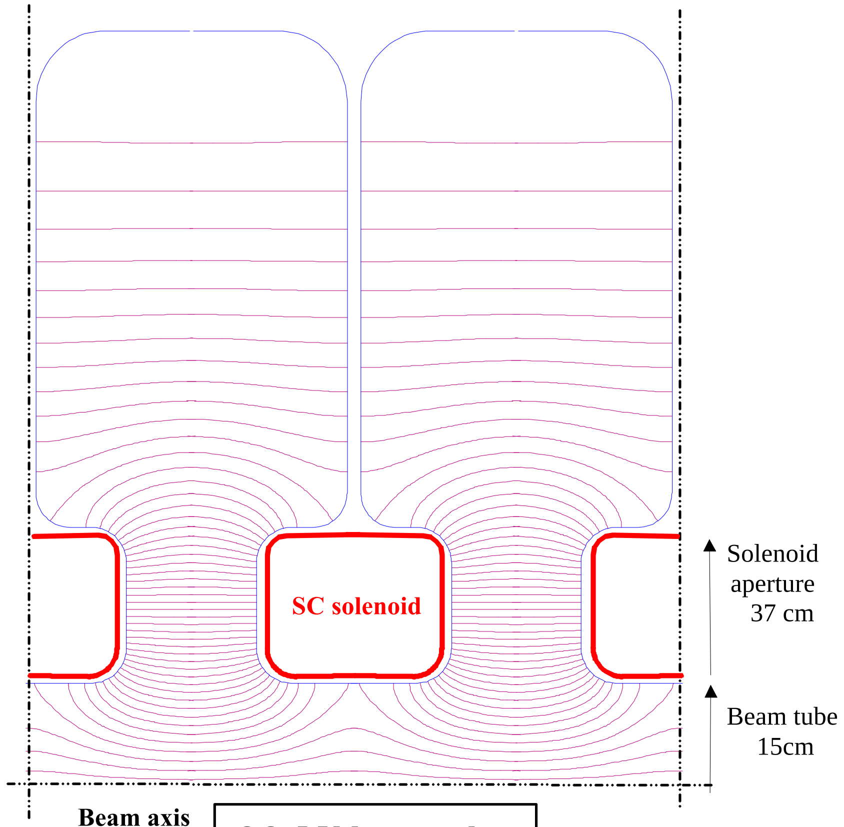
Cavities and solenoids for muon cooling channel

- Layout of the cooling channel,
- engineering constraints,
- new 44/88 MHz cavities,
- power efficiency,
- actual tests at CERN with 88 MHz cavity,
- solenoids for testcavity.

Previous scheme for 44/88 MHz cavities for cooling and acceleration

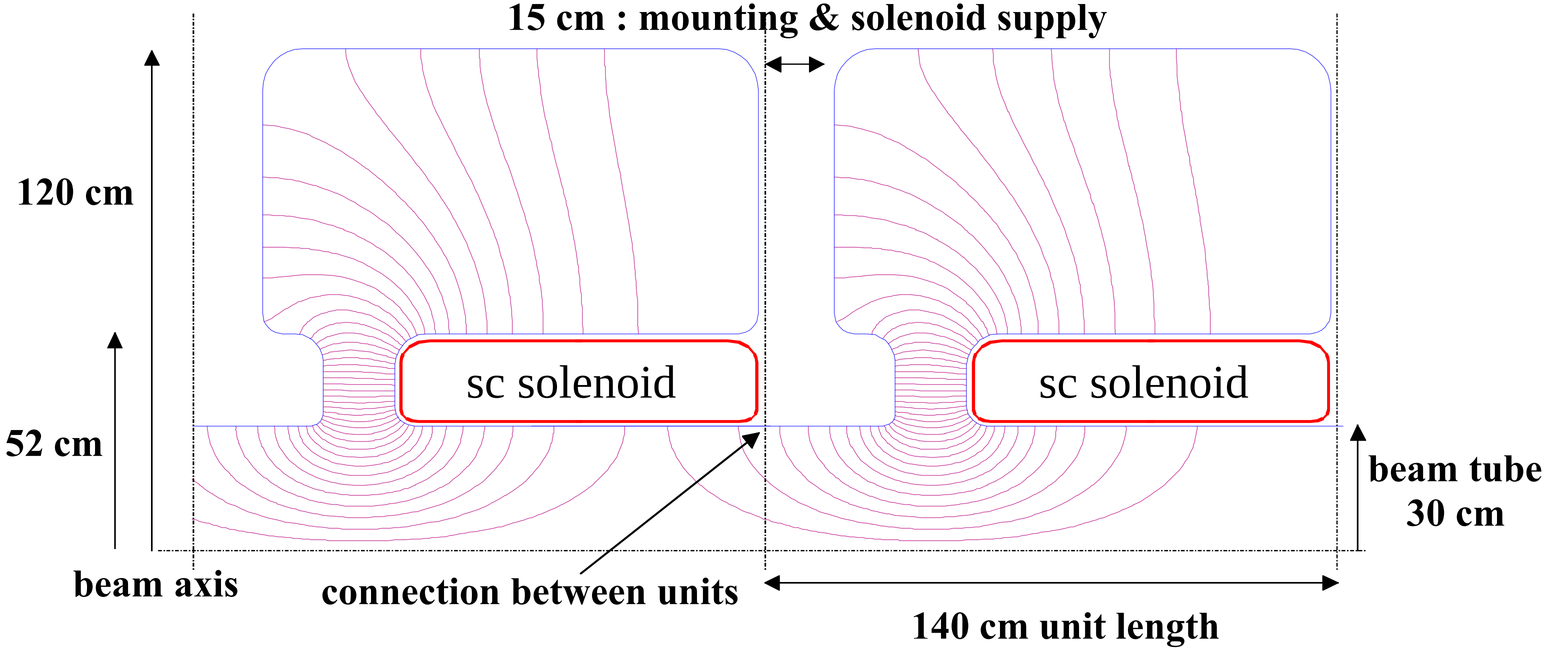
- Huge diameter: 3.3 m / 2.1 m,
- complicated construction,
- no access to solenoids,
- lousy efficiency.

E_0T	= 4 MV/m
Z_{TT}	= 10.8 MΩ/m
P_{PEAK}	= 0.74 MW/cavity
R/Q	= 60 Ω
T_{FILL}	= 164 µs
f_{REP}	= 75 Hz
P_{MEAN}	= 54 kW/m
Kilpatrick: 1.2	



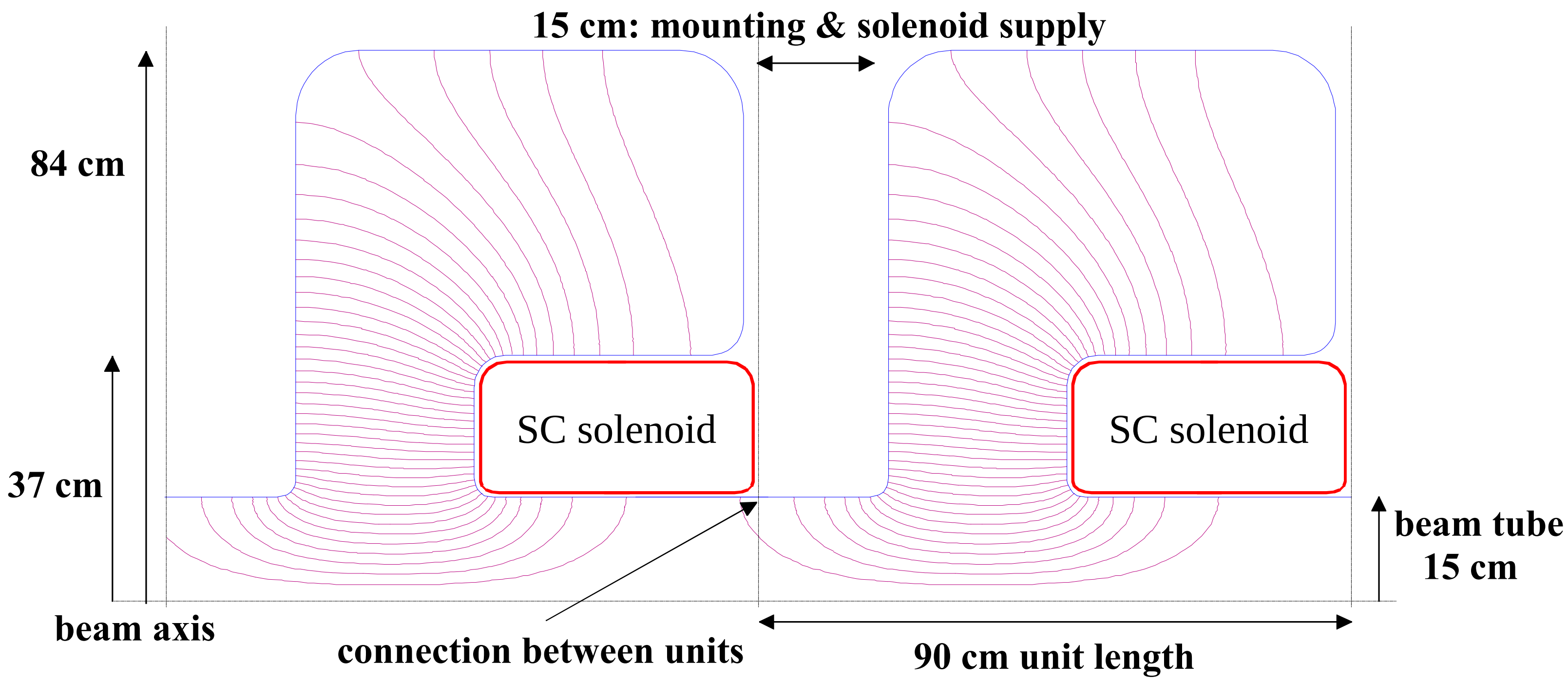
88 MHz cavity

Asymmetric 44 MHz cavities for muon capture and bunch rotation



E_0T	= 2 MV/m	τ	= 318 µs	solenoid: 88 x 20 cm
Z_{TT}	= 3.6 MΩ/m	P_{PEAK}	= 1.57 MW/cavity	Kilpatrick: 2.5
R/Q	= 114 Ω	P_{MEAN}	= 80 kW/m for 75 Hz repetition rate	

Asymmetric 88 MHz cavities for muon cooling and acceleration



E_0T	= 4 MV/m	τ	= 156 µs	solenoid: 40 x 20 cm
Z_{TT}	= 5 MΩ/m	P_{PEAK}	= 2.19 MW/cavity	Kilpatrick: 2.3
R/Q	= 137 Ω	P_{MEAN}	= 85 kW/m for 75 Hz repetition rate	

Power efficiency optimization

using $P_{mean} = P_{wall} \cdot 3t \cdot f_{rep}$ and

$$P_{wall} = \frac{V_0^2}{r_S}, t = \frac{Q}{p\, f_{cav.}}$$

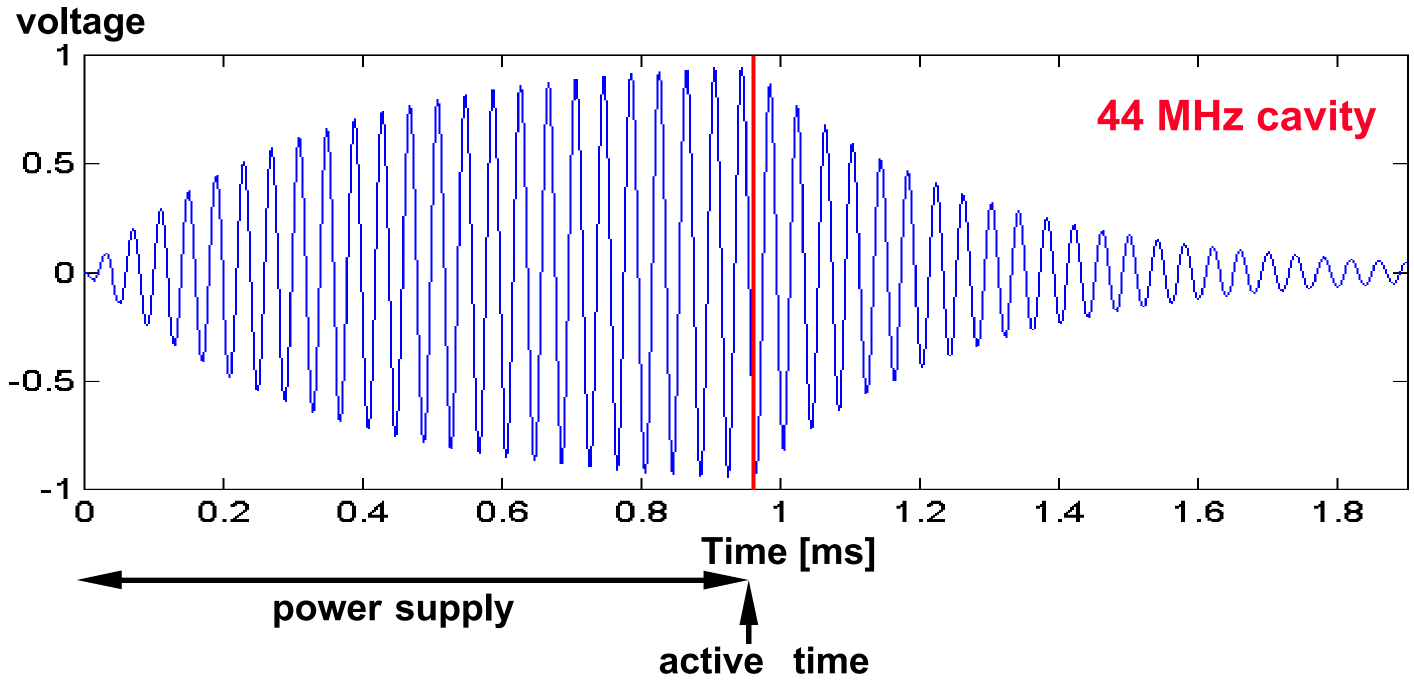
$$r = r_S \cdot T^2 = \frac{V_0^2}{P_{wall}} \cdot T^2$$

$$P_{mean} = 3\frac{V_0^2 T^2}{p} \cdot \left(\frac{f_{rep}}{f_{cav}}\right) \cdot \left(\frac{Q}{r}\right)$$

λ=6.8m@44MHz,
T>0.95

$$\left(\frac{r}{Q}\right) = \sqrt{\frac{L}{C}} \uparrow \Rightarrow L \uparrow, C \downarrow \Rightarrow \text{large gap, large volume}$$

Why is the efficiency still lousy?

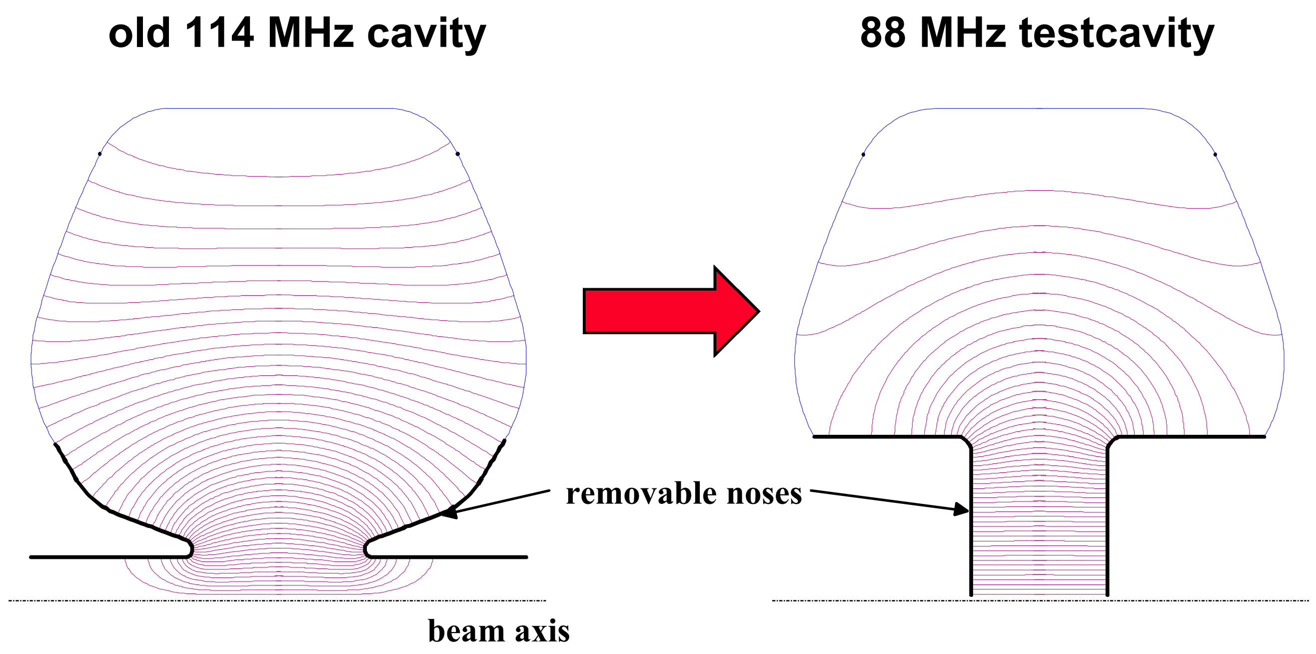


99.7% of the generator power is used to heat copper

Challenges:

- High gradient at low frequency (Kilpatrick: 2.3/2.5) ⇒ sparking,
- high magnetic fields penetrating the cavities ⇒ multipactor studies,
- large cavity dimensions for 44 MHz ⇒ mechanical stability,
- field emission induced by lost particles ⇒ cavity test with beam.

RF tests for 88 MHz cavity
- during this year -



1. Without solenoids, 2. with solenoids, 3. open gap?, 4. with beam?

Properties of 88 MHz testcavity

Cavity with closed gap:

E_0	= 4 MV/m
f_{rep}	= 1 Hz
r/Q	= 113 Ω
τ	= 180 µs
t_{pulse}	= 10.5 ms
P_{peak}	= 1.4 MW
P_{mean}	= 15 kW
Kilp.	= 2.3
gap	= 280 mm
length	= 1 m
diameter	= 1.77 m

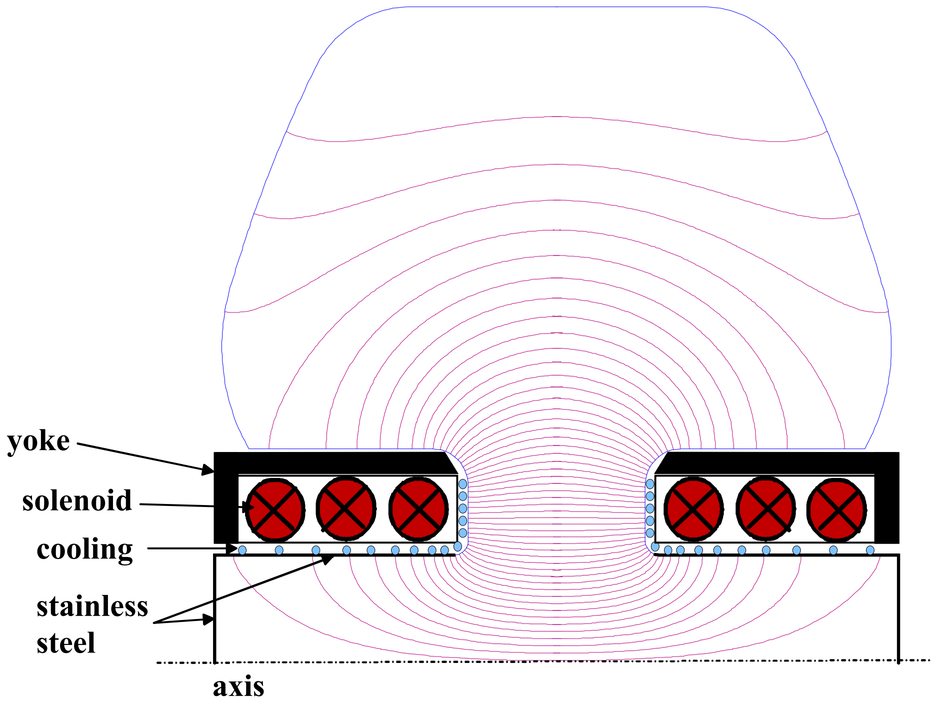
Cavity with open gap:

E_0	= 4 MV/m
f_{rep}	= 1 Hz
r/Q	= 107 Ω
τ	= 180 µs
t_{pulse}	= 10.5 ms
P_{peak}	= 1.5 MW
P_{mean}	= 16 kW
Kilp.	= 2.3
gap	= 260 mm
length	= 1 m
diameter	= 1.77 m

Solenoids for test cavity I

Normalconducting solenoids:

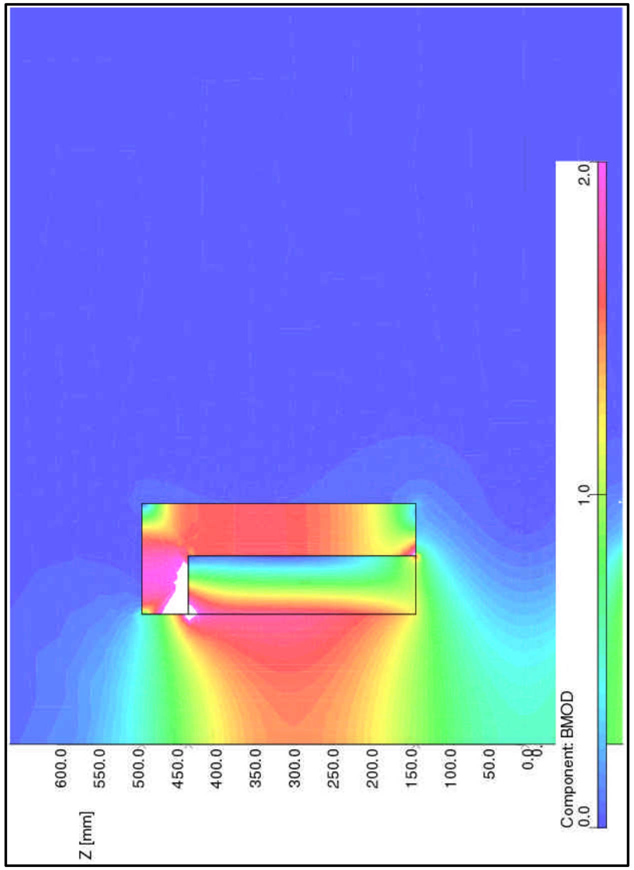
f_{pulse} = 50 Hz
f_{rep} = 1 Hz
B = 1 - 1.5 T
beam tubes: stainless steel to reduce induced currents

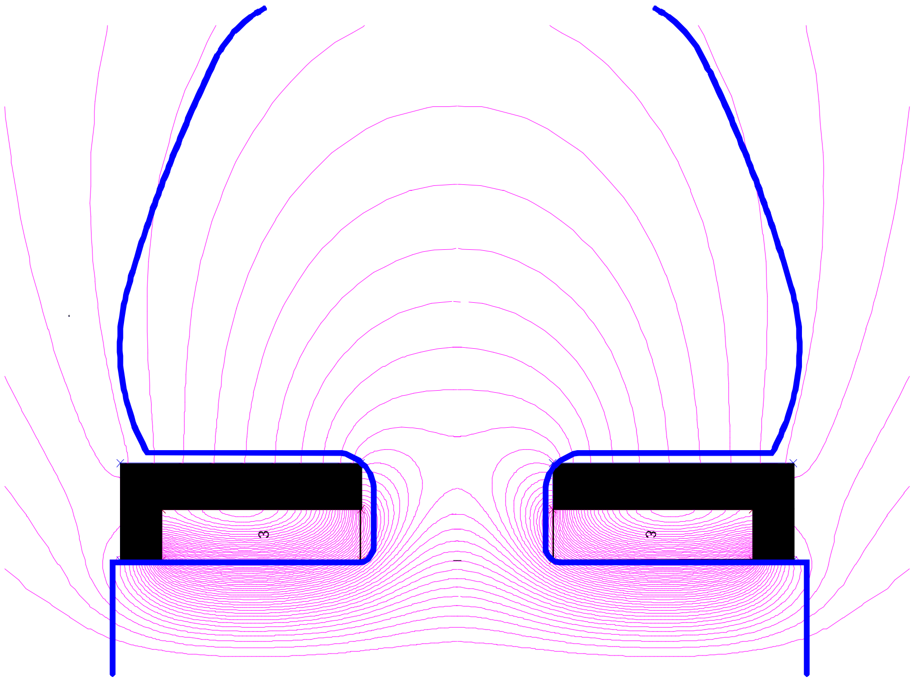


Superconducting solenoids:

DC field
B = 1 - 5 T
~ 0.5 MCHF per solenoid

Solenoids for test cavity II
- magnetic field pattern -





NC solenoid design with OPERA
- courtesy of M. Sassowsky -

Appendix I: power loss in beam tubes for pulsed magnets (1.5 T)

$$\frac{H_o}{H_i} = \cosh\left(\sqrt{i w m_0 k}\cdot t\right) + \frac{1}{2}\sqrt{i w m_0 k}\cdot r_z \cdot \sinh\left(\sqrt{i w m_0 k}\cdot t\right)$$

thickness: $t = 1\,mm$, tube radius: $r_z = 150\,mm$, $f_{pulse} = 50\,Hz$, $k_{copper} = 55e^6\,\frac{1}{\Omega m}$, $k_{steel} = 1.37e^6\,\frac{1}{\Omega m}$

$$\left|\frac{H_o}{H_i}\right|_{copper} = 1.917 \qquad \left|\frac{H_o}{H_i}\right|_{steel} = 1.00083$$

with

$$I' = \frac{I}{l_{tube}} = \frac{1.5T}{m_0}\left(1 - \left|\frac{H_i}{H_o}\right|\right) \qquad R_{tube} = \frac{2pr_z}{ktl_{tube}} \qquad P = \frac{1}{2}R_{tube}I^2$$

and 1% duty cycle

$$P_{copper} = 28\,\frac{kW}{m} \qquad P_{stainless\ steel} = 3.4\,\frac{W}{m}$$

Conclusions

- Mechanical assemblage is a problem,
- smaller cavities require bigger amplifiers and raise power consumption,
- 220 m of cooling channel require ~ 20 MW RF power (24 MW for the H^- linac),
- power consumption can be substantially reduced by: lower rep-rate, lower gradient, higher frequency
- multipactoring could become an issue, especially with beam,
- solenoids require detailed study and cost optimization.

→ **Engineering part of cooling channel is expensive but feasible**