Normal Conducting vs Superconducting Cavities

CERN Accelerator School (CAS)

High Power Hadron Machines

Bilbao, Spain

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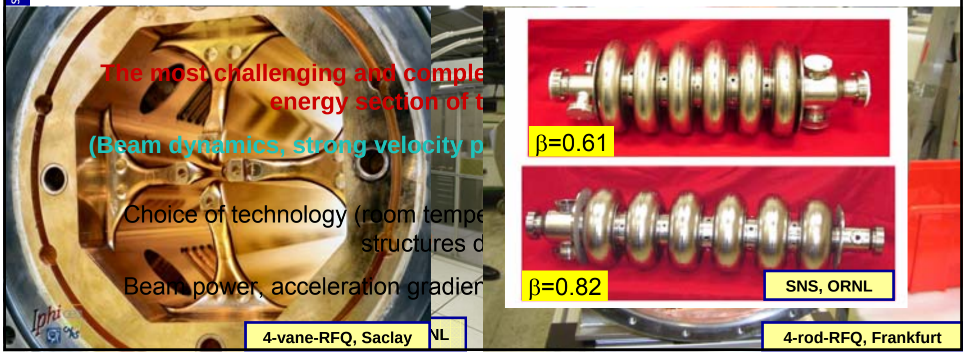
Outline

- Important RF parameters
- RF power and Grid power requirements
- NC and SC cavities: Design criteria
- Limitations of NC and SC cavities
- Case studies: FAIR p-Linac and cw SHE-Linac

High Power Hadronen-Linac

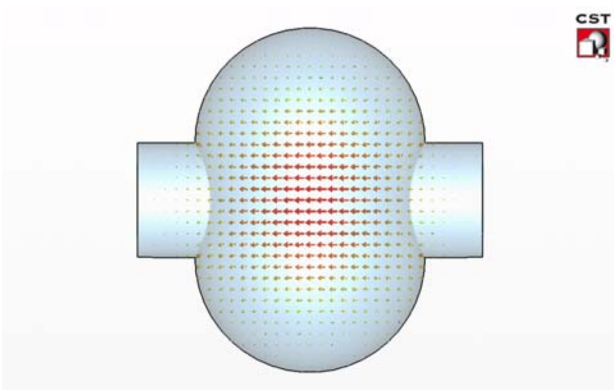
Typical Layout

ECR Ion Source	RFQ	DTL	superconducting elliptical cavities
~0.1 MeV	0.5-5 MeV	40-200 MeV	300-1000 MeV



RF Cavities

Purpose: Create time varying electric fields for acceleration

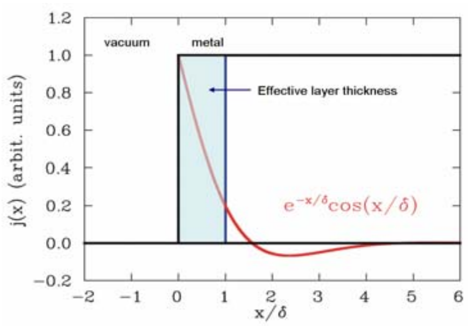


Normal Conducting: Surface Resistance R_s

Skin-Effect

$$\delta = \sqrt{\frac{2}{\sigma \mu_r \mu_0 \omega}}$$

δ≈3.5 µm
(350 MHz, Cu)



Surface Resistance R_s

$$R_s = \frac{1}{\sigma \delta}$$

$$R_s \propto \sqrt{\omega}$$

Superconducting: Surface Resistance R_s

DC fields → No losses
But: Cooper pairs have inertia → cannot follow RF fields immediately
Un-paired electrons feel electric field
→ RF losses proportional to density of un-paired electron n_n

$$n_n \propto \exp\left(-\frac{\Delta}{k_B T}\right)$$

Strong T-dependence (Boltzmann)

Surface Resistance for Niobium

$$R_{s,BCS} = 2 \cdot 10^{-4} \frac{1}{T} \left(\frac{f}{1.5}\right)^2 \exp\left(-\frac{17.67}{T}\right)$$

Surface Resistance Comparison NC-SC

Normal Conducting

$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0\omega}{2\sigma}}$$

→ 1-10 mΩ

Superconducting

$$R_s(BCS) = 2 \cdot 10^{-4}\,\frac{1}{T}\left(\frac{f}{1.5}\right)^2 \exp\left(-\frac{17.67}{T}\right)$$

→ 1-100 nΩ

Typically 5 Orders of magnitude lower Resistance

Power Consumption P_c

$$P_c = \frac{1}{2} R_s \int_S |\mathbf{H}|^2 \, dA$$

Power consumption of sc cavities significantly lower (factor 10^4-10^5)

$$P_c = \frac{U_a^2}{R_a} = \frac{U_a^2}{(R_a/Q_0)\,Q_0}$$

Impedance (R_a)

Geometrical Impedance (R_a/Q_0)

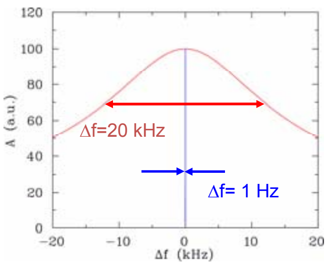
Q-value

$$Q_0 = \frac{\omega W}{P_c}$$

Ratio between stored Energy and cavity losses

$$Q_0 = \frac{f}{f_2 - f_1} = \frac{f}{\Delta f}$$

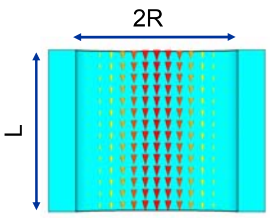
Width of resonance curve



Normal conducting: Q=10^3-10^5

Superconducting: Q=10^7-10^{11}

RF Parameter Comparison



Pillbox Cavity

Fundamental mode TM_{010}

f=1.5 GHz

L=10 cm

NC

$$\begin{aligned} E_a &= 10\ \mathrm{MV/m} \\ R_s &= 10\ \mathrm{m\Omega} \\ Q_0 &= 25500 \\ R_a &= 5 \cdot 10^6\ \Omega \\ P_c &= 198000\ \mathrm{W} \end{aligned}$$

SC

$$\begin{aligned} E_a &= 10\ \mathrm{MV/m} \\ R_s &= 20\ \mathrm{n\Omega} \\ Q_0 &= 1.3 \cdot 10^{10} \\ R_a &= 2.5 \cdot 10^{12}\ \Omega \\ P_c &= 0.4\ \mathrm{W} \end{aligned}$$

Power Consumption General Considerations

RF Power

↓

Gradient
Beam Current
Shunt Impedance

Plug Power

↓

Gradient
Beam Current
Shunt Impedance
Duty Factor
Efficiency

Power Consumption P_c

Without Beam, cw

Normal conducting

↓

U_a=3 MV
L=1 m
R_a/Q_0=2000 Ω
R_s=3.7 mΩ
$Q_0=2\cdot10^4$

↓

P_c=225000 W

$$P_c = \frac{U_a^2}{R_a} = \frac{U_a^2}{\left(\frac{R_a}{Q_0}\right) Q_0}$$

Superconducting

↓

U_a=3 MV
L=1 m
R_a/Q_0=2000 Ω
R_s=12.6 nΩ
$Q_0(BCS)=6\cdot10^9$

↓

P_c= 0.75 W

Power Consumption P_c

Power consumption of sc cavities significantly lower (factor 10^4-10^5)
BUT: Real life is more complicated

$$R_s = R_{BCS} + \underbrace{R_{magnet} + R_0}$$

Additional resistance (magnetic fields, material properties, surface preparation)

Superconducting → R_s=60 nΩ → P_c= 3.6 W

Efficiency of the cryogenic system

$$\eta = \left(\frac{4\ \mathrm{K}}{300\ \mathrm{K} - 4\ \mathrm{K}}\right) \cdot 0.25 \approx 0.003$$

Power Consumption (Plug Power P_{eff})

Without Beam, cw

Normal conducting → P_c=225000 W → (η = 0.6 (RF amplifier)) → P_{eff}=375000 W

Superconducting → P_c= 3.6 W → (15 W static losses) → P_{tot}= 18.6 W → (η = 0.003 (cryogenic system)) → P_{eff}= 6200 W

$$\frac{P_{nc}}{P_{sc}} \approx 60$$

Power Consumption (Plug Power P_{eff})

With 20 mA Beam, cw
P_{beam}=UI

Normal conducting	Superconducting
P_c=225000 W	P_{cryo}= 6200 W
P_{beam}=60000 W	P_{beam}= 60000 W
P_{eff}=475000 W	P_{eff}= 106200 W

η = 0.6 (RF amplifier)

$$\frac{P_{nc}}{P_{sc}} \approx 4.5$$

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Power Consumption (Plug Power P_{eff})

With 20 mA Beam
1% Duty Factor

Normal conducting	Superconducting
P_c=225000 W	P_{cryo}= 5000 W
P_{beam}=60000 W	P_{beam}= 60000 W
$P_{tot\ pulse}$=475000 W	$P_{tot\ pulse}$= 105000 W
P_{eff}=4750 W	P_{eff}= 6000 W

η = 0.6 (RF amplifier)

$$\frac{P_{nc}}{P_{sc}} \approx 0.8$$

Choice of Technology (NC-SC)

Normal Conducting	Superconducting
Low Energy	High Energy
High Beam Power	Low Beam Power
Low Duty Factor	High Duty Factor

„Systematic“ Investigation of Required Power

There is a large variety of parameters for the comparison of NC and SC cavities

Gradient E_a
Duty factor DF
Available RF structures at given β and energy
Beam current
Static losses (SC), R_s (SC)

NC and SC cavity comparison for β=0.1, β=0.2 and β=0.5

β=0.1: NC IH-cavity – SC CH-cavity
β=0.2: NC CH-cavity – SC CH-cavity
β=0.5: NC CH-cavity – SC elliptical cavity

„Systematic“ Investigation of Required Power

Several assumptions have been made:

Only RF power for field creation and acceleration is considered
→ No additional power due to optional overcoupling of SC cavities

No power of auxilliary systems considered (magnets, cable losses, …)

Duty factor of beam and RF is the equal

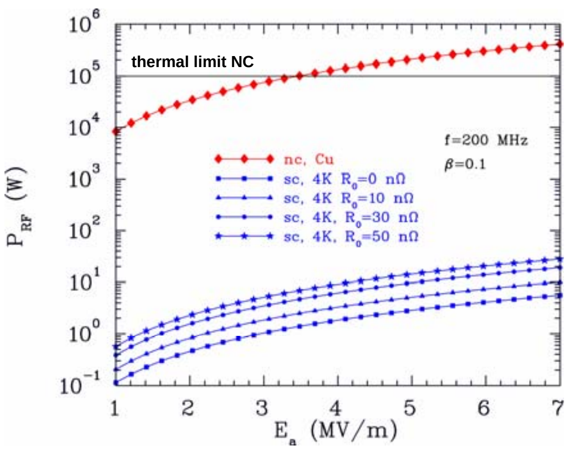
RF Losses (without beam) versus Gradient

RF structure length 1 m
β=0.1

NC IH-Cavity 200 MHz
Z_{eff}=120 MΩ/m

SC CH-Cavity
200 MHz

R/Q=2000 Ω
T=4.2 K
G=55 Ω



Normal Conducting versus Superconducting Cavities

RF Losses (without beam) versus Gradient

RF structure length 1 m
β=0.2

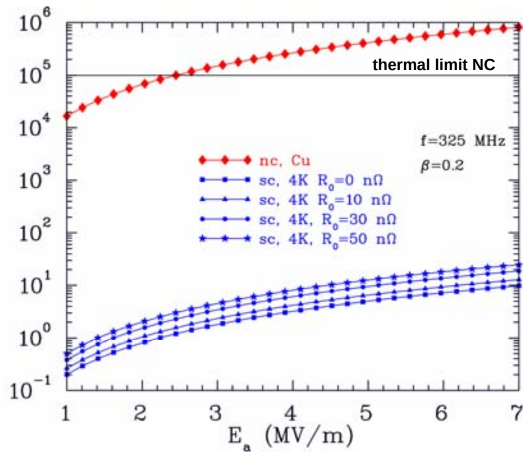
NC CH-Cavity 325 MHz

Z_{eff}=60 MΩ/m

SC CH-Cavity

325 MHz

R/Q=3000 Ω
T=4.2 K
G=55 Ω



Normal Conducting versus Superconducting Cavities

RF Losses (without beam) versus Gradient

RF structure length 1m
β=0.5

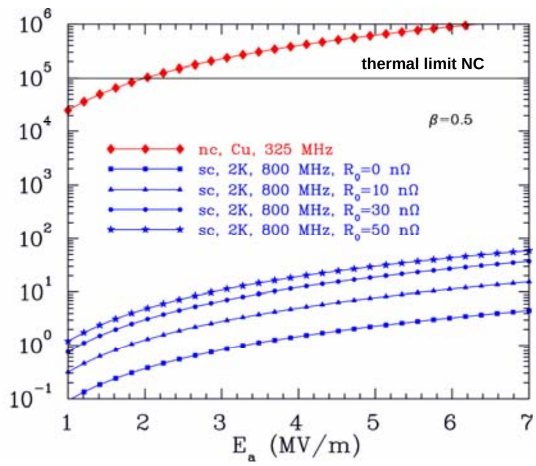
NC CH-Cavity 325 MHz

Z_{eff}=40 MΩ/m

SC elliptical Cavity

800 MHz

R/Q=330 Ω
T=2 K
G=126 Ω



Grid Power (without beam) versus Gradient

RF structure length 1 m
β=0.1
Duty Factor 100%

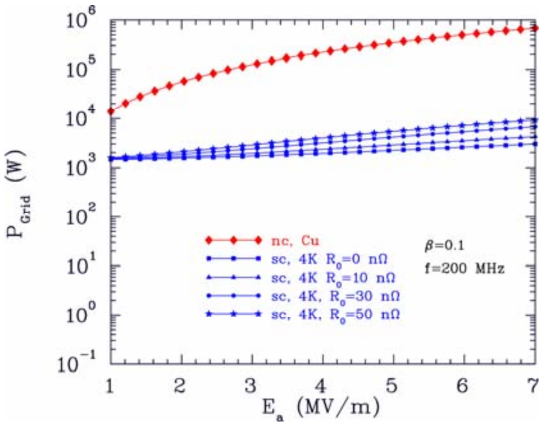
NC IH-Cavity 200 MHz

Z_{eff}=120 MΩ/m

SC CH-Cavity

200 MHz

Static losses 5 W
R/Q=2000 Ω
T=4.2 K
G=55 Ω



Grid Power (without beam) versus Gradient

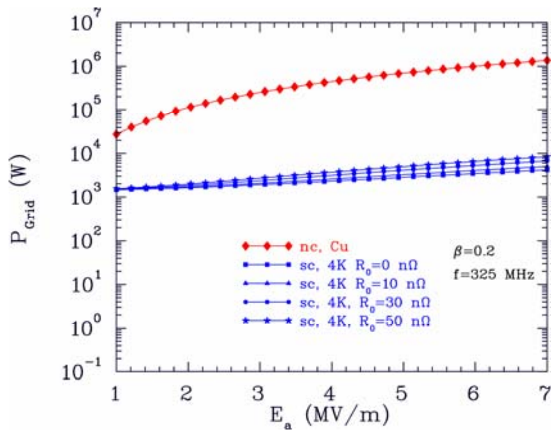
RF structure length 1 m
β=0.2
Duty Factor 100%

NC CH-Cavity 325 MHz

Z_{eff}=60 MΩ/m

SC CH-Cavity

325 MHz
Static losses 5 W
R/Q=3000 Ω
T=4.2 K
G=55 Ω



Grid Power (without beam) versus Gradient

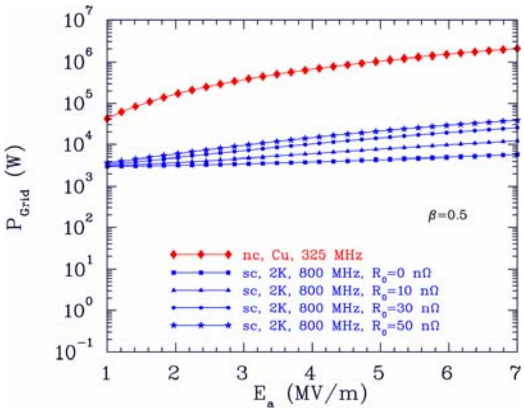
RF structure length 1m
β=0.5
Duty Factor 100%

NC CH-Cavity (325 MHz)

Z_{eff}=40 MΩ/m

SC elliptical Cavity
800 MHz

Static losses 5 W
R/Q=330 Ω
T=2 K
G=126 Ω



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Normal Conducting versus Superconducting Cavities

RF Power with Beam versus Beam Current

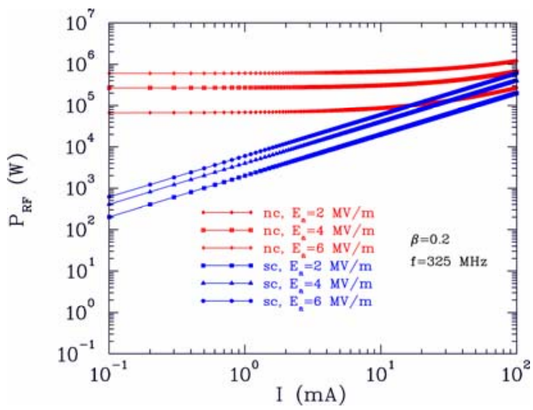
RF structure length 1 m
β=0.2

NC CH-Cavity 325 MHz

Z_{eff}=60 MΩ/m

SC CH-Cavity

325 MHz
R/Q=3000 Ω
T=4.2 K
G=55 Ω



Grid Power with Beam versus Beam Current

RF structure length 1 m
β=0.2
E_a=4 MV/m

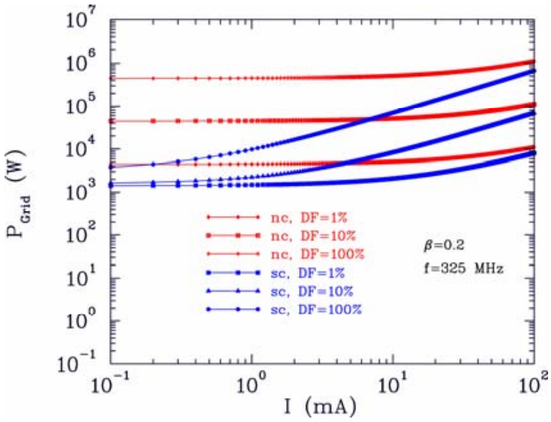
NC CH-Cavity 325 MHz

Z_{eff}=60 MΩ/m

SC CH-Cavity

325 MHz

Static losses 5 W
R/Q=3000 Ω
T=4.2 K
G=55 Ω



Grid Power without Beam versus Duty Factor

RF structure length 1 m
β=0.2
E_a=4 MV/m

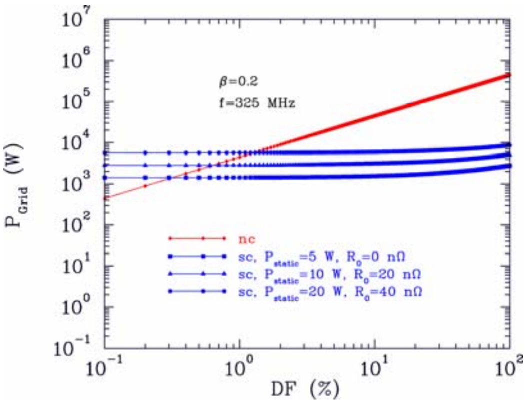
NC CH-Cavity 325 MHz

Z_{eff}=60 MΩ/m

SC CH-Cavity

325 MHz

R/Q=3000 Ω
T=4.2 K
G=55 Ω



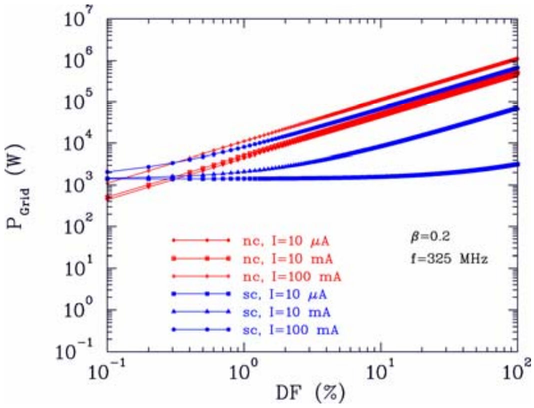
Grid Power with Beam versus Duty Factor

RF structure length 1 m
β=0.2
E_a=4 MV/m

NC CH-Cavity 325 MHz
Z_{eff}=60 MΩ/m

SC CH-Cavity
325 MHz

R/Q=3000 Ω
T=4.2 K
G=55 Ω

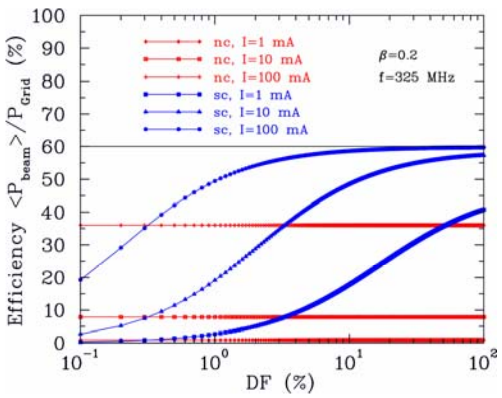


Efficiency P_{Beam}/P_{Grid} versus Duty Factor

RF structure length 1 m
β=0.2
E_a=4 MV/m

NC CH-Cavity 325 MHz
Z_{eff}=60 MΩ/m

SC CH-Cavity
325 MHz
P_{static}=5 W
R/Q=3000 Ω
T=4.2 K
G=55 Ω



Efficiency P_{Beam}/P_{Grid} versus Beam Current

RF structure length 1 m
β=0.2
E_a=4 MV/m

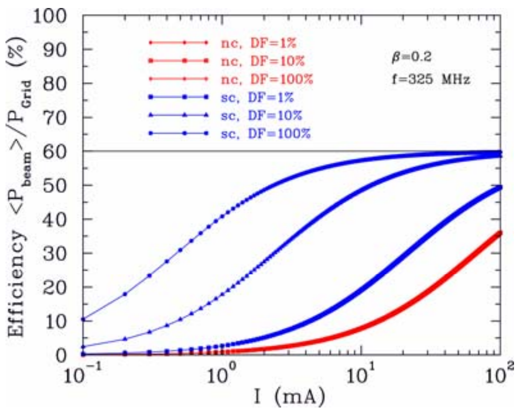
NC CH-Cavity 325 MHz

Z_{eff}=60 MΩ/m

SC CH-Cavity

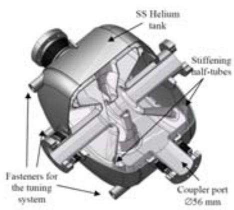
325 MHz

P_{static}=5 W
R/Q=3000 Ω
T=4.2 K
G=55 Ω



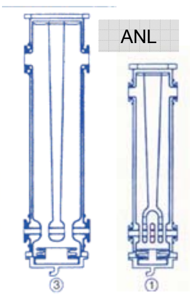
Superconducting Low and Medium Energy Cavities

INFN Legnaro

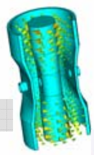


IPN, Orsay

ANL



ANL



MSU

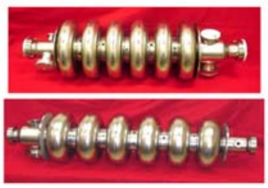
ANL

IAP Frankfurt

ANL

IPN, Orsay

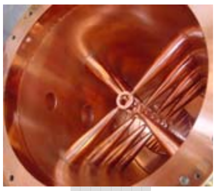
LANL



SNS

Room Temperature Low and Medium Energy Cavities

IAP Frankfurt



IAP

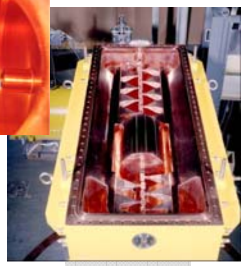
GSI

INFN Legnaro

CERN

MPI-HD

FNAL



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Design Criteria

Normal conducting

- Optimization of shunt impedance
- Optimization of cooling
- Optimization of field distribution

Superconducting

- Minimization of electric peak fields
- Minimization of magnetic peak fields
- Multipacting
- Mechanical issues

General

Cost minimization
Reliability

Design Criteria SC Cavities and Limitations

- Thermal breakdown of superconductivity
- Field emission
- Multipacting
- Lorentz Force Detuning
- Mechanical issues
- Fast frequency tuning

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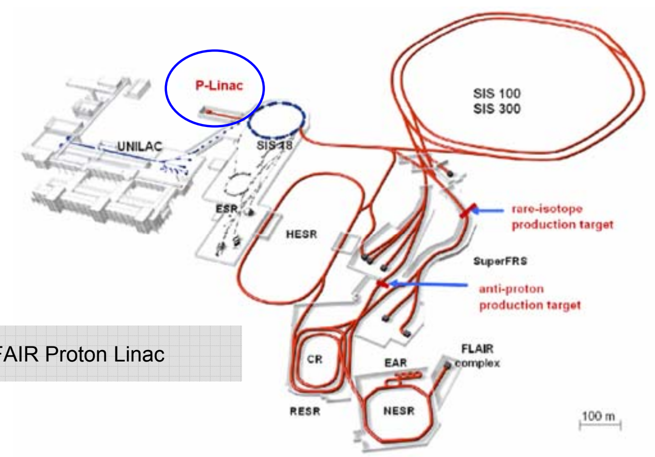
Normal Conducting versus Superconducting Cavities

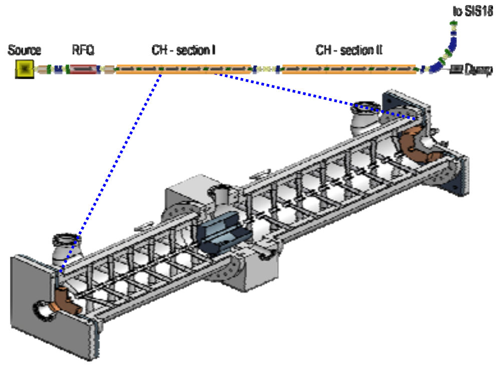
Case Studies

Only RF cavities are considered, no magnets, water cooling etc.



FAIR Proton Linac

FAIR Proton Linac

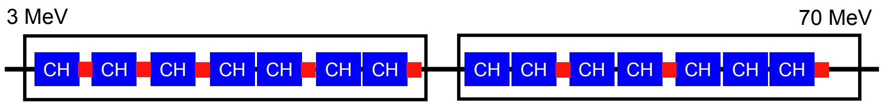


Particles	Protons	---
Frequency	325	MHz
Energy	70	MeV
Current	70	mA
RF Structure	CCH-DTL	---
Length	25	m
RF Pulse	200	µs
Repetion Rate	4	Hz
Duty Factor	0.08	%
Klystron	3	MW
No. Klystrons	6	---
Operation	NC	---

RF power (average)=8 kW

→ P_{eff}=14 kW

FAIR Proton Linac (if superconducting)



RF Structure	SC CH-DTL	---
Gradient	5	MV/m
Length	25	m
RF Pulse	200	µs
Repetion Rate	4	Hz
Duty Factor	0.08	%
Klystron	500	kW
No. Klystrons	14	---
Operation	SC	---

Assumption: P_{static}=10 W/m

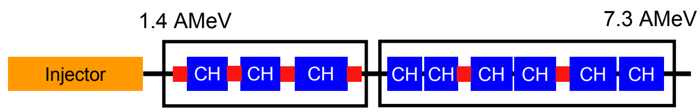
Heat load cryo system: 250 W @ 4K

→ P_{eff}=85 kW

Much more expensive:

Cryogenic system, cavities, Klystrons

CW Heavy-Ion SHE-Linac at GSI



Heat load cryo system: 500 W @ 4K

→ P_{eff}=200 kW

RF power (plug): 75 kW

Total: 275 kW

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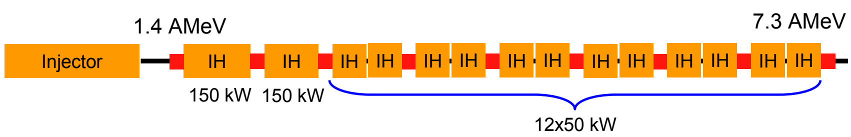
Ds
(281)

Particles	Heavy ions	---
Frequency	217	MHz
Gradient	5	MV/m
Energy	7.3	AMeV
Current	200	µA
RF Structure	SC CH-DTL	---
Length	12	m
Duty Factor	100	%
RF Driver	5	kW
No. RF Driver	9	---
Operation	SC	---

S. Minaev et. al, Phys. Rev. ST Accel. Beams, **12**, 120101 (2009)

CW Heavy-Ion SHE-Linac at GSI (if NC)



RF power: 750 kW

Plug power: 1250 kW

Superconducting version:

→ Savings more than 6 Mio kWh/a

Particles	Heavy ions	---
Frequency	217	MHz
Gradient	1.8-3.0	MV/m
Energy	7.3	AMeV
Current	200	µA
RF Structure	NC IH-DTL	---
Length	25	m
Duty Factor	100	%
RF Driver	40-150	kW
No. RF Driver	14	---
Operation	NC	---

Transition Energy NC-SC

There are several linac projects under design, construction or comissioning

What is the typical transition energy between room temperature and superconducting cavities?

Project	Particles	Current (pulse)	Transition energy	Duty factor	Final energy
SNS	Protons	38 mA	180 MeV	6%	1000 MeV
SARAF	Deuterons	2 mA	1.5 AMeV	100%	20 AMeV
SPIRAL-2	Deuterons	5 mA	1.5 AMeV	100%	20 AMeV
FRIB	Heavy Ions	0.3 mA	0.3 AMeV	100%	200 AMeV
LINAC-4/SPL	Protons	80 mA	160(180) MeV	0.08%	4000 MeV
Myrrha	Protons	4 mA	3.5 MeV	100%	600 MeV
GSI cw Linac	Heavy Ions	0.2 mA	1.4 AMeV	100%	7.3 AMeV
IFMIF	Deuterons	125 mA	2.5 AMeV	100%	20 AMeV

The higher the duty cycle the lower the transition energy!!

Summary

NC Cavities

+ Less infrastructure required
+ Simpler technology (if pulsed)
+ Simpler tuning (f and field)

- Higher RF power
- Expensive Amplifiers
- Thermal problems (if high DF)
- Lower gradients (if high DF)

SC Cavities

+ No thermal problems
+ Stable operation
+ Less RF Power
+ Smaller amplifiers
+ Well suited for cw operation
+ Larger aperture

- Less tolerant against beam loss
- Cryogenic system required
- Complicated cavity fabrication
- Sensitive cavities