * |

# PS (Proton Synchrotron)

Started: 1959

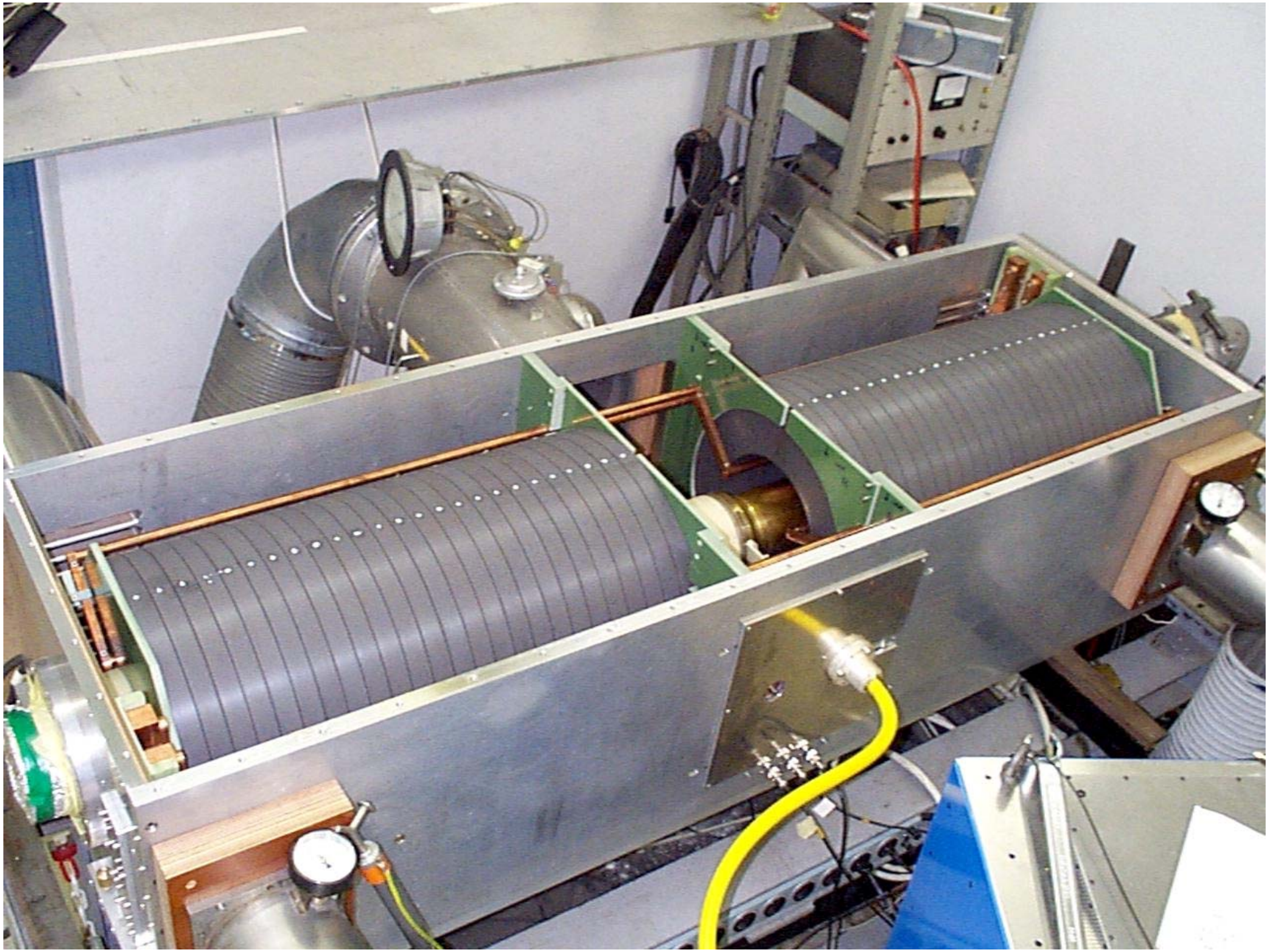
Output energy (protons): 26 GeV

Beam current: up to 2.9 $10^{13}$ protons per pulse

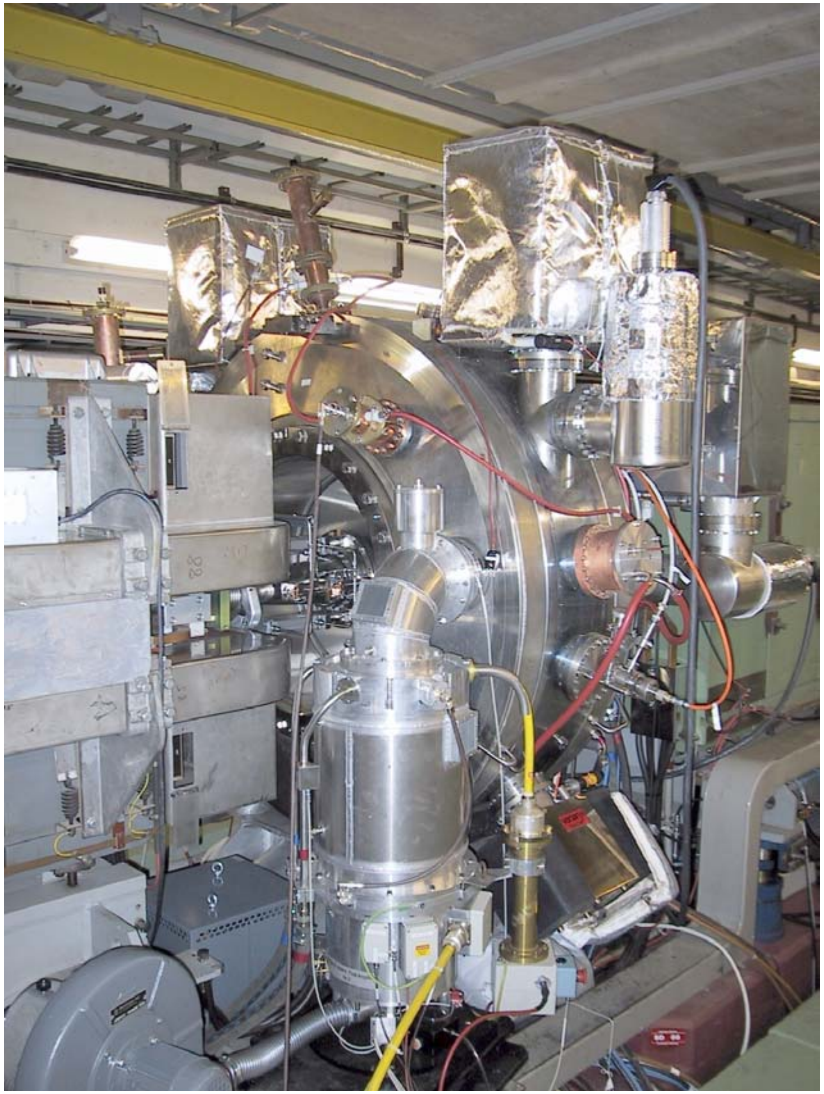
Repetition period: 1.2 s

| TYPE OF STRUCTURE | FREQUENCY | VOLTAGE (per cavity) | RF INPUT POWER (per structure | QUANTITY |
|---|---|---|---|---|
| Ferrite loaded cavities | 2.7 to 9.5 MHz | 20 kV | ~ 30 kW | 11 |
| Pill-box cavities | 200 MHz | 30 kV | 25 kW | 8 |
| Nose-Cone cavities | 114 MHz | 70 kV | 30 kW | 2 |
| *Capacitively loaded cavity* | *40 MHz* | *300 kV* | *300 kW (pulsed)* | *2 ** |
| *Capacitively loaded cavity* | *80 MHz* | *300 kV* | *300 kW (pulsed)* | *3 ** |

# PS



# PS



# 200MHz Acceleration system for the **SPS** machine

4 x 1 MW power amplifiers
(2 Siemens and 2 Philipps)
connected via coaxial line (~200m)
to the 4 travelling wave cavities in
Long Straight Section 3 of the SPS


- System 1 (shown):

4 x 500 kW Siemens tetrode amplifiers
Finals: 4 x 125 kW RS 2004 Thales
Driver: 1 x 125 kW RS2004 Thales
Predriver: 1 x 10 kW YL1520 Richardson
Pre-predriver: 1 x 1 kW YL1440 Richardson
Powers combined using hybrids

- System 2:

4 x 500 kW Philips tetrode amplifiers
Finals: 16 x 30 kW YL1530 Richardson

This RF system is the main accelerating system for the SPS machine – all beam modes. Provides 8 MV total accelerating voltage.

- bandwidth ~ ±2 MHz at 200 MHz

# 800MHz Landau damping system for the SPS machine

• 2 x 200 kW klystron amplifiers connected via waveguide (~120m) to 2 travelling wave cavities in Long Straight Section 3 of the SPS

• 4 x 60 kW klystrons Valvo YK1198 per amplifier combined using hybrids

• bandwidth ~ ±1 MHz at 800 MHz

System used for stabilising the high intensity beams in the SPS (SPS as LHC injector) and producing controlled emittance increase.

# 400MHz Acceleration system for the LHC machine

This RF system will be the main accelerating system for the LHC collider. It provides 16 MV total accelerating voltage/beam.

8 Superconducting cavities per beam at Point 4 of the LHC machine. Each cavity is connected via circulator and waveguide to its klystron, 16 klystrons total.

Klystron (shown in test stand) Thales 2167
- 300 kW, 400.8 MHz ± 1 MHz
- group delay <120 ns
- gain ~37 dB

Circulator AFT
- max fwd power 300 kW
- max reflected pwer 330 kW, any phase
- group delay <30ns

Klystron (shown in test stand)
Thales 2167

- 300 kW, 400.8 MHz ± 1 MHz
- group delay <120 ns
- gain ~37 dB

# 2) RF requirements for Neutrino Factories

## A Basic Concept for a Neutrino Factory

⇒Proton driver

⇒High-power proton beam onto a target

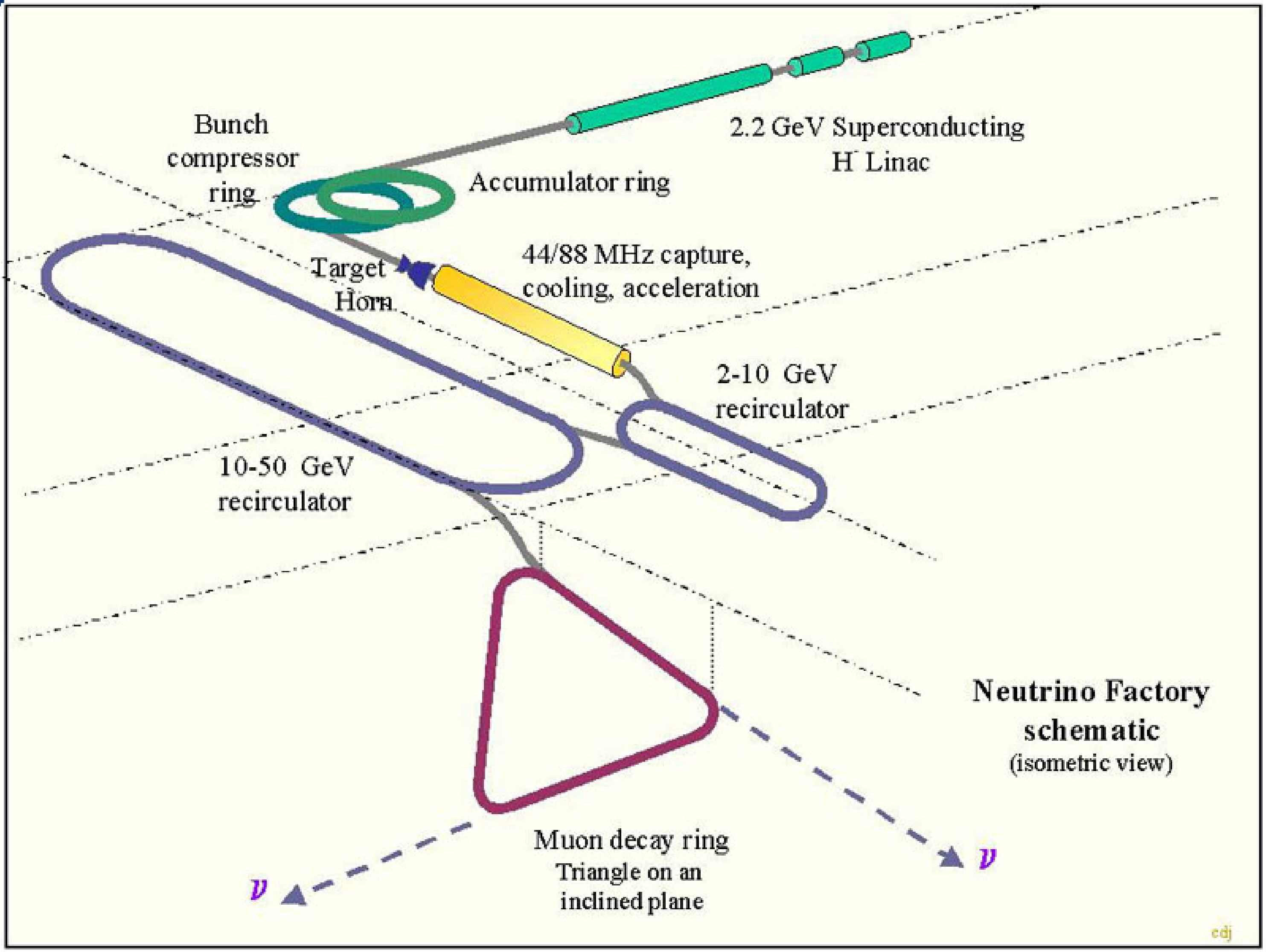
⇒System for collection of the produced pions and their decay products, the muons.

⇒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 (?)

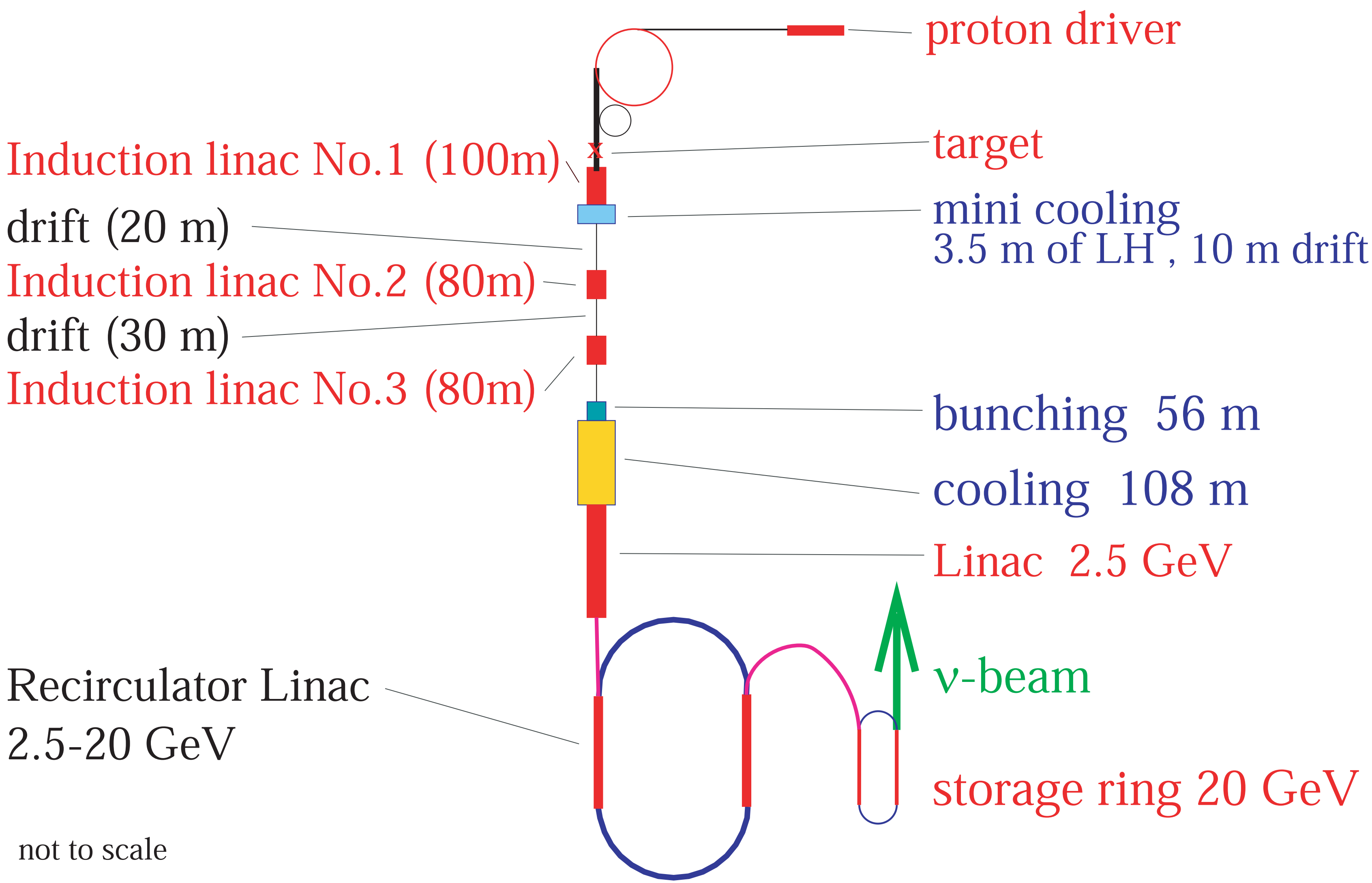
⇒Muons are injected into a storage ring (decay ring), where they decay in long straight sections in order to deliver the desired neutrino beams.

# CERN Scheme

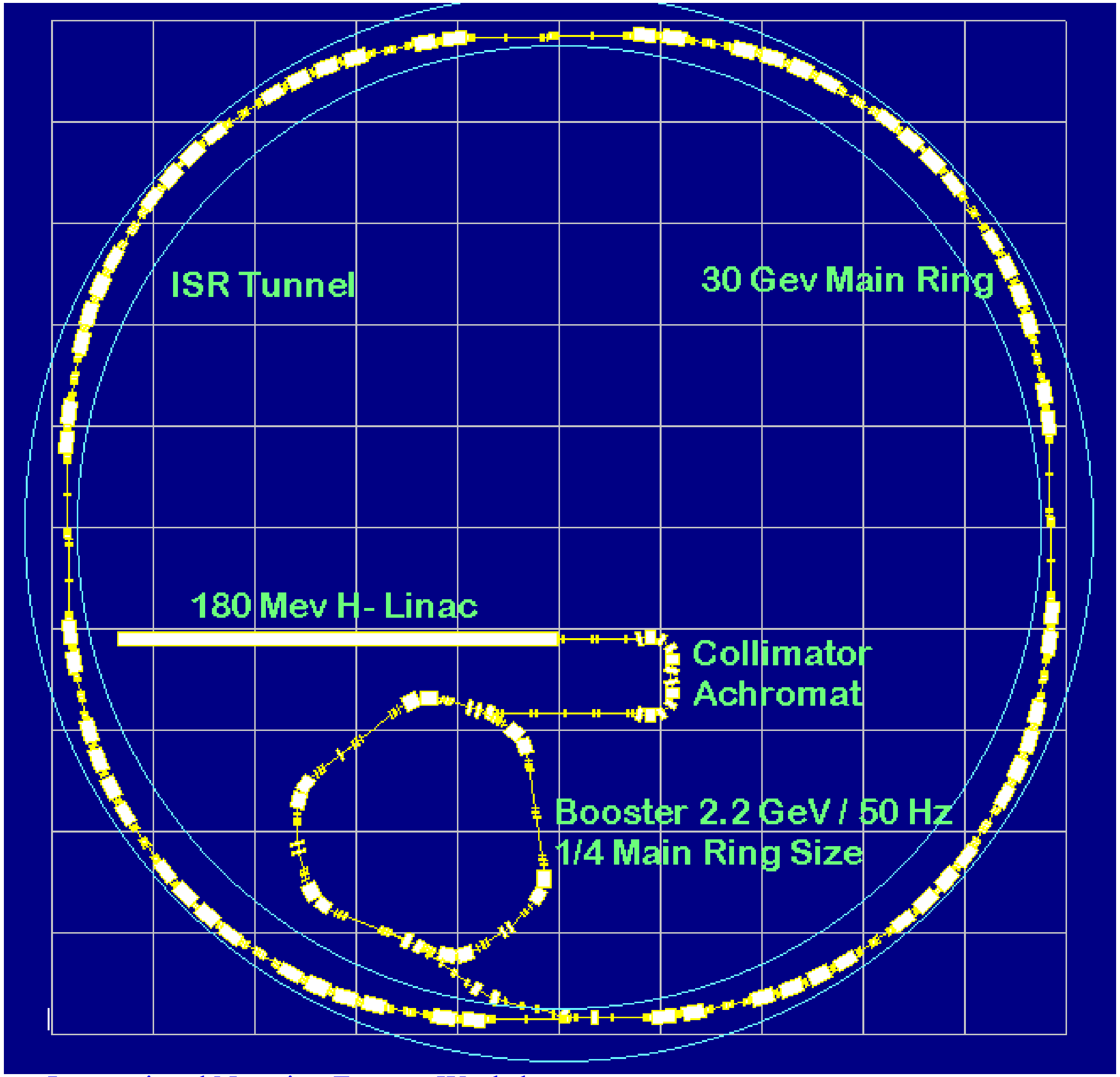


Bunch compressor ring
Accumulator ring
2.2 GeV Superconducting H⁻ Linac
Target
Horn
44/88 MHz capture, cooling, acceleration
2-10 GeV recirculator
10-50 GeV recirculator
Neutrino Factory schematic
(isometric view)
Muon decay ring
Triangle on an inclined plane
ν
ν
cdj

# American Study II

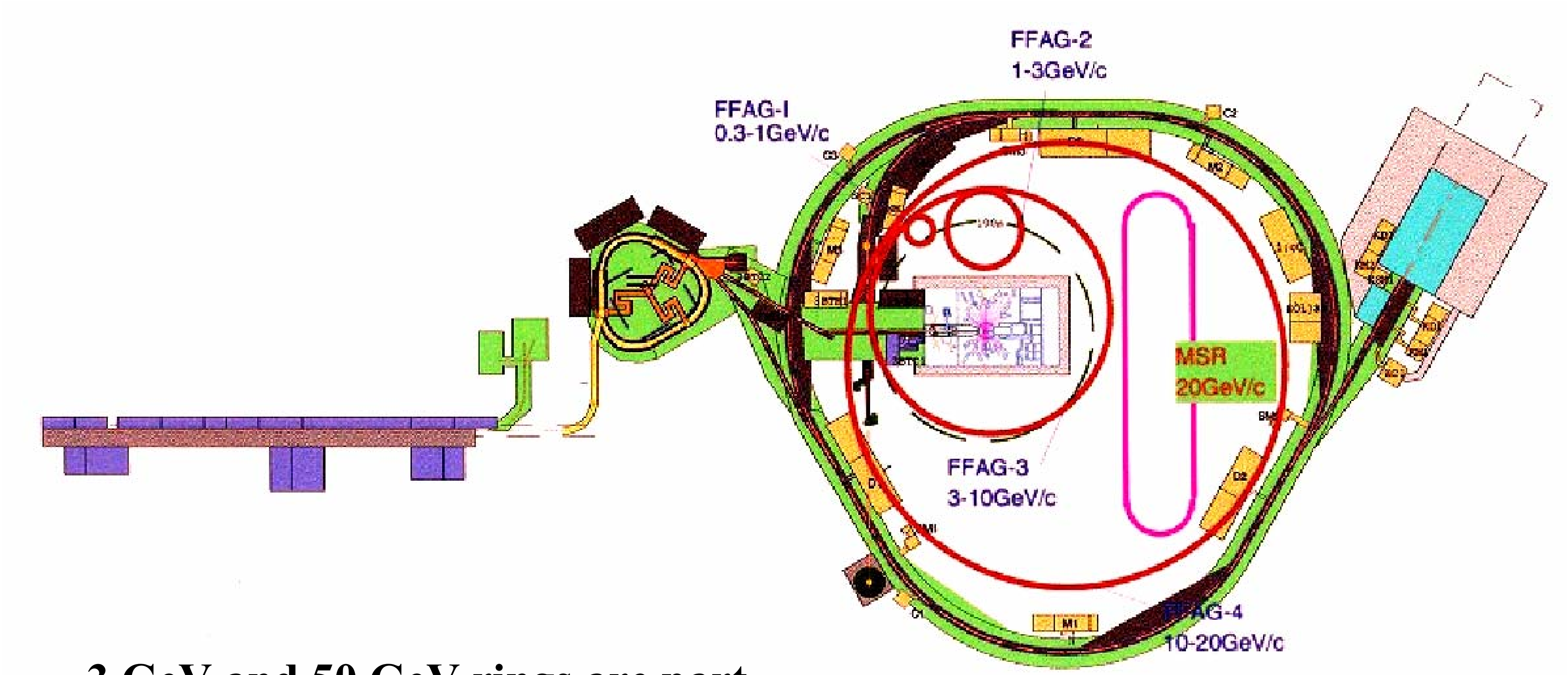


## 30 GeV Rapid Cycling Synchrotron in the ISR tunnel




***RAL Proposal for CERN***

# Japanese Scheme




**3 GeV and 50 GeV rings are part of JAERI-KEK Joint Project**

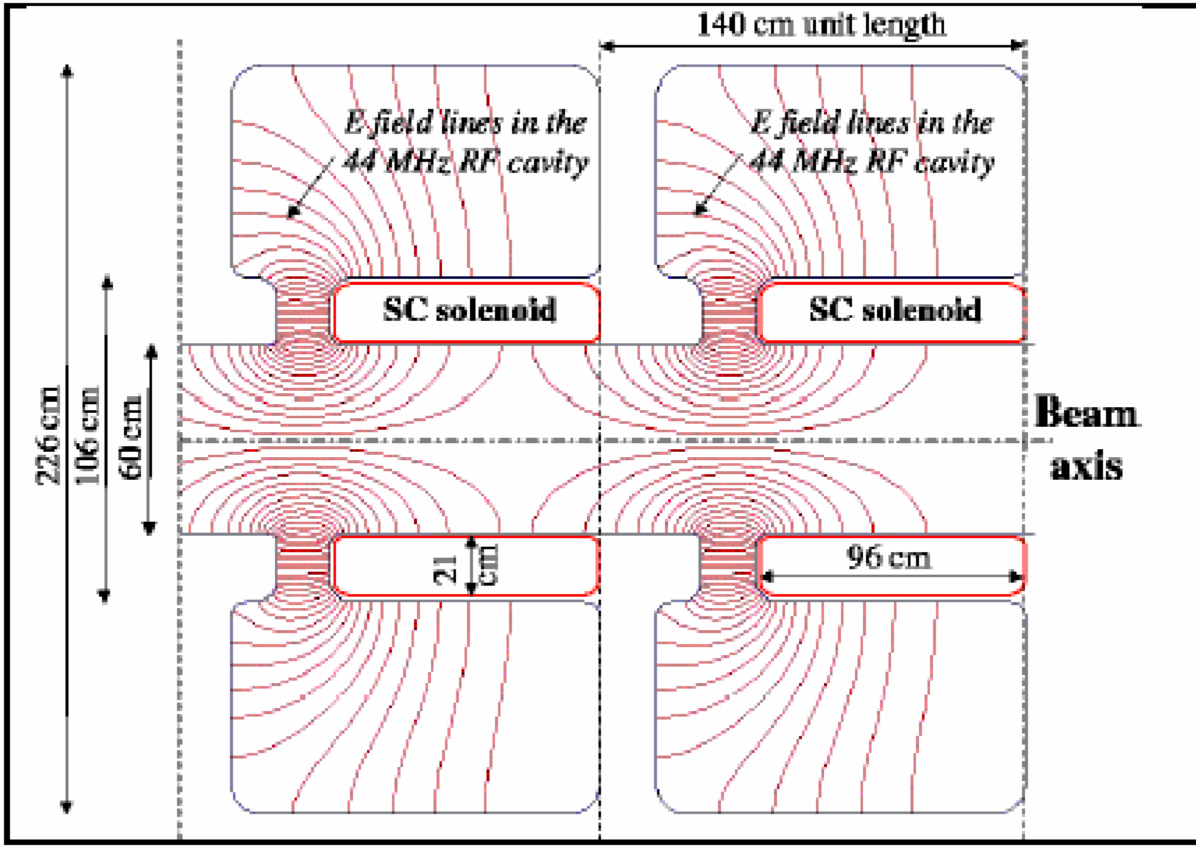
# CERN study / cooling and first acceleration

Overview of the geometry and the beam parameters of all subsystems.
Note that over 90% of the muons are lost (see column 'intensity')

| Part | Geometry | | Beam (at the *end* of the part) | | | | | RF system | |
|---|---|---|---|---|---|---|---|---|---|
| | Size [m] | Turns | Particle | $E$ [GeV] | Intensity [particles/s] | Total $\Delta E$ [MeV] | Bunch length [ns] | Freq. [MHz] | Real estate gradient/ tot. voltage |
| SPL | l = 691 | — | p | 2.2 | $1.1 \times 10^{16}$ | 0.4 | — | 352.2 | 3.5 … 9 MV/m |
| Accumulator | c = 942 | ≈ 1000 | p | 2.2 | $1.1 \times 10^{16}$ | 0.4 | 17 | 44 | 0.3 MV |
| Compressor | c = 942 | 7 | p | 2.2 | $1.1 \times 10^{16}$ | 0.4 | 6 | 44 (88) | 2 (0.35) MV |
| After the horn | — | — | π | 0…1 | $2.2 \times 10^{15}$ | >1000 | 6 | — | — |
| Decay channel | l = 30 | — | π → μ | 0.2 | $2.15 \times 10^{15}$ | >1000 | >6 | — | — |
| Phase rotation | l = 30 | — | μ | 0.2 | $1.14 \times 10^{15}$ | 80 | 5.6 | 44 | 2 MV/m |
| Cooling I | l = 46 | — | μ | 0.2 | $3.96 \times 10^{14}$ | 80 | 5.6 | 44 | 2 MV/m |
| Acceleration | l = 32 | — | μ | 0.28 | $3.96 \times 10^{14}$ | 80 | 5.6 | 44 | 2 MV/m |
| Cooling II | l = 112 | — | μ | 0.3 | $2.42 \times 10^{14}$ | 80 | 2.8 | 88 | 4 MV/m |
| Acceleration IIa | l ≈ 500 | — | μ | ≈ 2 | $1.54 \times 10^{14}$ | 80 | 2.8 | 88 | 4 MV/m |
| Phase rotation II | l ≈ 200 | — | μ | ≈ 2 | $1.54 \times 10^{14}$ | 400 | 0.5 | 220 | 4 MV/m |
| Acceleration IIb | l ≈ 250 | — | μ | 3 | $1.54 \times 10^{14}$ | 400 | 0.5 | 220 | 4 MV/m |
| RLA I (w/o arcs) | l = 350 | 4 | μ | 11 | $>10^{14}$ | 800 | 0.5 | 220 | 4 MV/m |
| RLA II (w/o arcs) | l = 1900 | 4 | μ | 50 | $>10^{14}$ | >800 | 0.5 | 352 | 4 MV/m |
| Decay ring | c = 2075 | <500 | μ → ν | ≤ 50 | $>10^{14}$ | >800 | 0.5 | 352 | (100 MV) |

# CERN study / cooling and first acceleration

## CERN 44 MHz cavity (88MHz similar) for the cooling channel




| RF characteristics | |
|---|---|
| $E_{0T}$ | 2 MV/m |
| $Z_{TT}$ | 3 MΩ/m |
| R/Q | 103 Ω |
| Filling time | 296 μs |
| $P_{PEAK}$ | 1.86 MW/cavity |
| $P_{MEAN}$ (50 Hz) | 89 kW/m |

# *CERN study / cooling and first acceleration*

What is needed?

50 times 2 MW at 44 MHz

200 times 2 MW at 88 MHz

Similar numbers for acceleration to 3 GeV at 220 MHz

# 2) RF requirements for Neutrino Factories

American Study I

High beam power: $\boldsymbol{P}_{\text{beam}} = 1.2$ MW

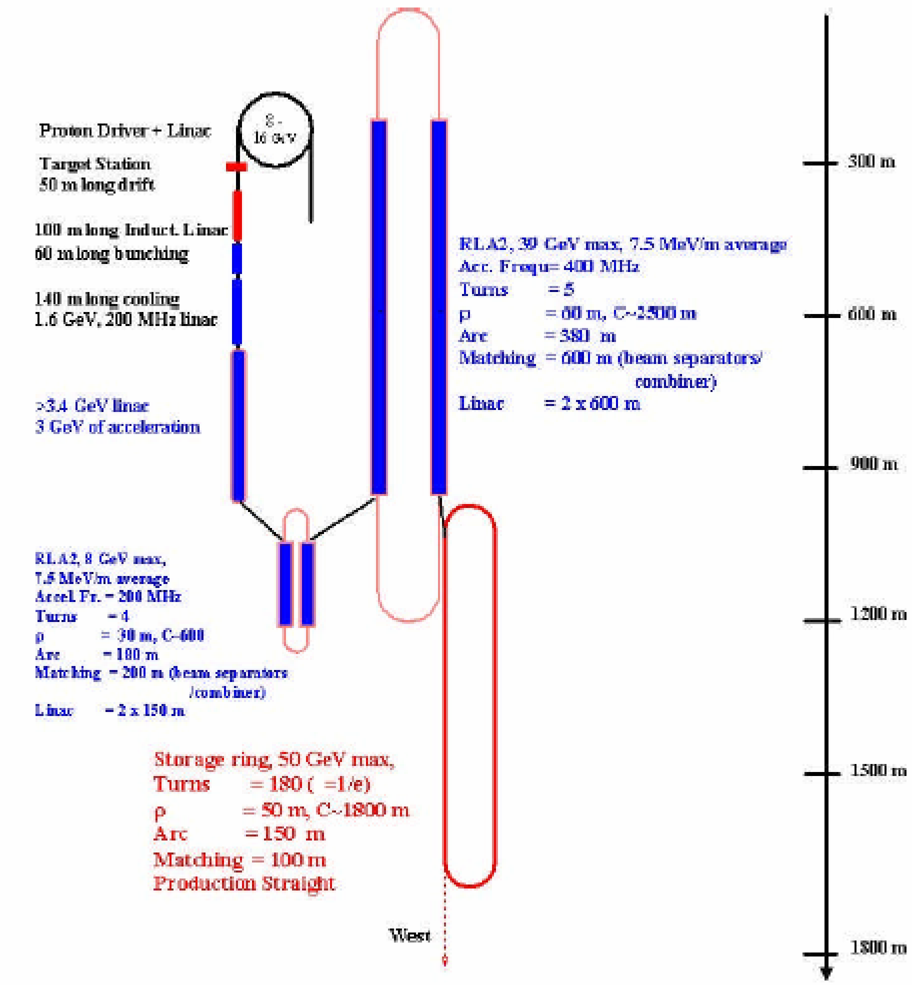


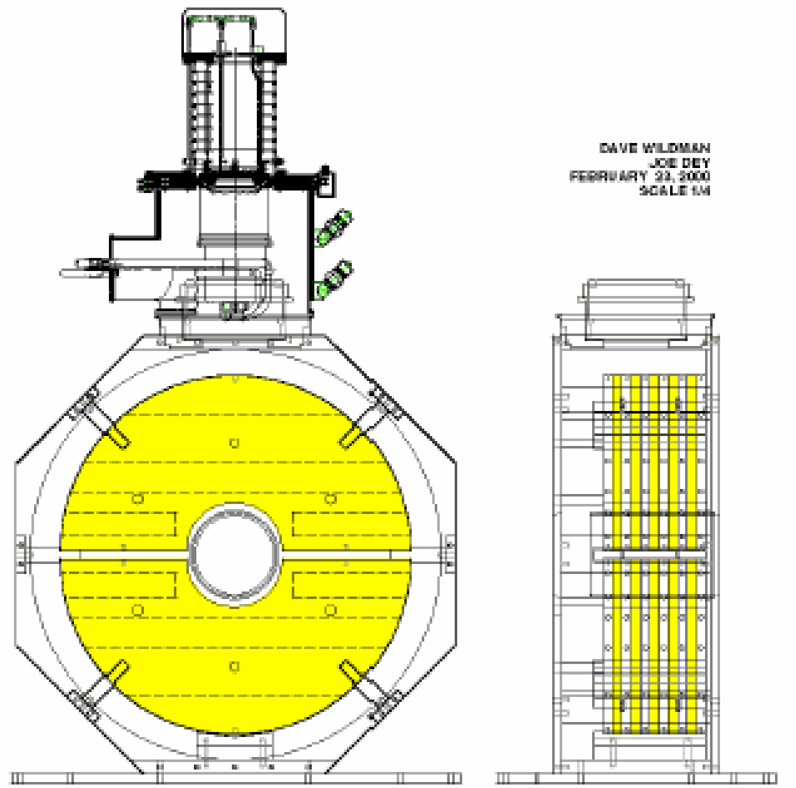

**Figure 1:** Footprint (to scale) of the whole facility.

# US Study I Proton Driver

| | PRESENT | (ν-FACTORY) PHASE I | UPGRADE PHASE II |
|---|---|---|---|
| **Linac** (operating at 15 Hz) | | | |
| Kinetic energy (MeV) | 400 | 400 | 1000 |
| Peak current (mA) | 40 | 60 | 80 |
| Pulse length (μs) | 25 | 80 | 200 |
| $H^-$ per pulse | $6.3 \times 10^{12}$ | $3 \times 10^{13}$ | $1 \times 10^{14}$ |
| Average beam current (μA) | 15 | 72 | 240 |
| Beam power (kW) | 6 | 29 | 240 |
| **Pre-booster** (operating at 15 Hz) | | | |
| Extraction kinetic energy (GeV) | | | 3 |
| Protons per bunch | | | $2.5 \times 10^{13}$ |
| Number of bunches | | | 4 |
| Total number of protons | | | $1 \times 10^{14}$ |
| Norm. 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 | $6 \times 10^{10}$ | $7.5 \times 10^{12}$ | $2.5 \times 10^{13}$ |
| Number of bunches | 84 | 4 | 4 |
| Total number of protons | $5 \times 10^{12}$ | $3 \times 10^{13}$ | $1 \times 10^{14}$ |
| Norm. transverse emittance (mm-mrad) | 15π | 60π | 200π |
| Longitudinal emittance (eV-s) | 0.1 | 2 | 2 |
| RF frequency (MHz) | 53 | 1.7 | 7.5 |
| Extracted bunch length $\sigma_b$ (ns) | 0.2 | 3 | 1 |
| Average beam current (μA) | 12 | 72 | 240 |
| Target beam power (kW) | 100 | 1200 | 4000 |

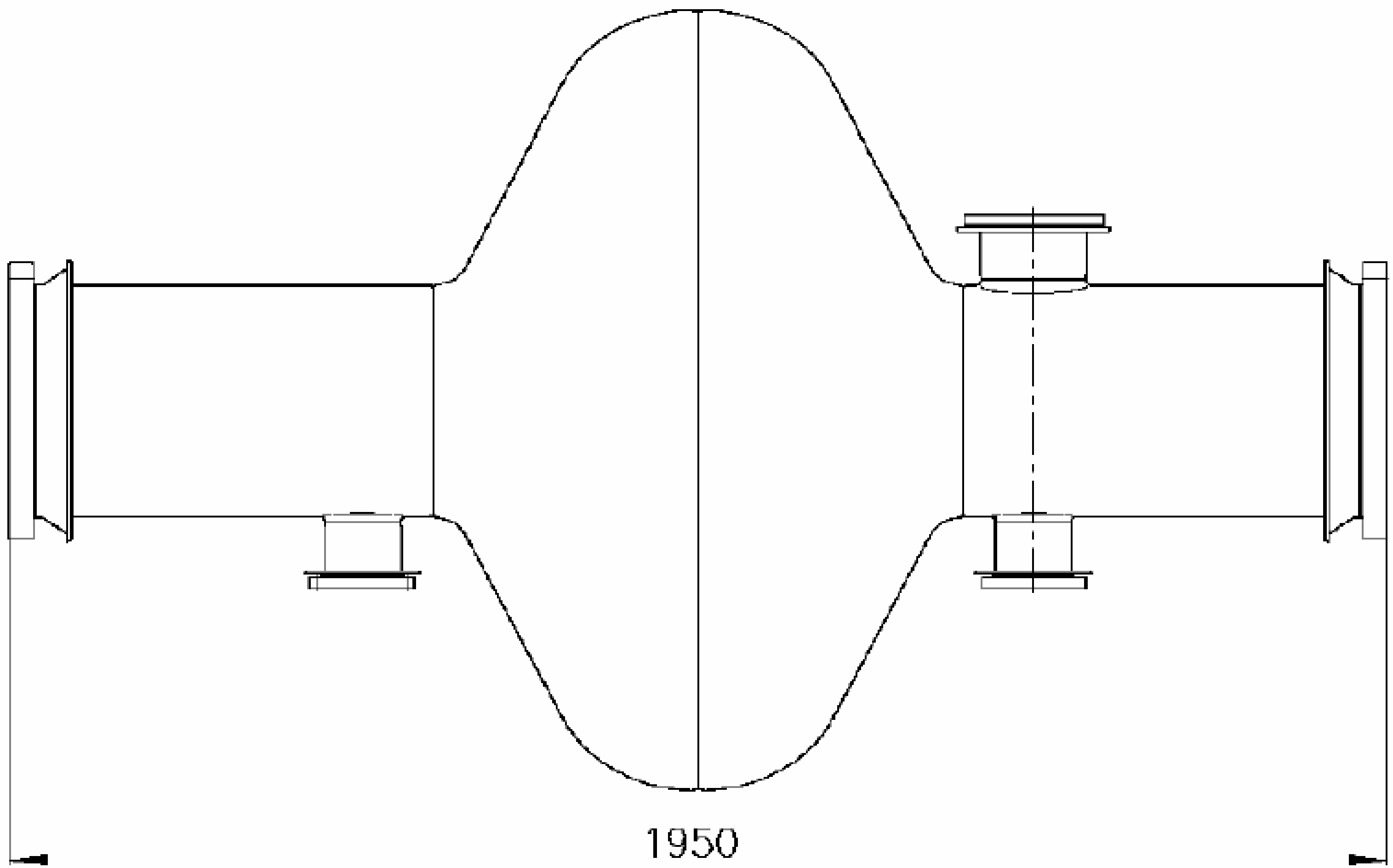
# RF cavity for the FNAL 16 GeV proton driver in Study I
# (7.5 MHz; Phase II)

A prototype 20 kV, 7.5 MHz Finemet cavity has been built at Fermilab in collaboration with KEK




The required total rf voltage is about 1.4 MV. Due to the small circumference of this machine, the cavities must have a high gradient (30 kV/m). Finemet cores can withstand higher rf B-fields than regular ferrite and thus provide higher gradient. The disadvantage is ***higher losses and lower Q.***

# 200 MHz superconducting rf cavity built at CERN for Cornell



Study I

Pre-accelerator

and RLA1

sc cavity

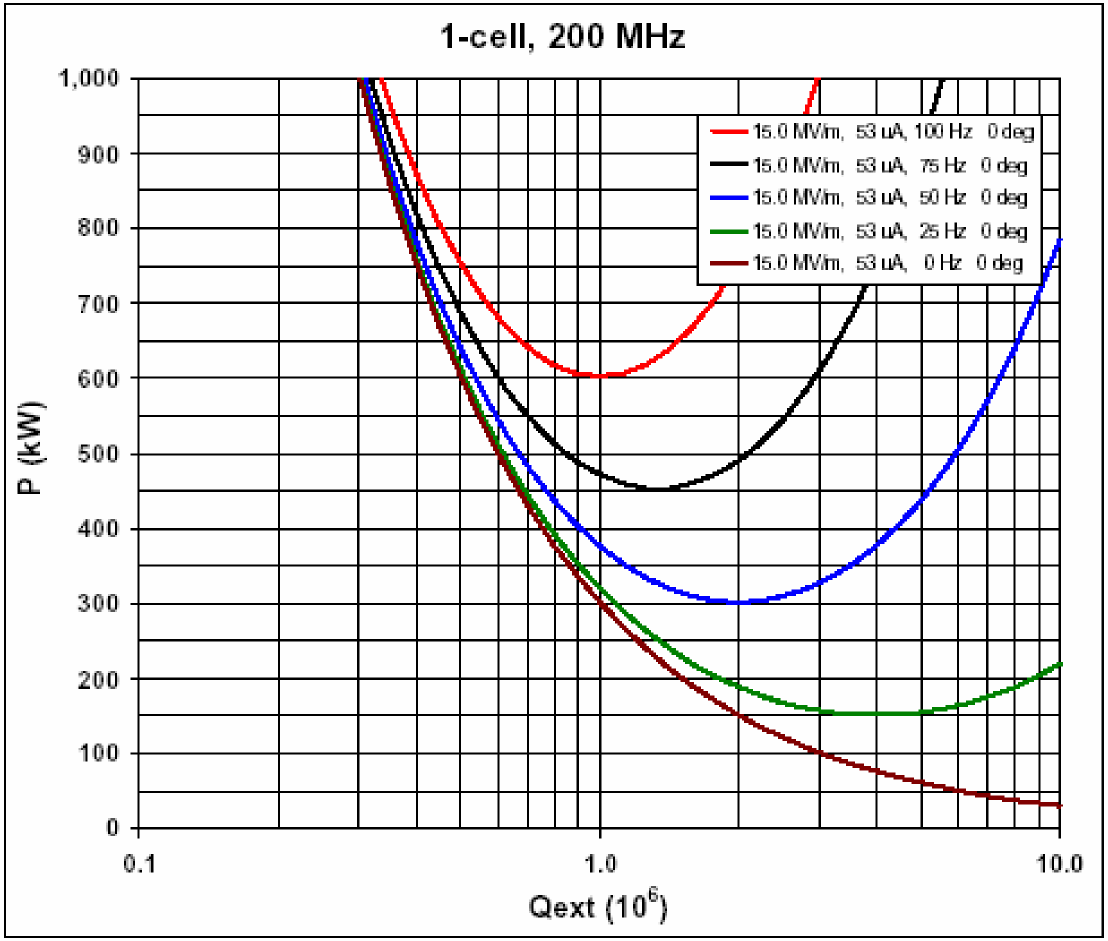



**Figure 9:** RF power requirements for 200 MHz single cells. 200 MHz, $Q_0=5\times10^9$, V=11.25 MV, R/Q=105 Ω, $I_{average}$=7.2 µA. Calculated for infinite filling time.

# Study II

The rf systems for the **buncher and the cooler** are required to match the muon beam into the longitudinal acceptance of the cooling channel and to replenish the beam energy lost during ionization cooling. Since they must operate inside the strong solenoid fields they must be normal conducting.

**These systems require a large number of rf cavities operating at high gradient, and a large amount of pulsed rf power.**

# Study II

The proposed **buncher, cooling channel, and matching section** is approximately 183 m long and requires **184 cavities** and **84 klystrons at 201.25 MHz** and an additional **6 cavities** and **3 klystrons at 402.5 MHz**. The total installed power is approximately **780 MW (~ 1.56 MW average)**, and the installed voltage is 1080 MV.

The cooling channel is followed by an **acceleration section** employing **299 two-cell superconducting rf cavities operating at 201.25 MHz**. These structures are also challenging because of the high gradient and large physical size. Peak power requirements for the acceleration section are not as high as for the normal conducting rf sections, but the pulse length is much longer.

Many superconducting cavities can be powered from a single klystron station. Several multi-cell rf cavities may share a common cryostat.

| Omega cavities | | | | | | |
|---|---|---|---|---|---|---|
| Section | Radius (m) | Length (m) | Freq. (MHz) | No. of cavities | $E^{*}_{pk}$ (MV/m) | $V_{eff}$ (MV) |
| b1 | 0.607 | 0.405 | 201.25 | 4 | 7.41 | 2.07 |
| b2 | 0.607 | 0.405 | 201.25 | 8 | 6.95 | 1.94 |
| b3 | 0.607 | 0.405 | 201.25 | 8 | 9.27 | 2.59 |
| (1,1)-(1,3) | 0.607 | 0.405 | 201.25 | 68 | 20.62 | 5.76 |
| (2,1)-(2,3) | 0.615 | 0.483 | 201.25 | 74 | 23.06 | 6.71 |
| match | 0.615 | 0.483 | 201.25 | 22 | 23.06 | 6.71 |
| b1 402.5 MHz | 0.308 | 0.288 | 402.5 | 2 | 6.57 | 1.03 |
| b2 402.5 MHz | 0.308 | 0.288 | 402.5 | 4 | 8.21 | 1.29 |

This table summarizes the inventory of **normal conducting rf cavities** (NCRF). The cooling channel simulations were based upon ideal pillbox cavities with lengths determined by the space available in the chosen lattices (and zero space between cavities). The gradients and phases of these cavities were adjusted to optimize the cooling channel performance while keeping the gradients and rf power requirements within feasible limits.

# Peak cavity power and klystron output power to meet these requirements, and total power for each cavity type.

| Section | $Veff$ (MV) | $Rs^{\dagger}$ ($M\Omega$) | $P_c$ * (MW) | $P_{kly}$ ** (MW) | No. of cavities | $P_{tot}$ (MW) | Sum (MW) |
|---|---|---|---|---|---|---|---|
| Omega cavities | | | | | | | |
| b1 | 2.07 | 10.220 | 0.494 | 0.547 | 4 | 2.19 | |
| b2 | 1.94 | 10.220 | 0.434 | 0.481 | 8 | 3.85 | |
| b3 | 2.59 | 10.220 | 0.77 | 0.855 | 8 | 6.84 | |
| (1,1)-(1,3) | 5.76 | 10.220 | 3.818 | 4.228 | 68 | 287.54 | |
| (2,1)-(2,3) | 6.71 | 11.794 | 4.491 | 4.974 | 74 | 368.09 | |
| match | 6.71 | 11.794 | 4.491 | 4.974 | 22 | 109.43 | 778.0 |
| b1 402.5 MHz | 1.03 | 8.368 | 0.150 | 0.166 | 2 | 0.333 | |
| b2 402.5 MHz | 1.29 | 8.368 | 0.235 | 0.260 | 4 | 1.040 | 1.4 |

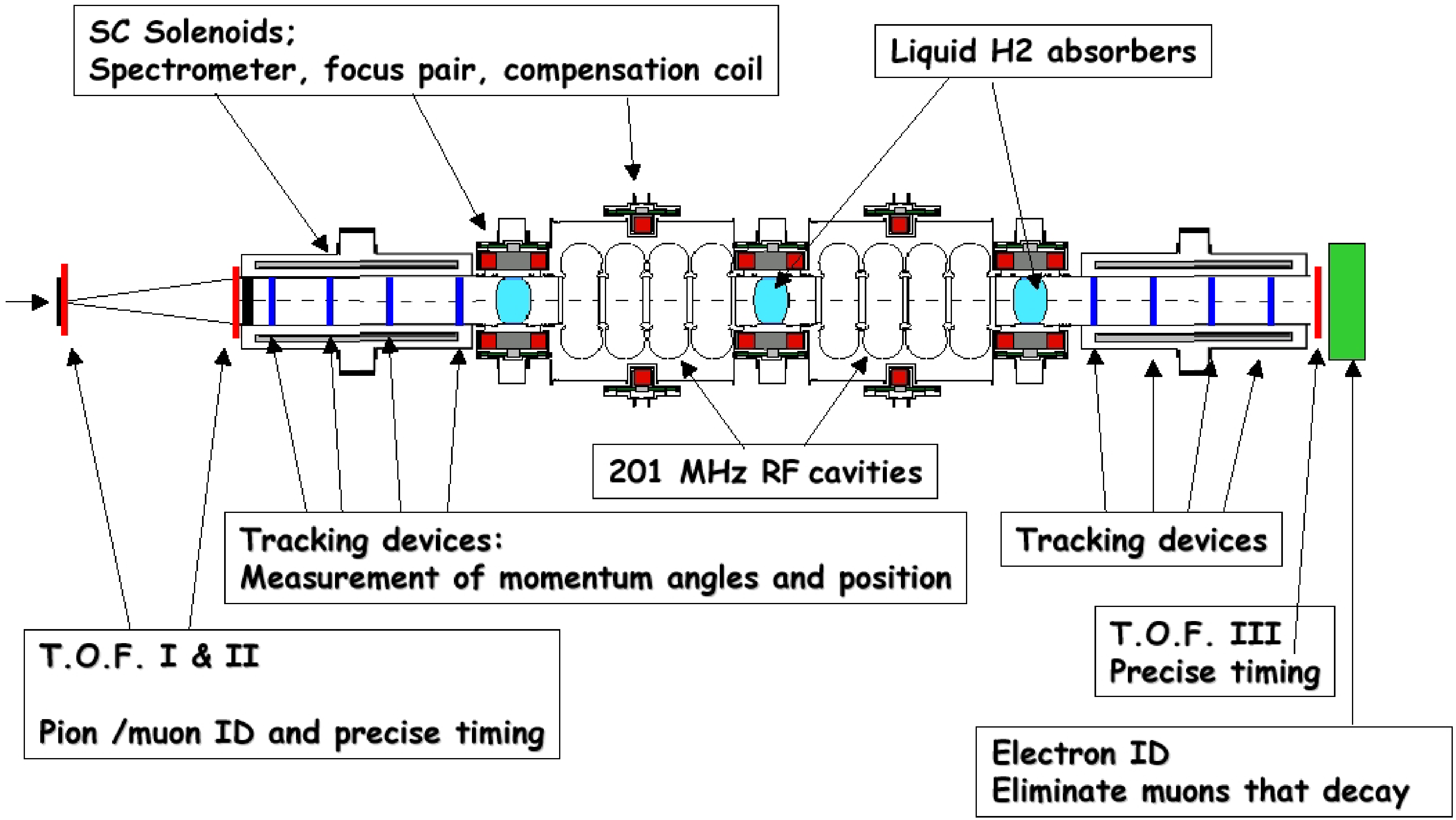
# RF Station (NC cavities)

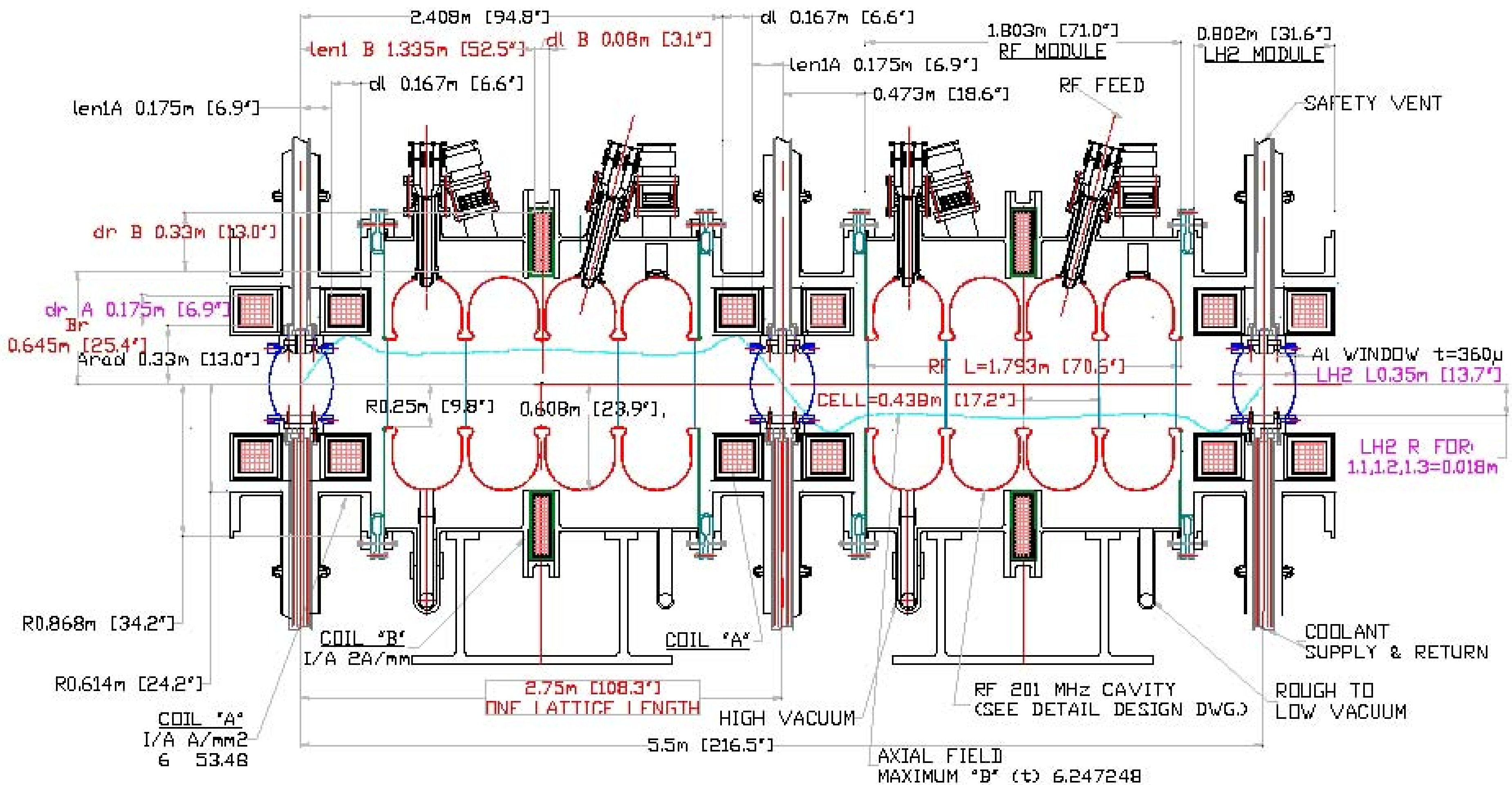
Each rf station consists of a modulator for two klystrons, a distribution system, and low-level rf and controls driving two or more cavities. The modulator must provide a flat top DC pulse of up to 125 μs with a recharge time of less than 20 ms. (This is equivalent to a repetition rate of 50 Hz, but not every 50 Hz pulse is required. The output from the AGS appears as 6 pulses spaced at 20 ms followed by a 300 ms gap, with a repetition rate of 2.5 Hz.) The average duty factor is $\sim 1.9 \times 10^{-3}$.

Each rf station must provide approximately 10 MW of peak power to drive two cavities. The power source is a multi-beam klystron, which should give good reliability and a long operational lifetime.

# *Muon Ionization Cooling Experiment (MICE)*

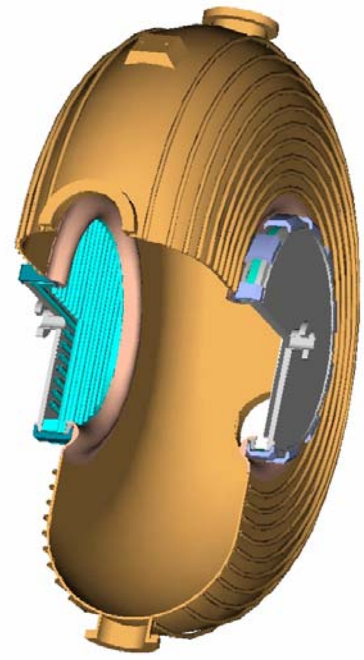
# *(planned at RAL by an international collaboration)*



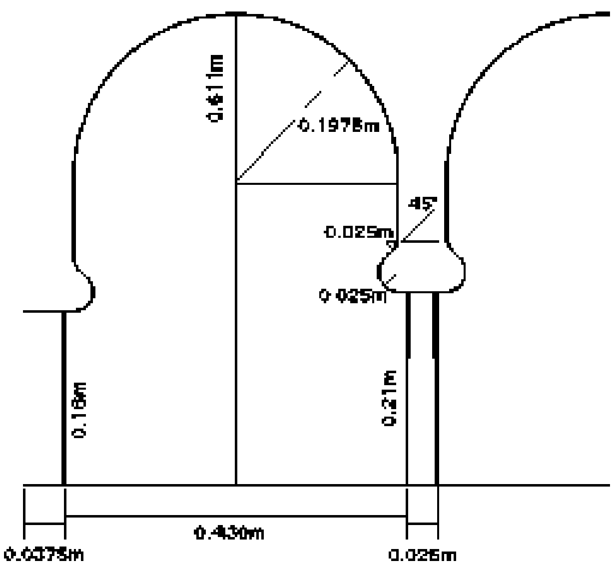

2.408m [94.8"]
dl 0.167m [6.6"]
len1 B 1.335m [52.5"]
dl B 0.08m [3.1"]
1.803m [71.0"]
RF MODULE
0.802m [31.6"]
LH2 MODULE
len1A 0.175m [6.9"]
dl 0.167m [6.6"]
0.473m [18.6"]
RF FEED
len1A 0.175m [6.9"]
SAFETY VENT
dr B 0.33m [13.0"]
dr A 0.175m [6.9"]
Br
0.645m [25.4"]
Arad 0.33m [13.0"]
Al WINDOW t=360μ
LH2 L0.35m [13.7"]
RF L=1.793m [70.6"]
CELL=0.438m [17.2"]
R0.25m [9.8"]
0.608m [23.9"]
LH2 R FOR
1,1,1.2,1.3=0.018m
R0.868m [34.2"]
COIL "B"
I/A 2A/mm
COIL "A"
COOLANT
SUPPLY & RETURN
R0.614m [24.2"]
2.75m [108.3"]
ONE LATTICE LENGTH
RF 201 MHz CAVITY
(SEE DETAIL DESIGN DWG.)
ROUGH TO
LOW VACUUM
COIL "A"
I/A A/mm2
6 53.48
HIGH VACUUM
5.5m [216.5"]
AXIAL FIELD
MAXIMUM "B" (t) 6.247248

# RF-Cavities

- Two 4-cell cavities, 201.25MHz
- At least 20MV required; max. 32MV possible
- ≥4MW/cell required
- Cell closed with thin Be foil or grid
- First one cell cavity being designed and built



| Available power supplies | Voltage from one 4-cell cavity | Voltage from two 4-cell cavities |
|---|---|---|
| 1 X 4 MW | 11.5 MV on crest<br>5.7 MV at 30° | 16 MV on crest<br>8 MV at 30° |
| 2 X 4 MW | 16 MV on crest<br>8 MV at 30° | 23 MV on crest<br>11.5 MV at 30° |
| 8 X 4 MW | | 46 MV on crest<br>23 MV at 30° |



# *RLA (Study II)*

SCRF overall parameters for a Neutrino Factory.

| | |
|---|---|
| No. of cryomodules | 94 |
| No. of 2-cell cavities | 311 |
| No. of input couplers | 622 |
| Overall length (m) | 1054 |
| Active length (m) | 467 |
| Filling factor | 0.44 |
| Total voltage (GV) | 7.5 |
| Average real estate gradient (MV/m) | 7.8 |
| Total heat load at 2.5 K, 5–8 K, 40–80 K (kW) | 7.7, 9.7, 94 |
| Cryo load (with $\times$1.5 safety factor) 2.5 K, 5–8 K, 40–80 K (kW) | 11.6, 14.6, 141 |
| Assuming efficiency multipliers of 600, 225 , 20 | |
| AC power for refrigeration (MW) | 13 |
| Total peak rf power (with 20% margin for control/losses)(MW) | 362 |
| Average rf power (MW) | 16.3 |
| AC power for rf (efficiency multiplier = 2) (MW) | 35.6 |
| Total AC power (MW) | 49 |

362 MW

16.3 MW

The superconducting linac and recirculating linear accelerator (RLA) designs employ a total of 311 cavities. The linac contains 119 cavities running at a gradient of up to 17 MV/m.

An examination of the requirements shows that an rf source of about 6 or 12 MW would be ideal for the 201.25 MHz cavities and a source of 500 to 750 kW for the 402.5 MHz cavities. The rf power for the 201.25 MHz cavities could be supplied by existing gridded tubes at about the 5 MW level. However, the low gain and lifetime of gridded tubes make the R&D effort to develop an alternative most attractive. Preliminary calculations at SLAC have shown that a 201.25 MHz klystron could be built with a reasonable amount of R&D.

The gain, efficiency, and lifetime are all higher than a gridded tube at 50 dB, 50-70% and 50,000 hours, respectively.

***Not completely my opinion…***

SLAC has examined two designs, a single-gun diode design, and a multibeam klystron (MBK). The multibeam klystron is the more attractive in that it reduces the overall length of the tube from 7.5 m to about 3.5 - 4.0 m. The length reduction factor of the multibeam klystron, and its potential for higher efficiency, make it the optimum candidate for the Neutrino Factory. Moreover, the length of the multibeam klystron is consistent with the manufacturing capabilities of current tube manufacturers, whereas the manufacture of a 7.5 m diode tube would be a big step and would require new and costly facility upgrades.

To provide rf power overhead for dynamic regulation of the rf phase and amplitude, a 12 MW multibeam klystron has been selected as the high-power rf source for the Neutrino Factory. This provides an rf power overhead margin of about 20% for regulation. The design will be a fully integrated horizontal package incorporating the tube, solenoid, and high-voltage terminal, as pioneered at CERN for LEP. This facilitates the replacement and installation of tubes in the facility. Another advantage of the horizontal design, besides the ease of handling, is the reduced cost of the rf building because of the lower building height requirement. With a mean-time-between-failures (MTBF) of 50,000 hours and 84 tubes, one tube will need to be replaced about every 30 days (after the initial break-in period). Since there is a comparable number of klystrons for the acceleration system, the rate of klystron failures for the facility as whole will be about two per month, on average. Many of these failures towards the end of life are gradual, and replacement can be scheduled for routine maintenance periods.

7 beam MBK developed for TESLA

Two such tubes have been built and tested, and have demonstrated efficiencies of 63-66%.

Because of the large size and high cost of waveguide, the transmission lines from the tubes to the cavities will be large coaxial lines of 0.31 to 0.36 m diameter, pressurized to 1.75 atmospheres of dry air. Power splitters divide the rf power from each tube to supply the cavities. Sections b1 and b2 of the buncher (see Chap. 5.1 and, in particular, Table 5.2) will require a 12-way splitting of the power; section b3 an 8-way split, and sections (1,1) to (2,3) of the cooling a 2-way split. Splitters with proper built-in phase delays further divide the power to each cell or cavity section of the cooling channel.

# What do we need:

- High pulsed power, MW range, 200 and 400 MHz, perhaps down to 80 or 40 MHz with a repetition rate of 10 to 50 Hz and pulse length of the order of ms
- High reliability or redundancy
- Good efficiency
- Cheap!!!

# *Cost*

**RF power at M$ 277 out of M$ 1,747 in US Study II.**

**This study did not include the RLA2 (to accelerate from 20 to 50 GeV) with a lot of additional RF.**

**The running costs for the RF will play an important role.**

# *Some important points*

**RF amplifiers are expensive:**

**-Price for a unit**

**-Replacement cost**

**-Downtime during replacement**

**-Power consumption is an issue too!**

**-Safety not a particular problem**

## *Some ideas to reduce (?) the cost*

**Can tubes be build with additional vacuum pumps and interchangeable filaments?**

**Can the price of a klystron be lowered by considering it as an accelerator and again have parts with limited lifetime (e.g. cathodes) easily interchangeable?**

**Can high power units be built by grouping lower power units together with easy replacement and redundant units?**

# *REMINDER*

**RF generators are an important part of the whole Neutrino Factory complex.**

**Their price has a big impact on the total budget for the facility.**

**Running costs (in terms of tube replacement costs and the power bill) are not at all negligible.**

**Reducing those costs may very well have a decisive impact on the decision how and whether at all to build such a facility.**

*The END*

**THANK YOU**