High Current Linacs

U. Ratzinger

Institute for Applied Physics, J.W.Goethe-University Frankfurt

Haereus Workshop
Bad Honneff
Oct 15’th - 19’th, 2012

Outline

- Linac characterization
- Current limiting parameters
- SC versus RT technology, duty factor
- Hybrid and coupled cavities
- Some linac projects
- Beam losses, activation studies

GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN

Linac Characterization

Linear accelerators give the highest acceleration rate.

Electrostatic beam formation and acceleration by rf cavities

	→	
10 MHz		10 GHz
1 MV/m		25 MV/m
cw operation		pulsed s.c. or r.t.
β ≥ 0.001		β ≈ 1

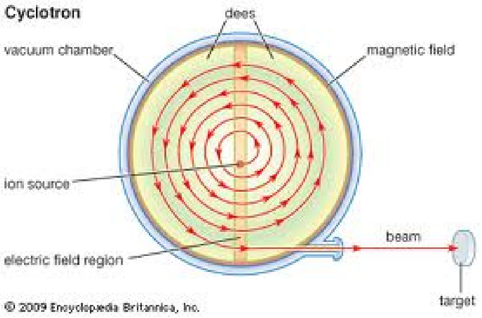
Disadvantages of Linacs:

-One dimensional array makes problems in the acquisition of a suited building site, length proportional to end energy

-Very large and expensive rf amplifier installations needed

Linac Characterization

All other accelerators use magnetic bending, taking most of the available space for transverse acceleration.

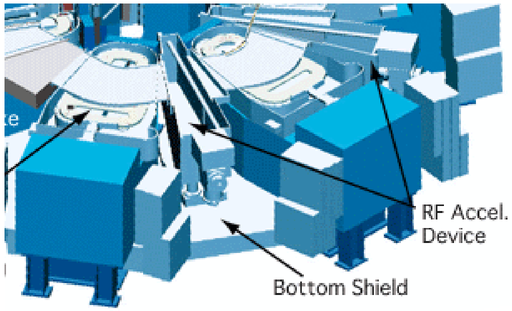


Comparison to cyclotron:

'Spiral' course, neighboured traces separated by several mm to several cm.

Cyclotron advantages:

- CW beam operation possible
- Small transverse dimensions



RIKEN SSC: K=2500, 7800 t, 18.4 m diam.

Disadvantages of Cyclotrons:

- Limited beam current due to injection, extraction, orbit separation, activation
- the compact setup hinders fast access and service of some key components

Linac Characterization

Comparison to synchrotron:

Closed orbit, variable rf frequency, voltage and magnetic field levels

Synchrotron advantages:

- High beam energies can be reached at relatively low investment costs
- Direct access to all components in the ring (after activation levels were checked)

Disadvantages of Synchrotrons:

- Very high pulsed beam intensities to be handled as the beam duty factor is very poor (fast extraction assumed for high current applications)
- Extremely complicated scenarios of transverse and longitudinal beam resonance crossings during one synchrotron cycle.

Linac Characterization

Consequence:

Linacs are the only choice above a certain level of time averaged or pulsed beam current request.

But it is not fixed, where these limits are, and they are depending on the state of the art in a manifold of technologies, like:

RF amplifiers, RF resonators, surface treatment and analysis

Cryotechnology, room temperature cooling technique

Magnet and vacuum technology

Beam diagnostics, alignment concepts

Ion production and beam formation

New developments like laser acceleration, plasma wake field acceleraion

Linac Characterization

What can be done to increase the current and energy limits of linacs?

1.Higher acceleration field

2.Improved rf amplifier technology

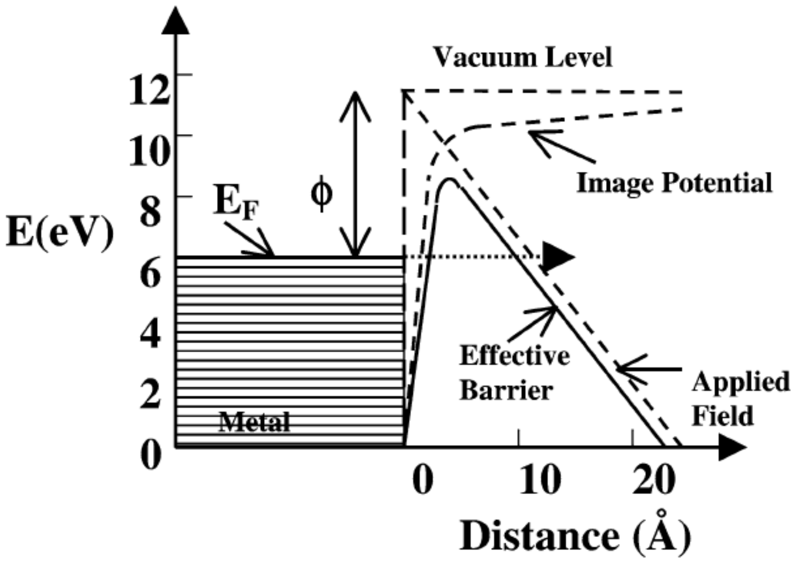
2.Efficient transverse focusing

3.Adequate beam dynamics and simulations for beam loss reduction

These topics will be discussed now

Current limiting parameters

1. Higher acceleration field



Fowler-Nordheim eq. for rf-operation:

$$d(\ln(I_F / E^{2.5}) / d(1/E) = -k/\beta \quad ;$$

$I_F =$ field emission current; $E =$ electric field;

$k = f(\Phi)$; material dependent

$\beta =$ field enhancement factor;

$E_F = \beta \cdot E$;

$E = E_{surf}$ for ideal surfaces

Typical β-range: 100 - 1000

Current limiting parameters

Aiming for high acceleration field

Kilpatrick criterion for the limiting electric field $E = V/g$, gap width g

$$f = 1.64\,E^2 \cdot e^{-\frac{8.5}{E}} \quad ; \qquad E\,/\,MV/m \quad ; \quad f\,/\,MHz$$

f / MHz	E / MV/m
7.5	5
70	10
429	20
2122	40
9438	80
15063	100
22001	120
30250	140

GSI-HSI, 36 MHz
too pessimistic

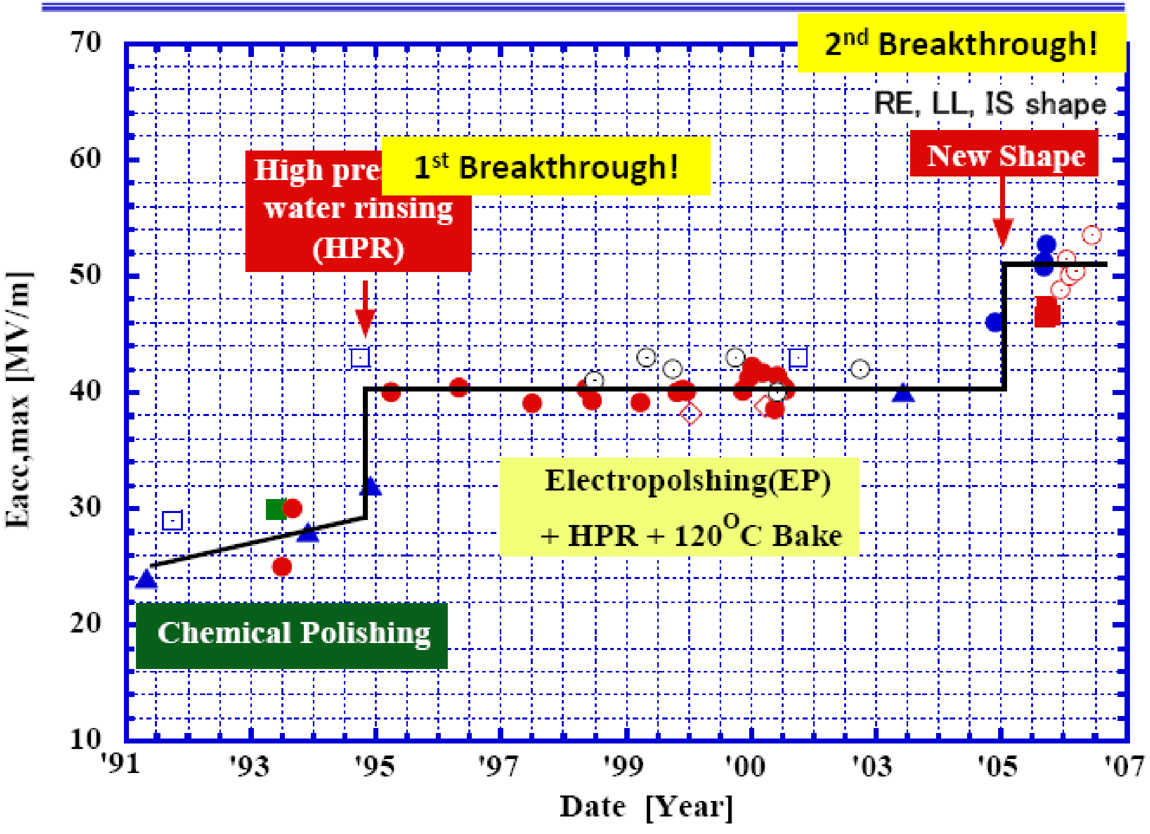
Fit to experiments

DESY-Tesla, 1.3 GHz
SLAC

too optimistic
CERN CLIC-TF

Current limiting parameters

DESY, TESLA - cavity



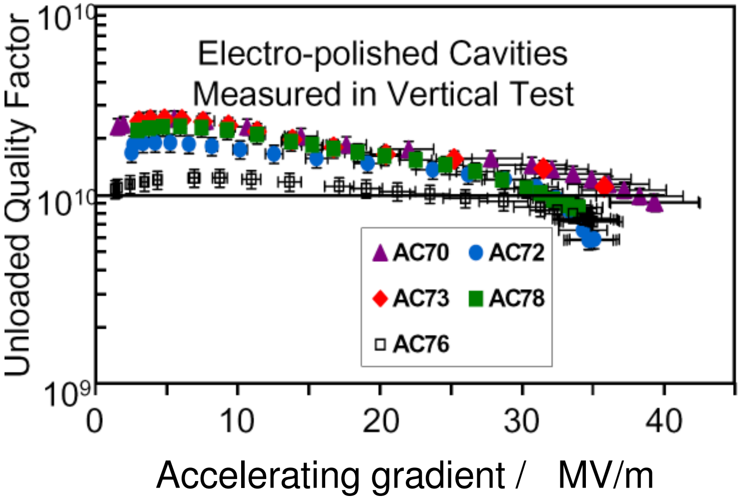
K.Saito IPAC2012 Talk

Tesla – type cavities

50 MV/m
at 1.3 GHz, 2K!
Critical magn.
field would allow
up to 57 MV/m!

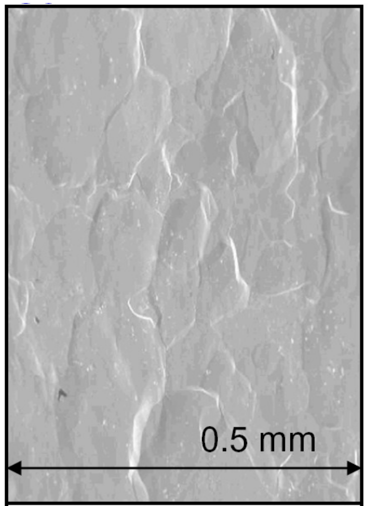
Current limiting parameters

Aiming for high acceleration field, surface preparation

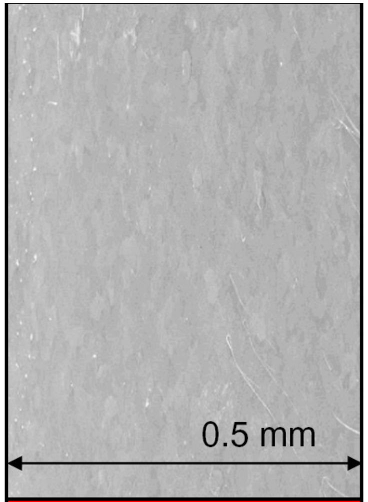


Achieved Q/E curves for Tesla cavities at DESY, D.Reschke et al.

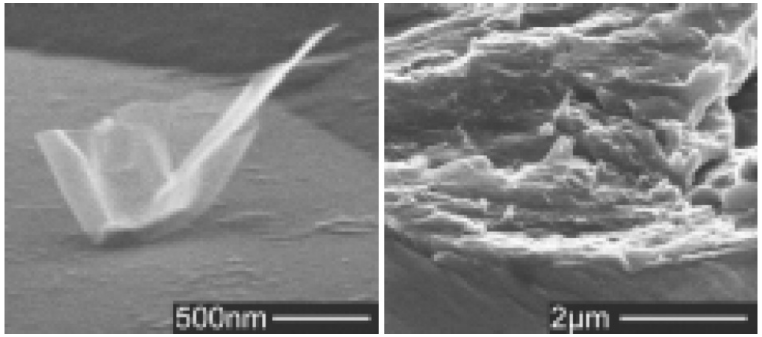
At ~ 50 MV/m the magnetic field limit of Nb (~ 200 mT) is reached for the TESLA type cavity.



BCP Surface
(1µm roughness)

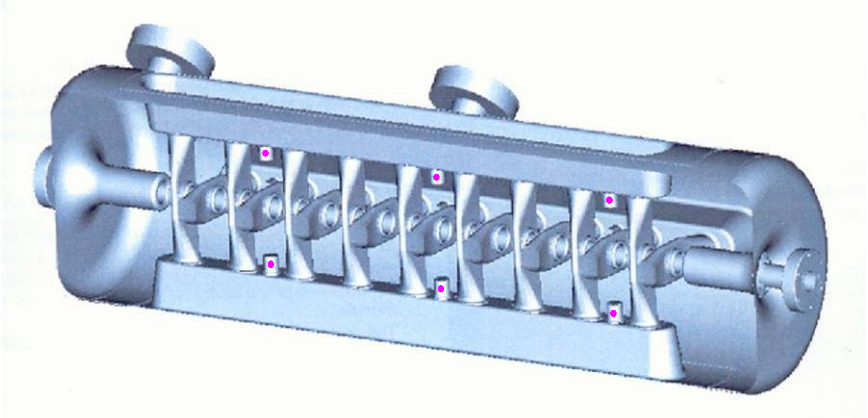


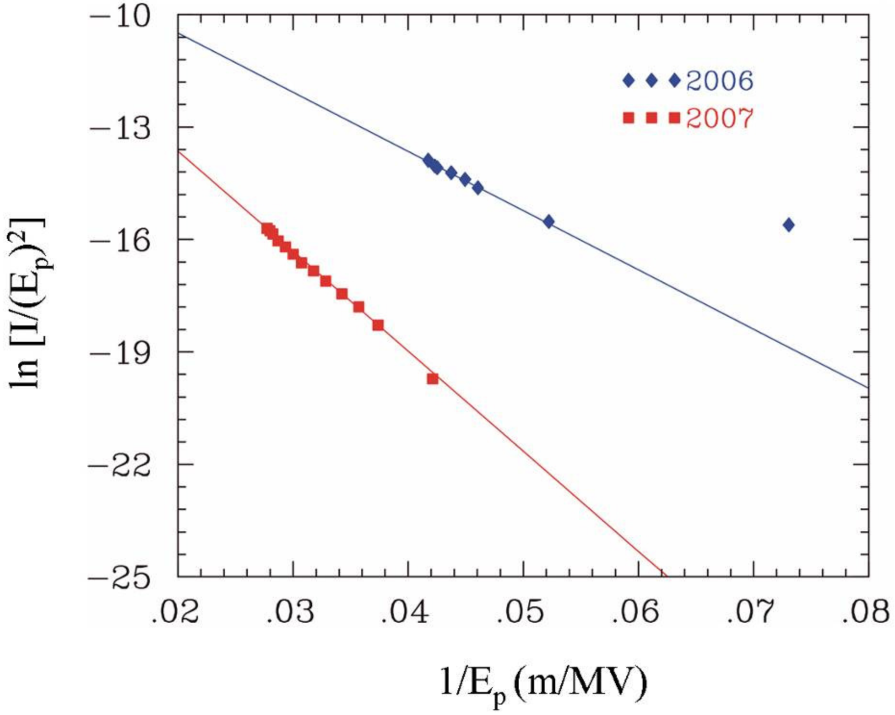
EP Surface
(0.1µm roughness)



Current limiting parameters

S.C. low energy structure development at IAP Frankfurt, 4 K



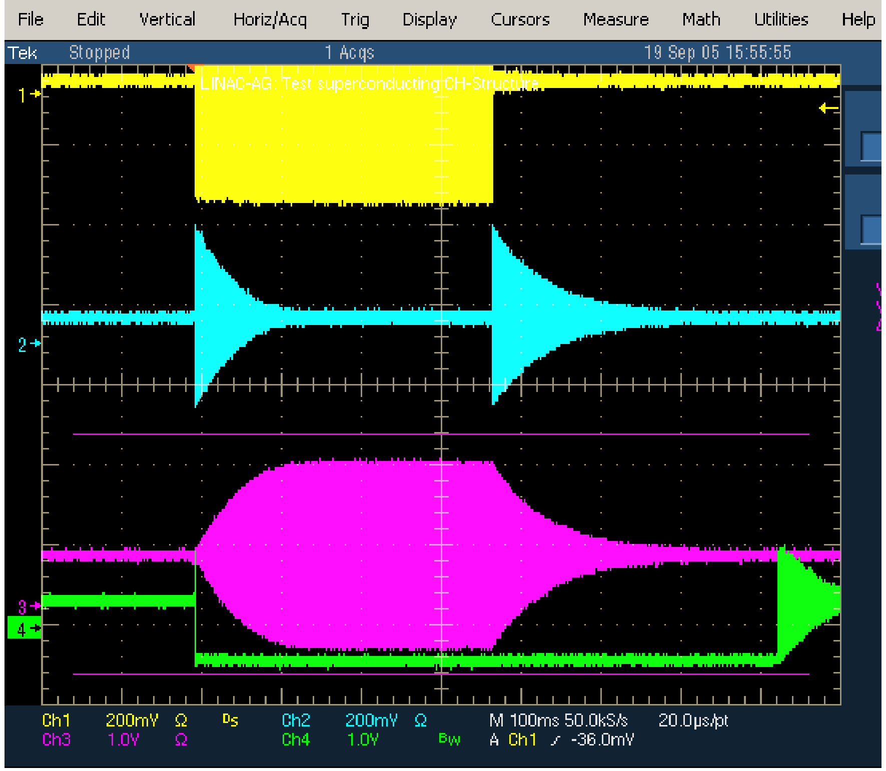


$\beta_{2006} = 350$
$\beta_{2007} = 200$

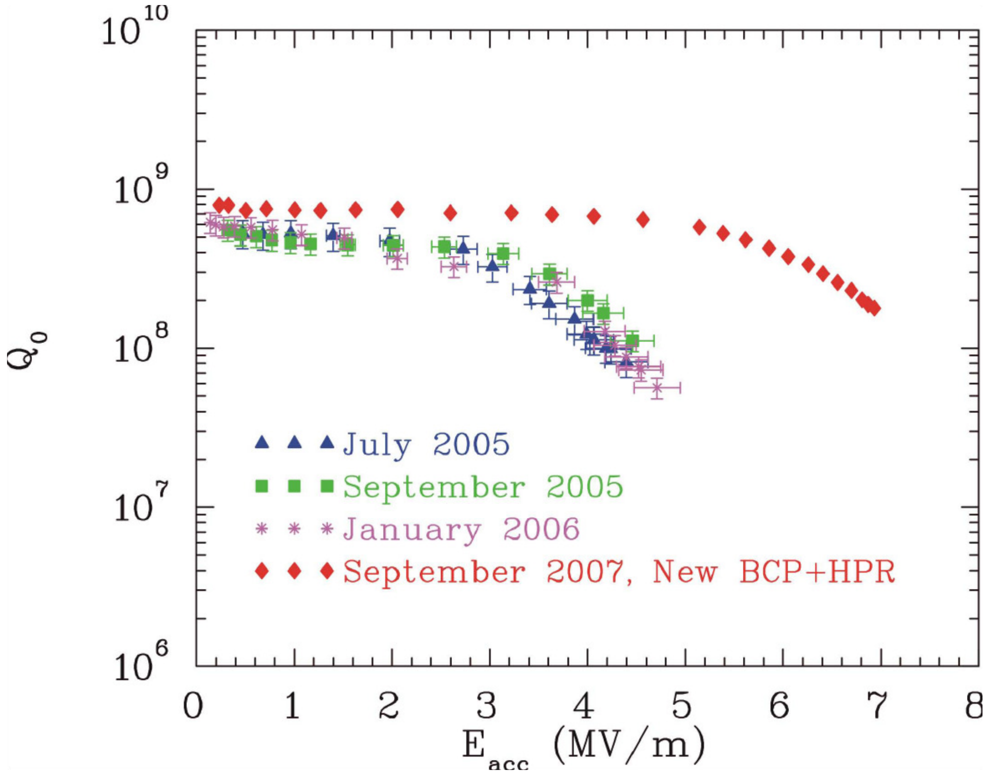
325 MHz, 4 K, 10 % speed of light

Current limiting parameters

Superconducting CH Cavity Development at IAP



Incoupled (yellow), reflected (blue) and outcoupled (pink) rf signal; 100 ms per div.



Quality factor against effective field gradient.

Current limiting parameters

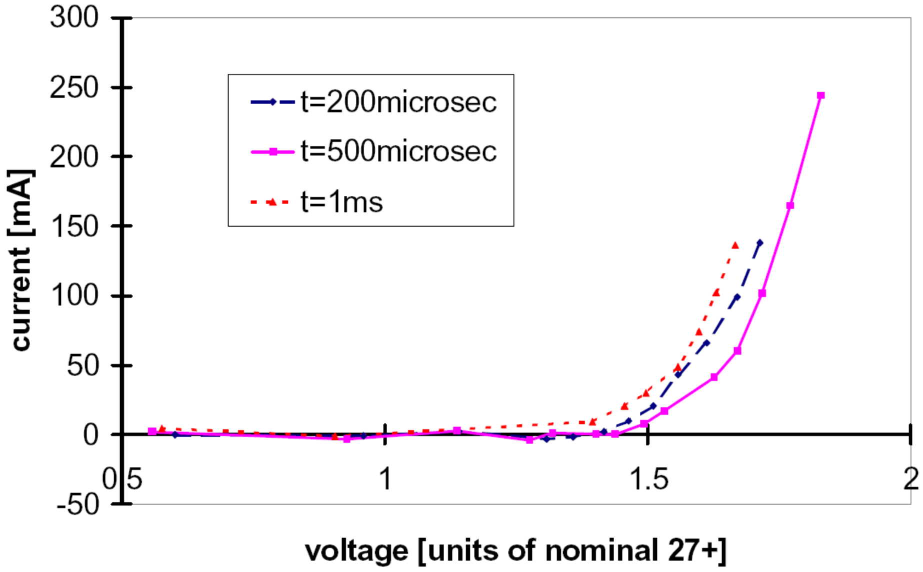
CERN Linac 3, design: 33 MV voltage gain along 8 m beam line

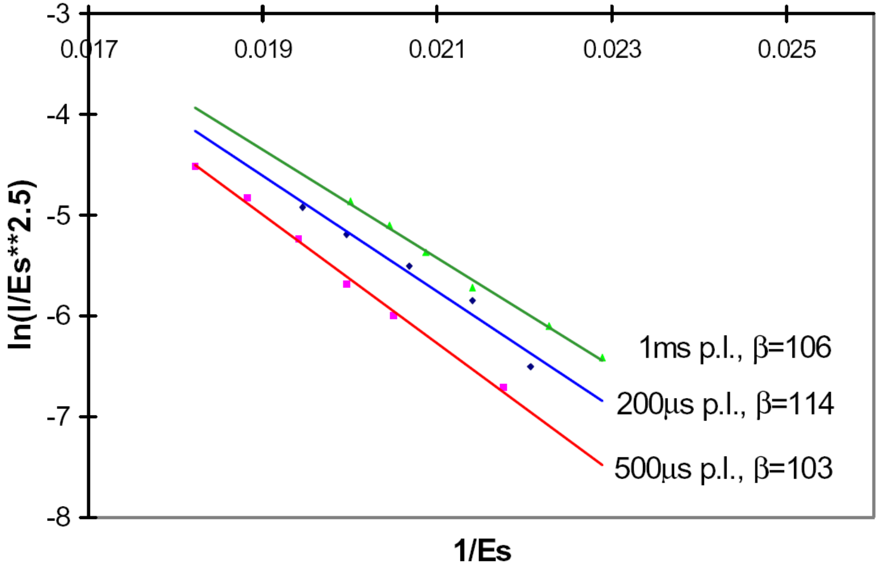
101 / 202 MHz combination, in operation since 1994.

Current limiting parameters

High power tests on CERN Linac 3, IH-Tank 2

Surface fields up to 54 MV/m, eff. acceleration up to 10.7 MV/m

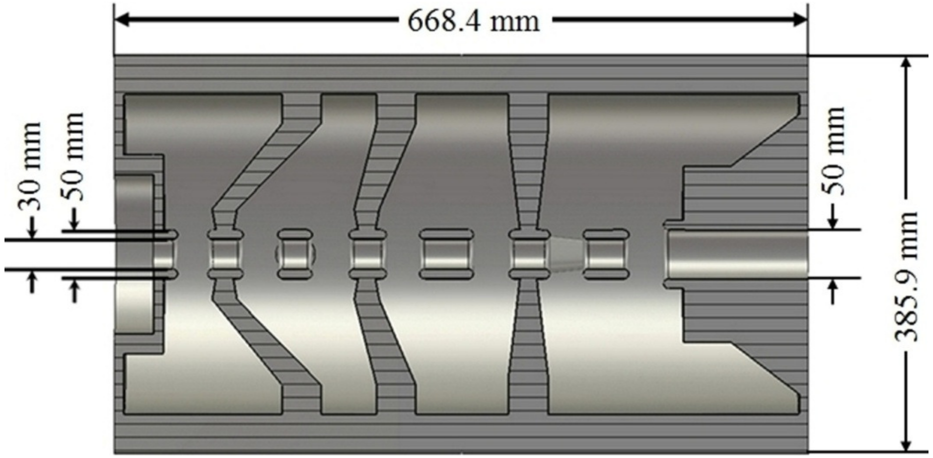




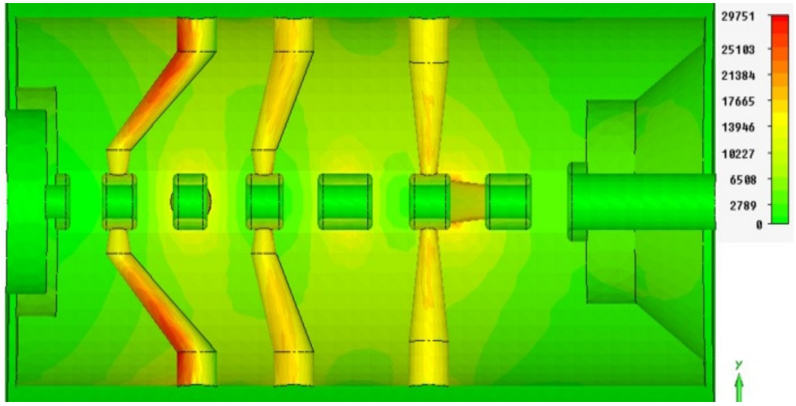
Q_0

Current limiting parameters

New BMBF -project at IAP Frankfurt: Layout , construction, surface treatment and rf power tests on a 325 MHz, r.t. CH - cavity

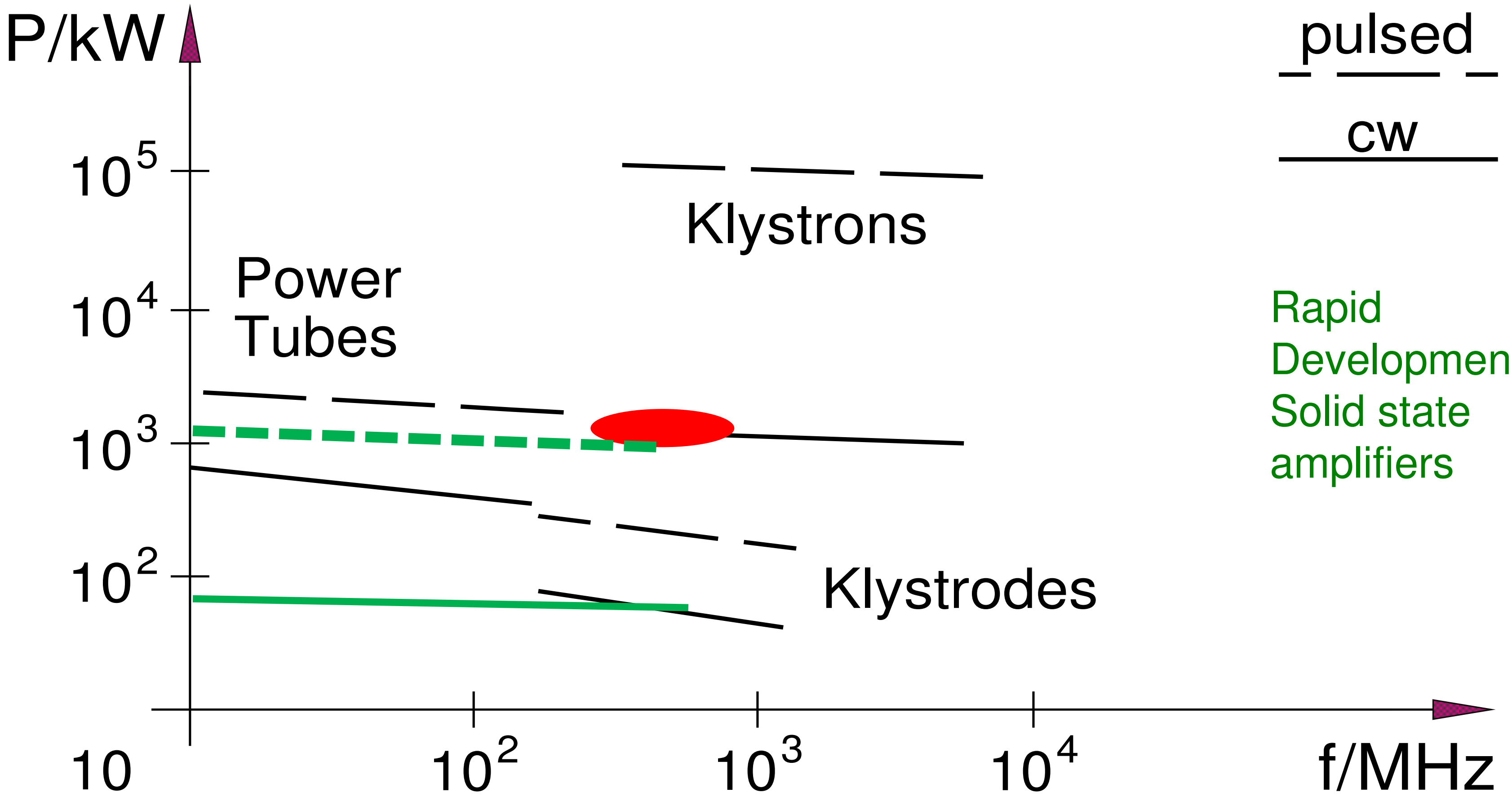


Number of Gaps	7
Frequency (MHz)	325.2
Energy Range (MeV)	10.05 – 16.09
Power Loss (MW)	1.92
– value	13289
Effective Shunt impedance (MΩ/m)	45.7
Accelerating Field Gradient (MV/m)	12.6
Beam Aperture (mm)	30
Outer Drift Tube Diameter (mm)	50
Total Length (mm)	668.4



Surface current distribution

Improved rf amplifier technology



Rapid Development: Solid state amplifiers

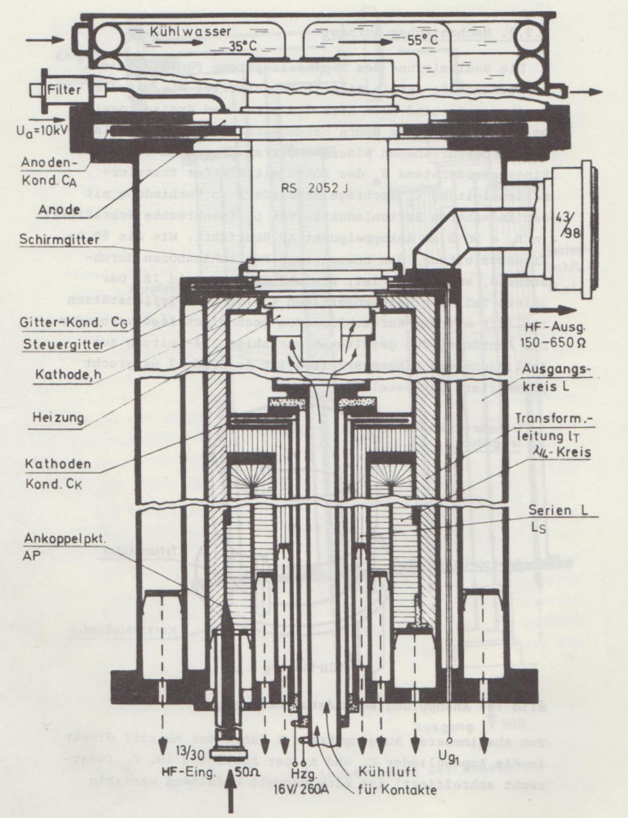
Improved rf amplifier technology

Tube driven cavity amplifiers
10 MHz to 300 MHz

Problems:

- Shrinking market because of revolution in communication technology
- power tube logistics, delivery guarantees, quality control

This is affecting heavy ion facilities mainly.



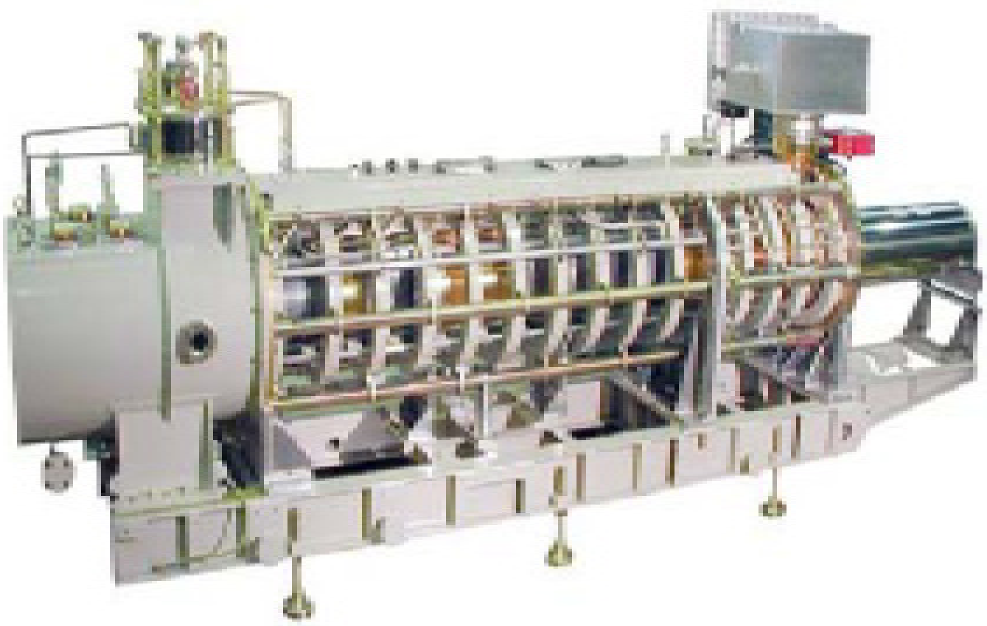
Improved rf amplifier technology

Power klystron technology pushed by electron machines first (SLAC)
Meanwhile frequencies down to 325 MHz are well established.

Advantage: - Long lifetime (about 40000 hours typically)

Disadvantage: - Becomes quite bulky at lower frequencies

- expensive modulator developments for every beam pulse structure (100 kV …. few 100 kV)



Toshiba, 3 MW, 325 MHz
Klystron,
100 kV modulator to be
developed specifically.

Improved rf amplifier technology

Solid state amplifiers

- MOSFET – transistors develop rapidly:
 Output power per transistor doubled every year

- Besides Si based technology (Freescale…) in future
 also SiC – technology may contribute (Infineon…)

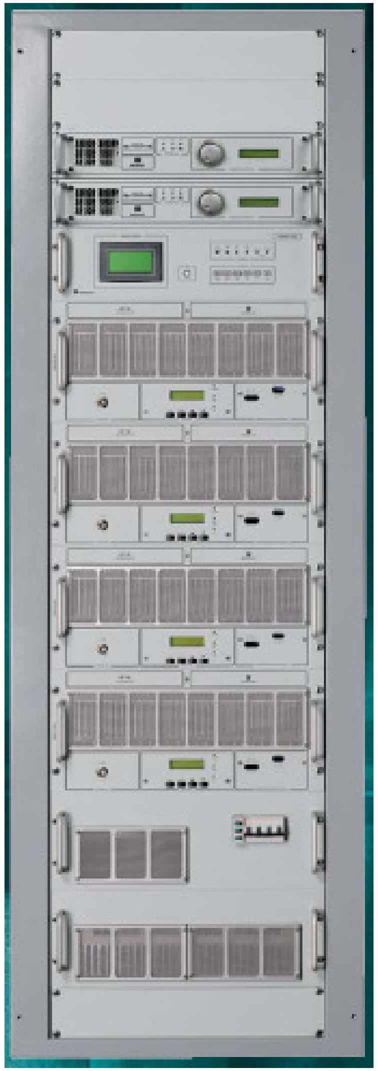
- Very attractive prizes in case of pulsed operation:
 (up to some 10 kW per transistor feasible, V up to 1 kV)

- Forced liquid cooling

- Service during operation at reduced power possible

- Falling investment costs per 1kW of installed power

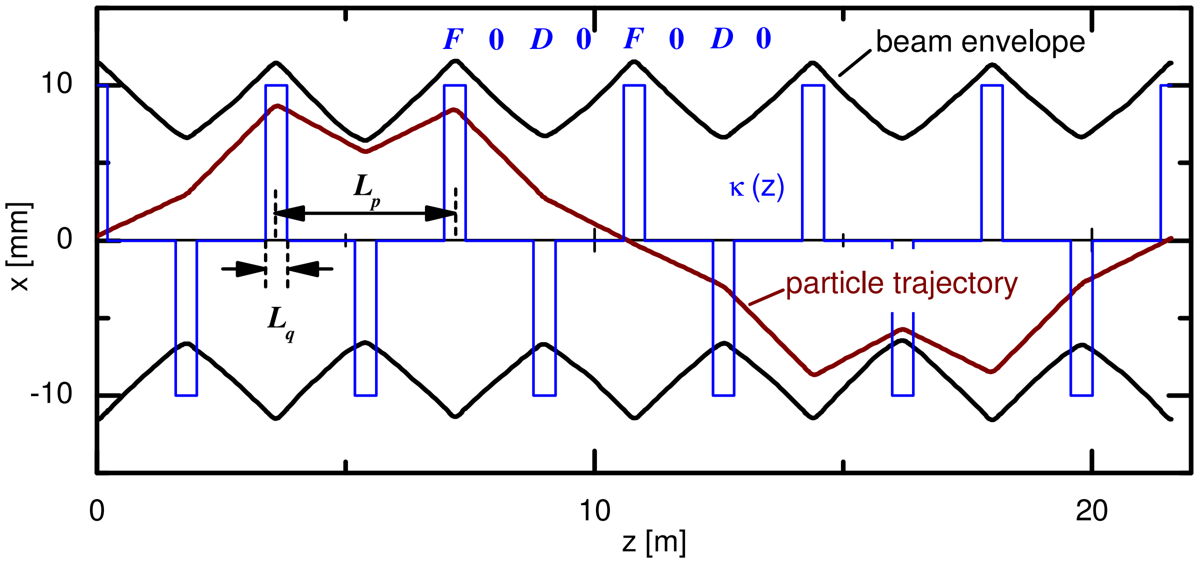
Example in Si – technology: 30 kW cw, 87 – 108 MHz,
Three 19 inch racks like shown in the photo will do the job.
Rf to plug power efficiency about 55 %;Mass about 1800 kg.

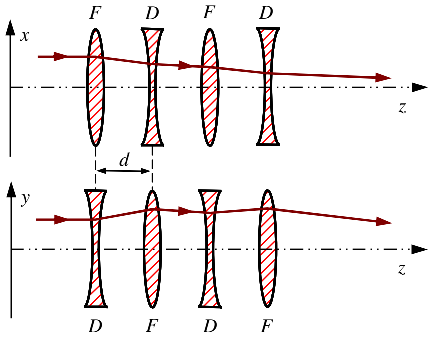


(Photo Digital Broadcast DB, Padova, Italy)

Linac focusing elements:

- Quadrupole singlet, doublet and triplet channels

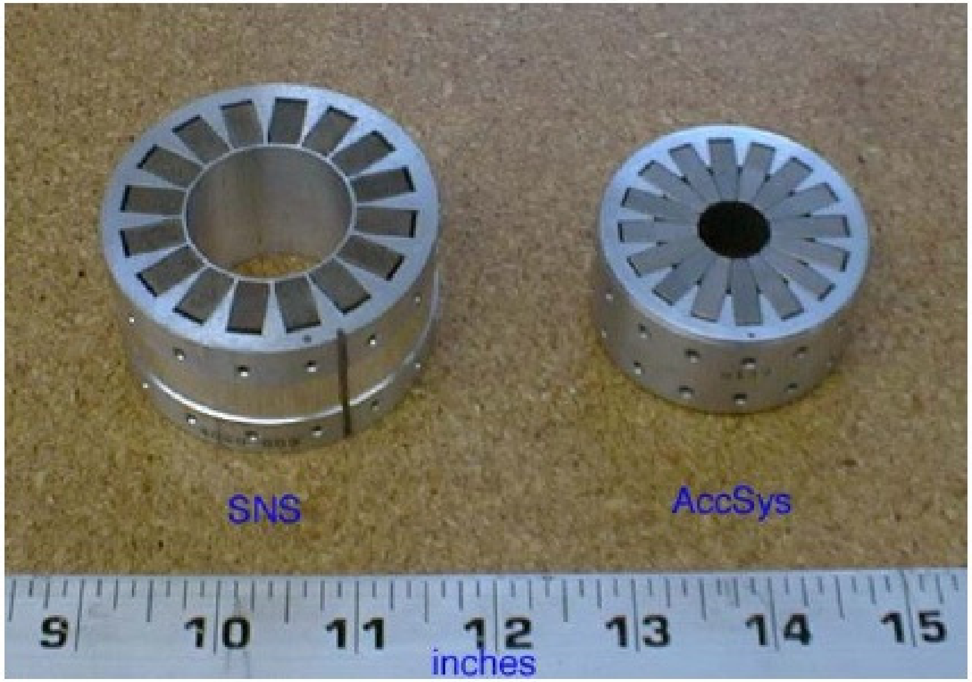




FODO – channel, 30 deg phase advance

Efficient transverse focusing

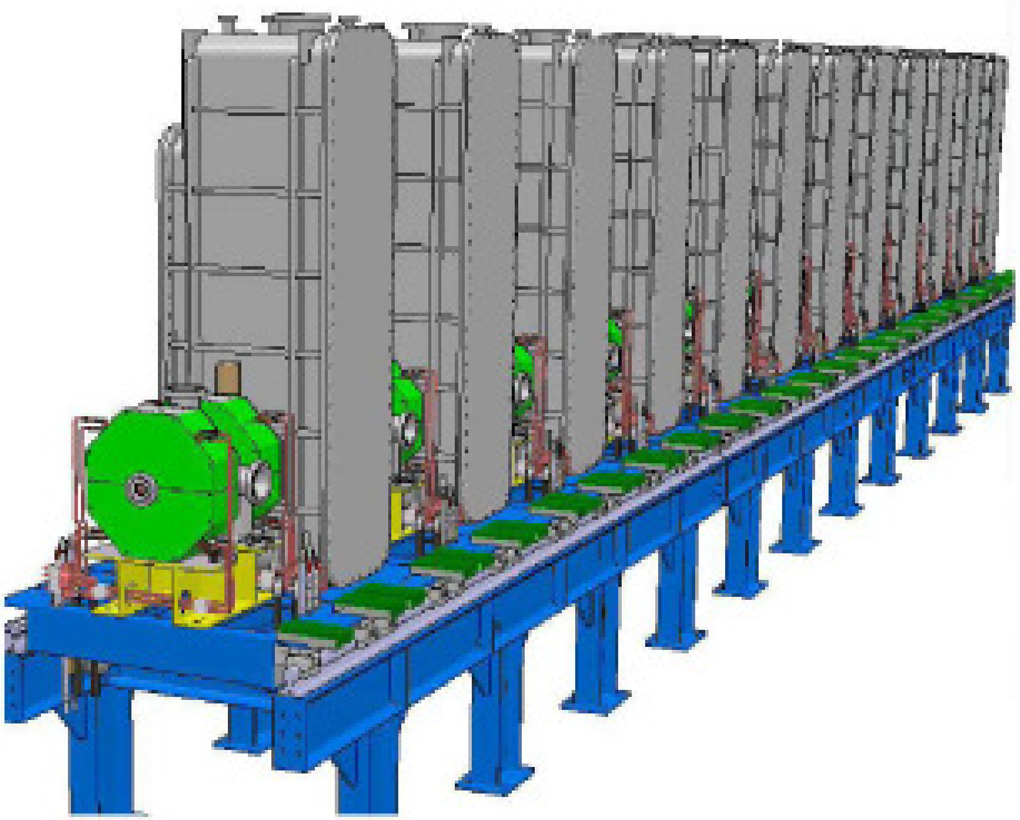
Especially at low beam energies DTL's with integrated electromagnetic quadrupoles suffer from multipacting between tubes with large outer diameter.
A new trend is to use more compact permanent magnetic quadrupoles.
At Los Alamos, IH-DTL development with PMQ's is underway (S.S. Kurennoy et al.) Phys.Rev.STAB2012



Efficient transverse focusing

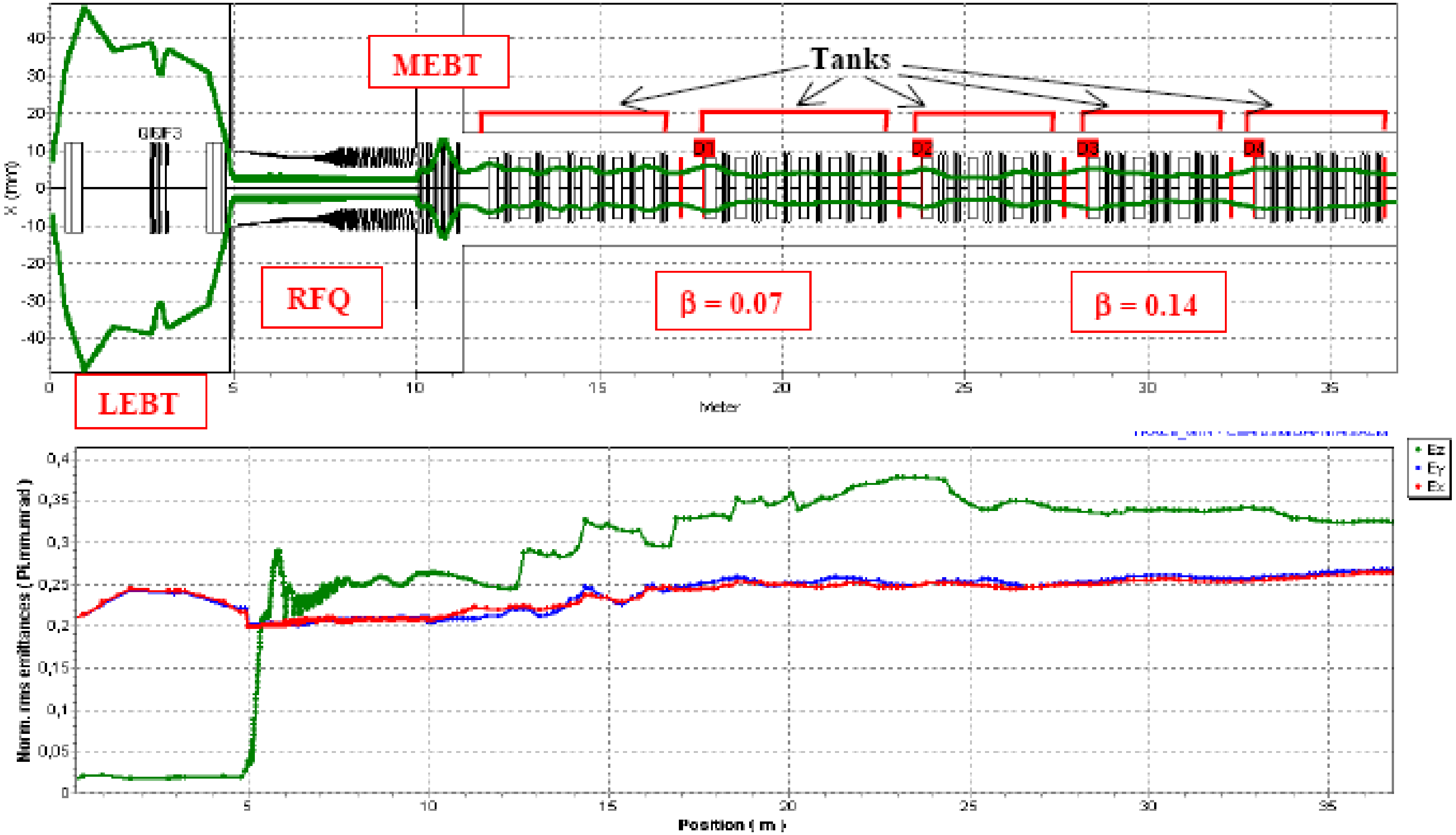
Quadrupole doublet focusing at the sc part of SNS between cryostats (>186 MeV) and at SPIRAL2, GANIL, France: 5 mA, 20 AMeV d

SC quarter wave resonators are combined with room temperature quadrupole doublets: Beamdynamics by R. Dupperier et al., PAC2003, p. 2802



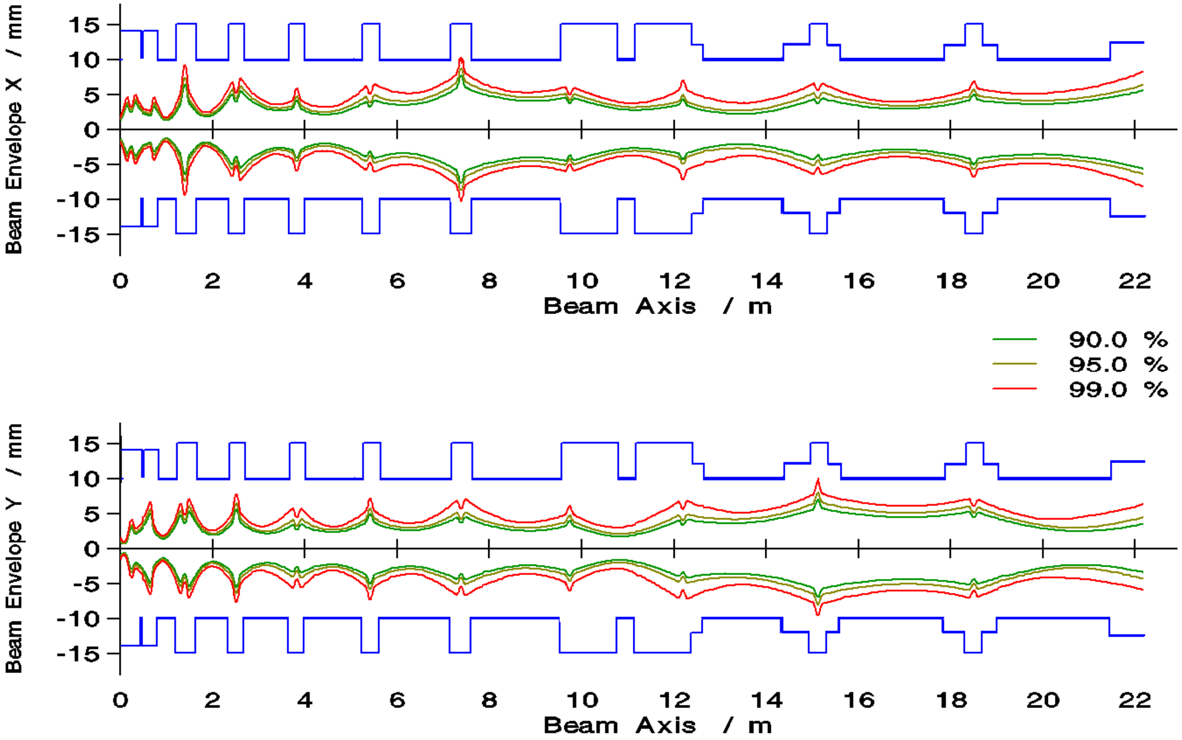
Efficient transverse focusing

SC quarter wave resonators are combined with room temperature quadrupole doublets: Beamdynamics by R. Dupperier et al., PAC2003, p. 2802



Efficient transverse focusing

Quadrupole triplet focusing between r.t. CH cavities at FAIR – proton linac:
3 -70 MeV, 70 mA, 22 m. Beam dynamics G. Clemente et al. IPAC10.

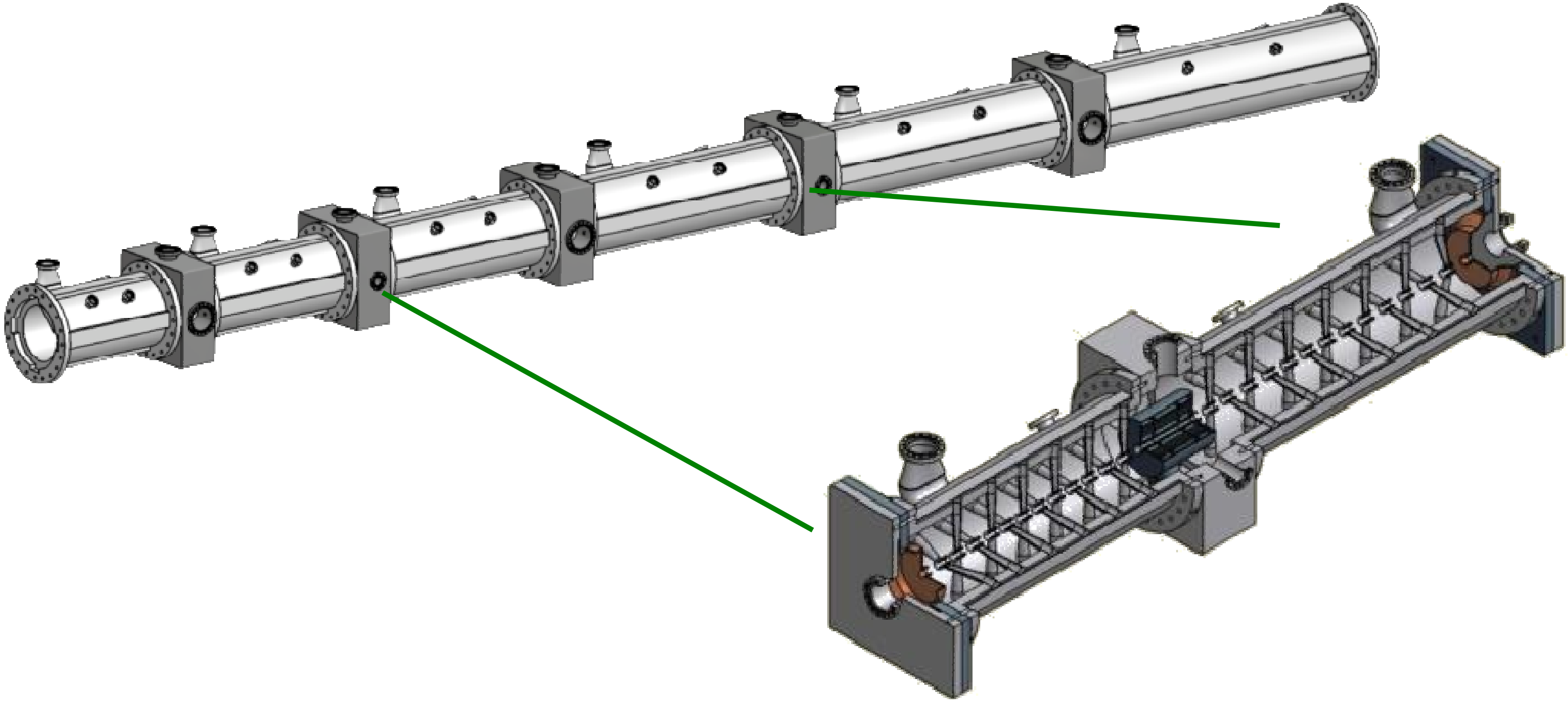


Efficient transverse focusing

Mechanical concept, 3–35 MeV, 70 mA section:

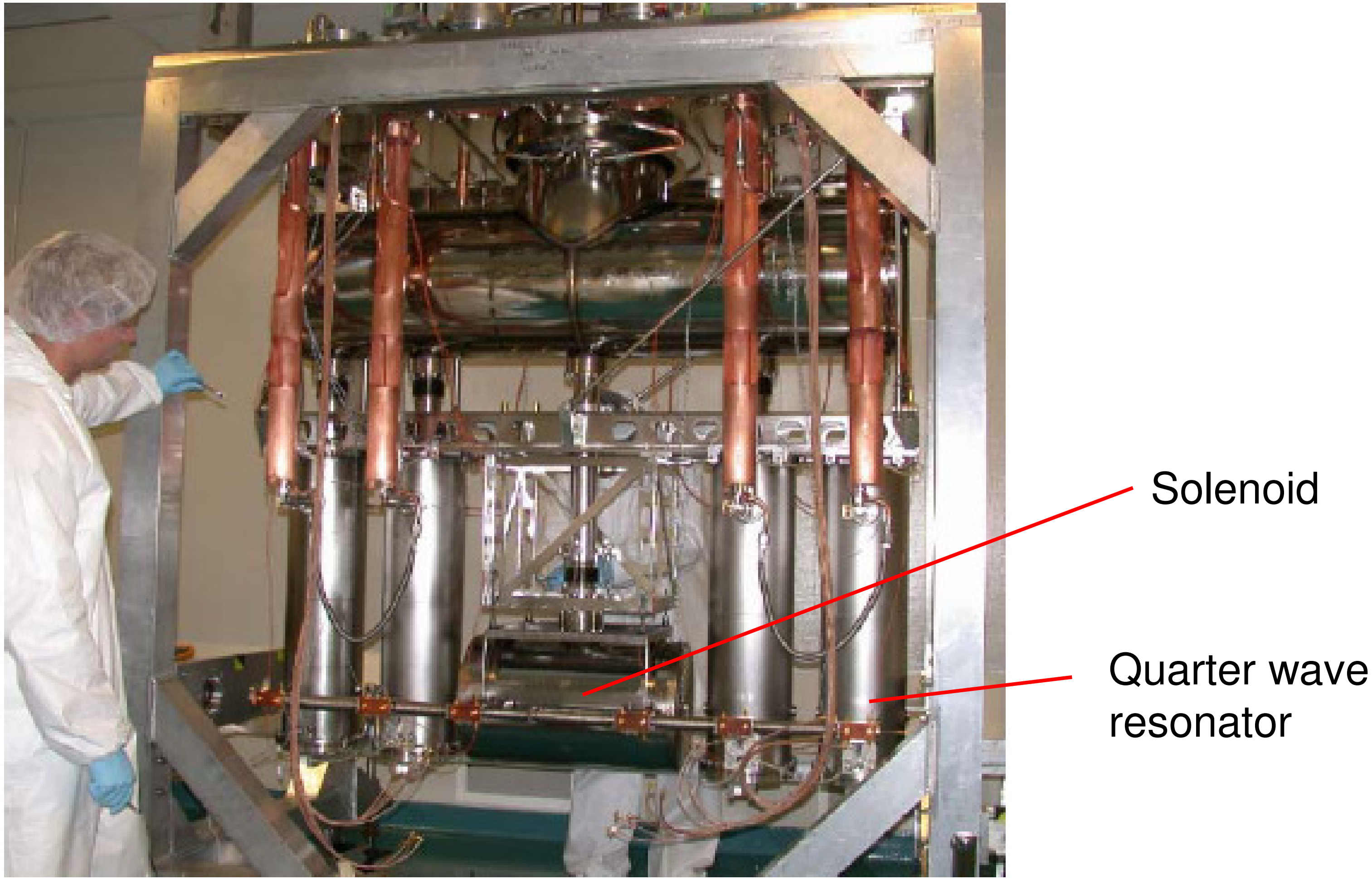
A 9 m long tank consists of 3 coupled CH – cavities. Every second triplet is housed in a drift tube for rf coupling to CH drift tube sections.

Doublets and triplets can be aligned mechanically at the workshop and form a complete transverse focusing unit. Not true for singlet channels!



Prototype cavity under construction at IAP

Efficient transverse focusing



S.C. solenoids integrated in cryostat with cavities. Coaxial shielding end coils provide steep field edges to protect the cavities.
TRIUMF ISAC2, Vancouver, Canada
R. Laxdal et al. LINAC 2006

Efficient transverse focusing

- Compact superferric quadrupoles:

  Would be very powerful.

  Some developments were done within the HIIF research, but the shielding of the remanent field of the iron yoke against the cavities seems to be a serious problem.
- Interesting plasma lens development for low energy beams (talk by O. Meusel).

Adequate beam dynamics and simulations for beam loss reduction

Particle In Cell PIC codes are improved with respect to:

- Space charge routines
- Coupling of external field solvers with beam internal field solvers
- Multi particle simulations
- Creation and loss of sencondary charged particles

SC versus RT technology, duty factor

RT cavity development started in the Fourties.
SC cavity development began in the Sixties.

Both technologies gain experience from numerous routinely operated facilities.

Main cost factors in rt technology:
RF amplifiers, civil engineering, electricity costs

SC versus RT technology, duty factor

Drawbacks of sc linacs:

- Complex technology
- Highly specialized experts needed during all phases of the facility

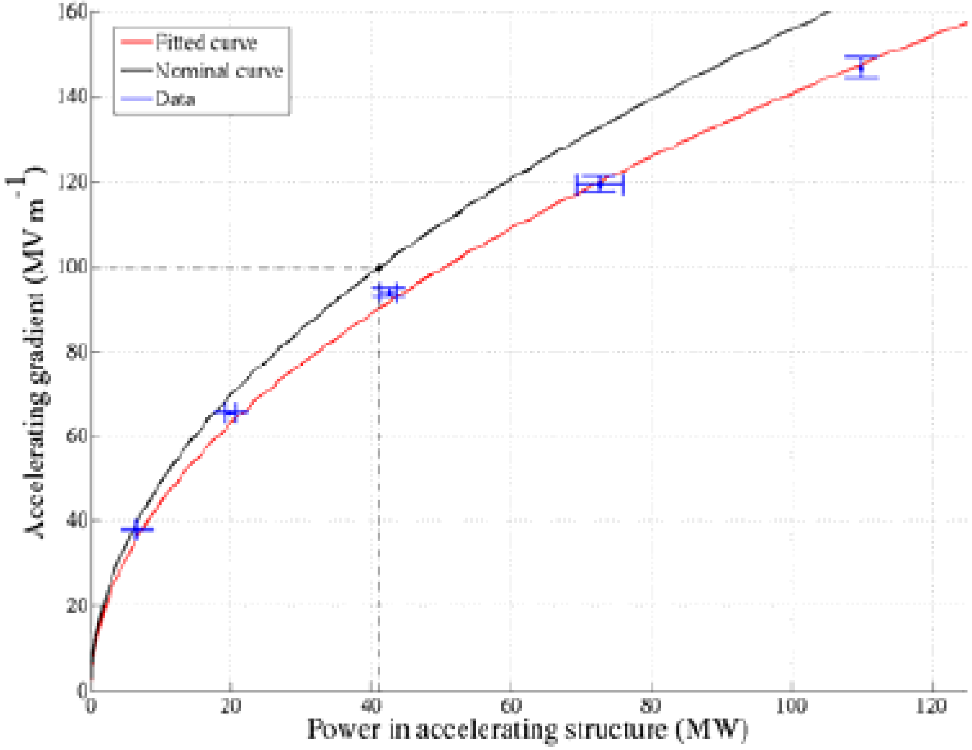
As a consequence, it is worth to check, whether a rt solution is feasible for a given task. Main parameters are the lowest acceptable duty factor and the needed rep. rate.

SC versus RT technology, duty factor

It is not yet clear, which technology can provide highest performance for defined user needs.

Present investigations:

CLIC r.t. 12 GHz cavities, against ILC s.c. 1.3 GHz cavities

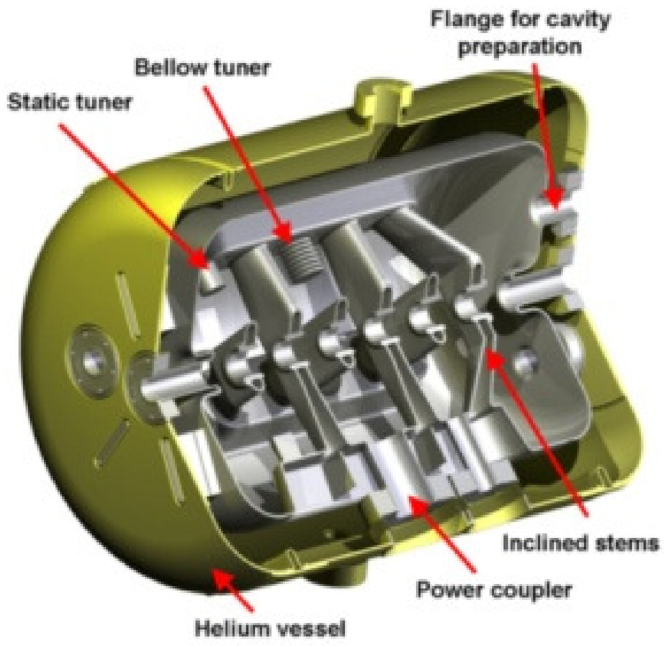


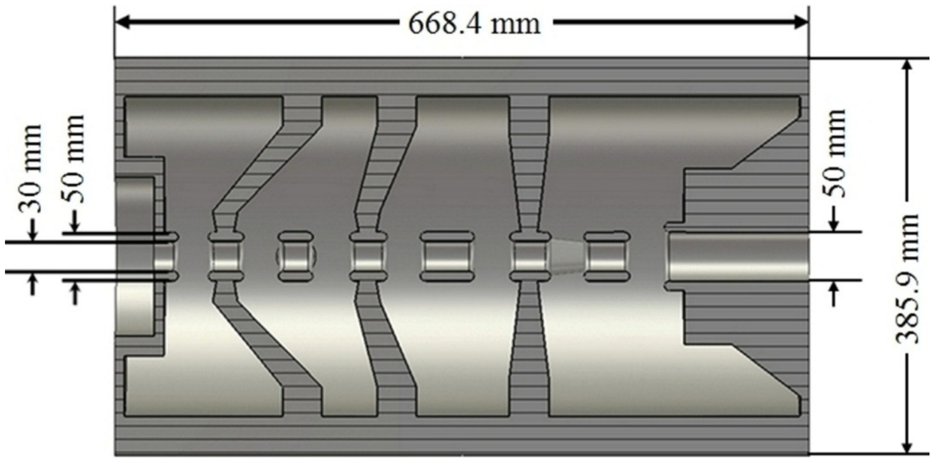
P.K. Skowronski et al. IPAC 11

Beam pulse ≈ 100 ns

SC versus RT technology, duty factor

S.C. CH – cavity, 325 MHz against pulsed R.T. CH – cavity, 325 MHz; β ≈ 0.15.





S.C. cavity ready for cold tests R.T. cavity under design
Cavity development at IAP Frankfurt and in cooperation with GSI Darmstadt

SC versus RT technology, duty factor

It is expected that r.t. approaches will benefit from new rf power generation schemes:

Solid state amplifier revolution!

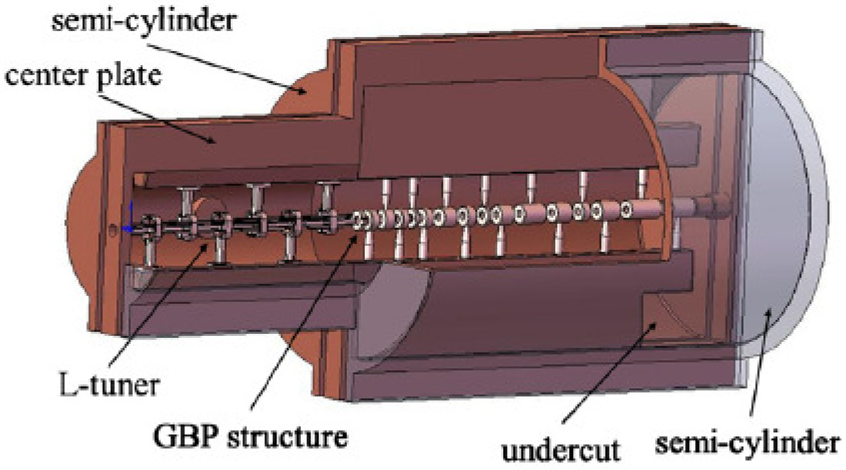
Beam driven concepts like for CLIC

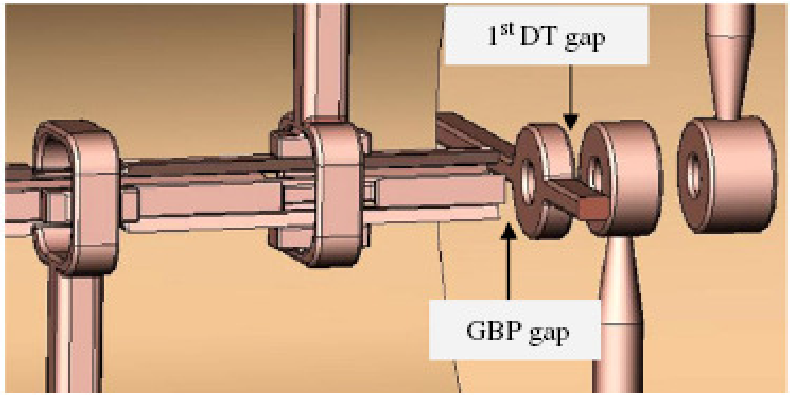
Hybrid and coupled cavities

Motivation for a coupling of structures to form one resonator:

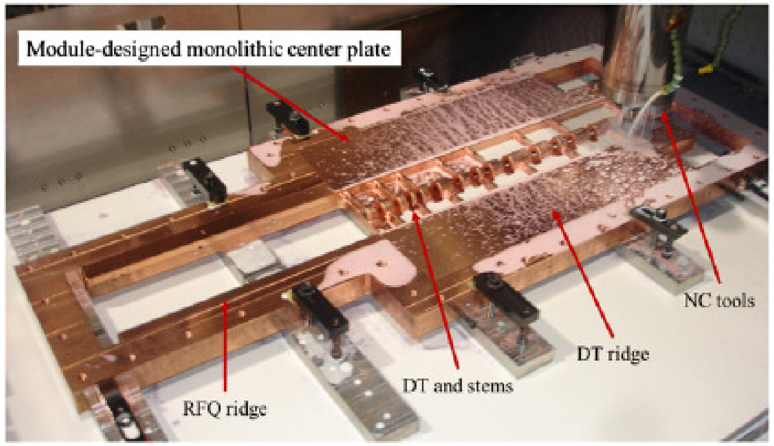
- Change of the structure at a certain beam velocity for an increased shunt impedance (at the end of an RFQ typically)
- Matching of the available rf amplifier power to the resonator
- Reduction of drift lengths between cavities.

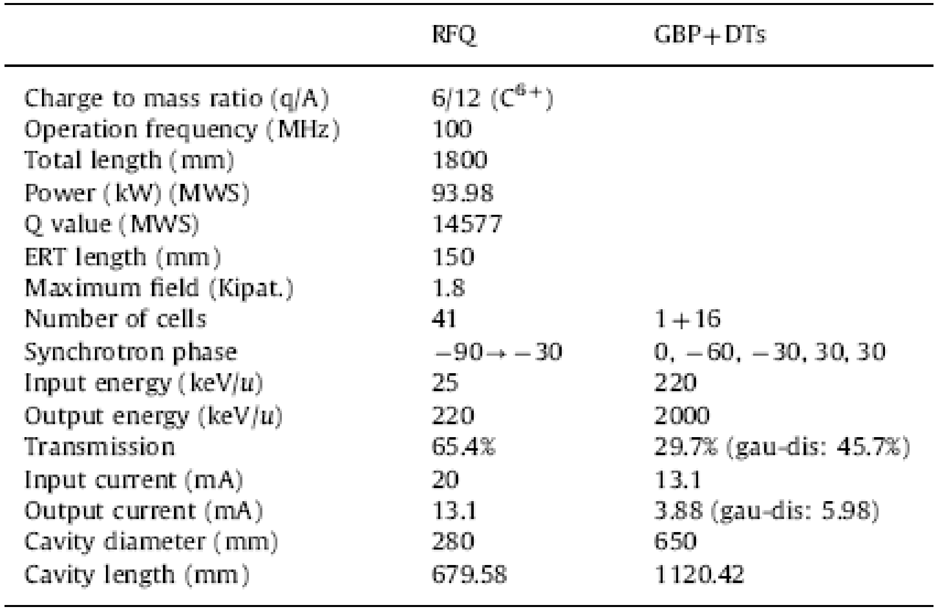
Hybrid and coupled cavities





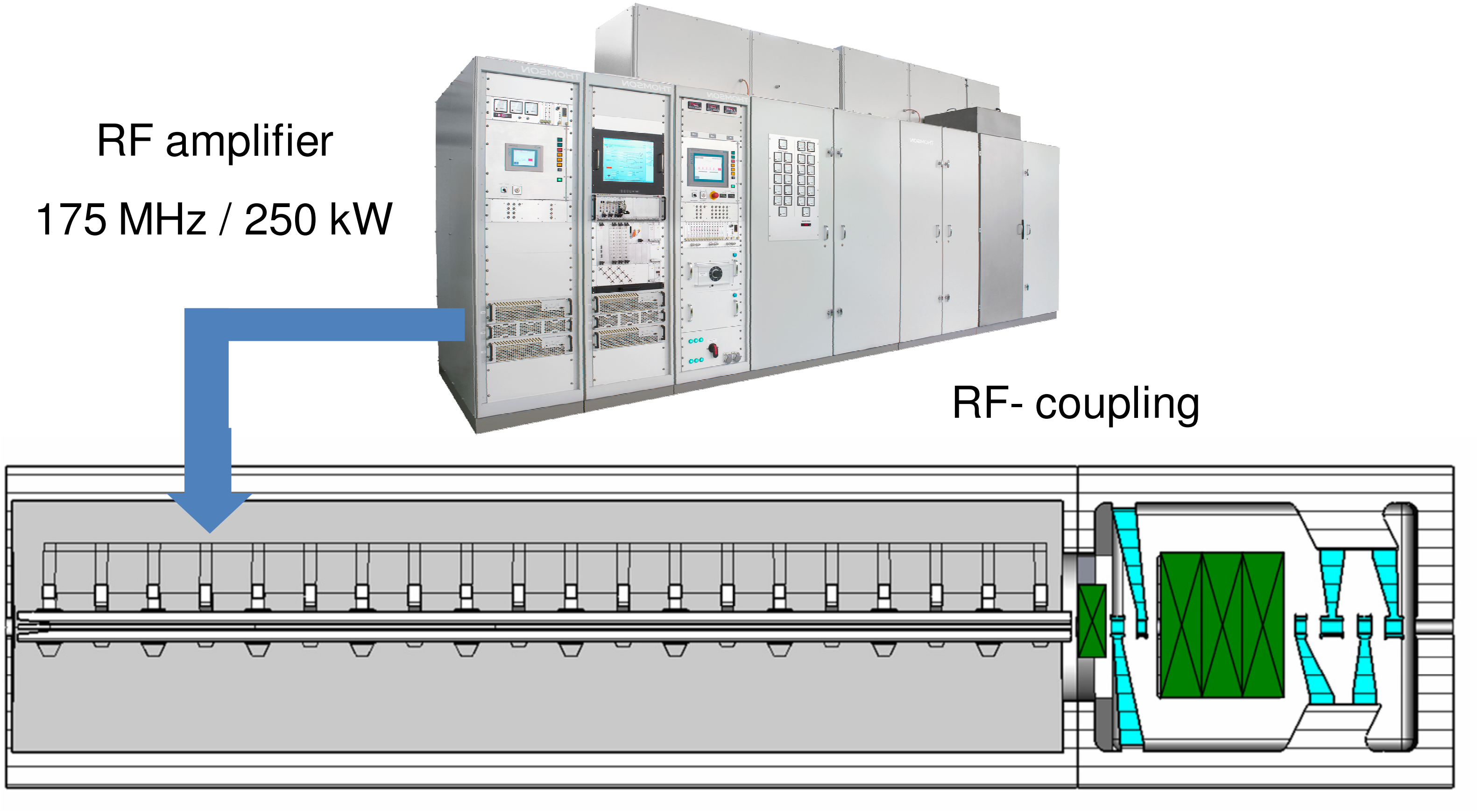
T. Hattori et al., NIMA 688 (2012), p.11





	RFQ	GBP+DTs
Charge to mass ratio (q/A)	6/12 (C^{6+})	
Operation frequency (MHz)	100	
Total length (mm)	1800	
Power (kW) (MWS)	93.98	
Q value (MWS)	14577	
ERT length (mm)	150	
Maximum field (Kipat.)	1.8	
Number of cells	41	1+16
Synchrotron phase	−90→−30	0, −60, −30, 30, 30
Input energy (keV/u)	25	220
Output energy (keV/u)	220	2000
Transmission	65.4%	29.7% (gau-dis: 45.7%)
Input current (mA)	20	13.1
Output current (mA)	13.1	3.88 (gau-dis: 5.98)
Cavity diameter (mm)	280	650
Cavity length (mm)	679.58	1120.42

Hybrid and coupled cavities



RF amplifier

175 MHz / 250 kW

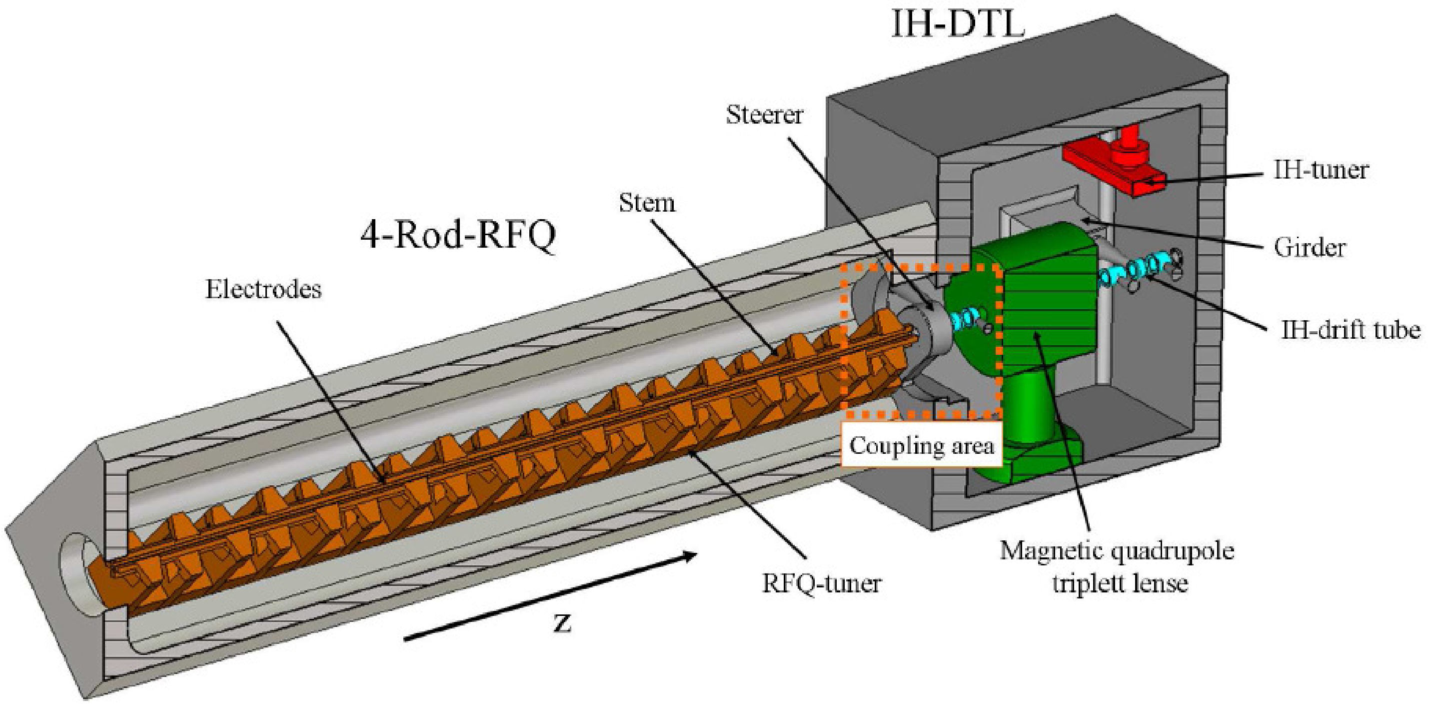
RF- coupling

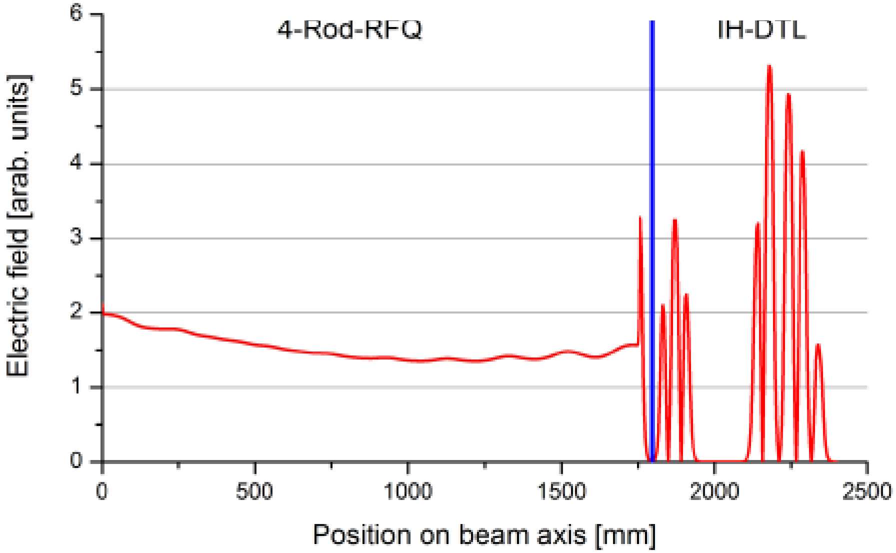
RFQ

IH- DTL

FRANZ accelerator cavity, 175 MHz, 2 MeV protons, cw operation
M. Heilmann et al., LINAC 12

Hybrid and coupled cavities

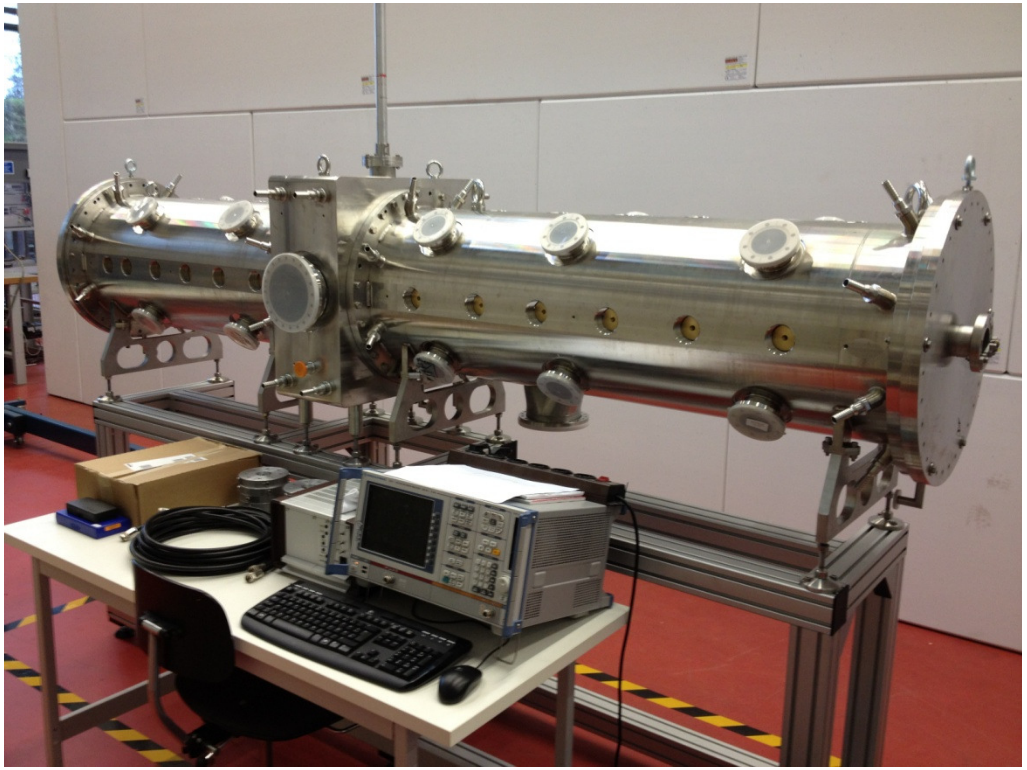


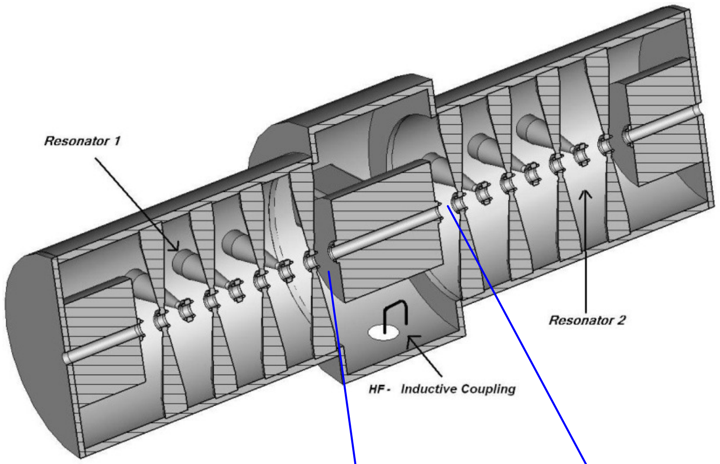


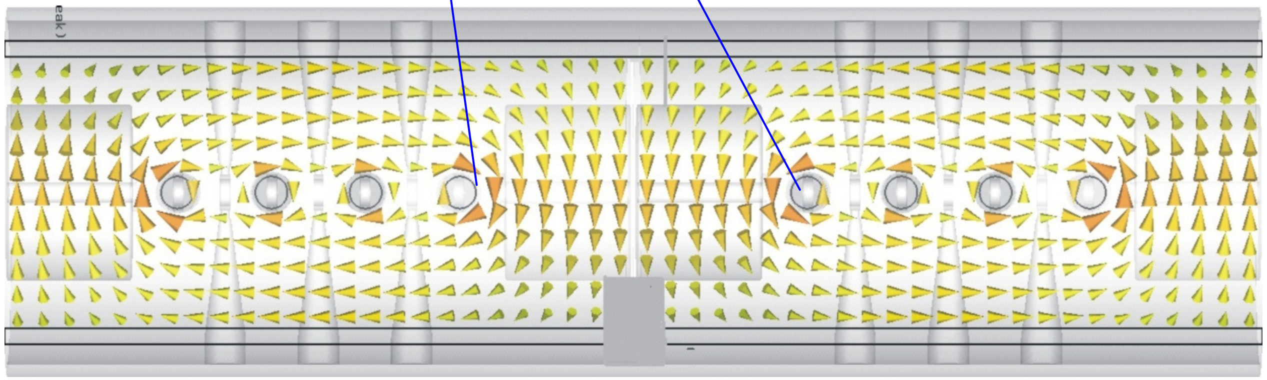
Cold model measurements have been successful with respect to voltage tuning
M. Heilmann et al., IPAC 11

Hybrid and coupled cavities

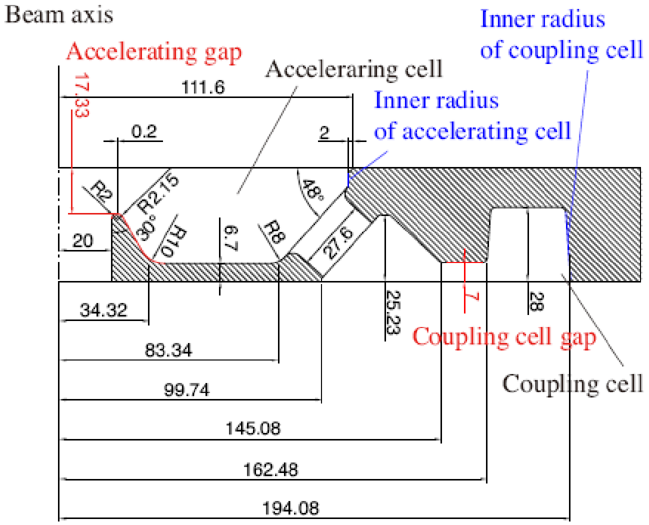
Two CH – sections are coupled to match the resonator rf power needs to the 3 MW klystron, 324 MHz from Toshiba

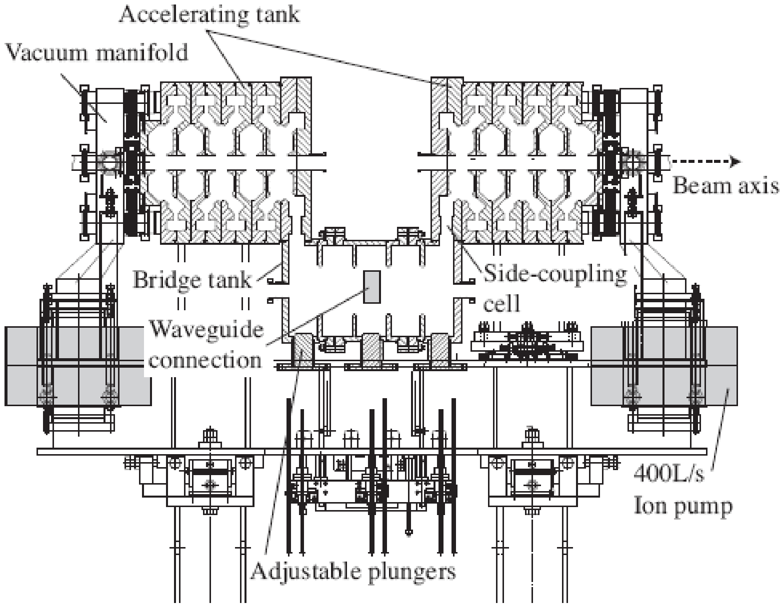


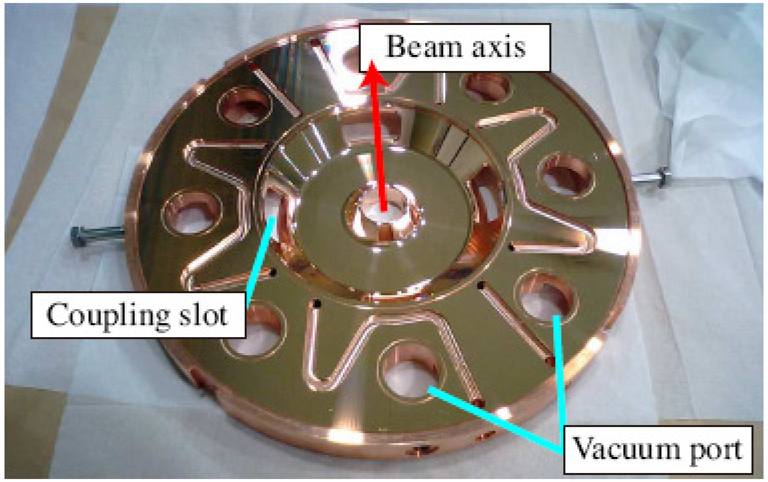




Hybrid and coupled cavities





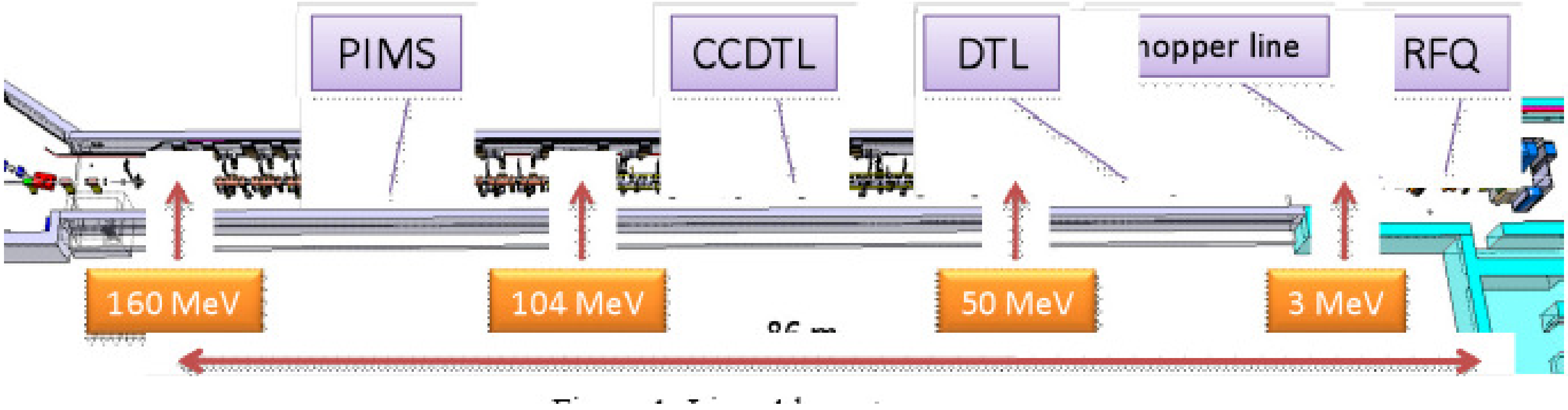


Annular coupled structure ACS for JPARC from 190 MeV – 400 MeV
Under construction
Y. Yamazaki et al. LINAC 2006
Phys.Rev.STAB 2011

Some linac projects

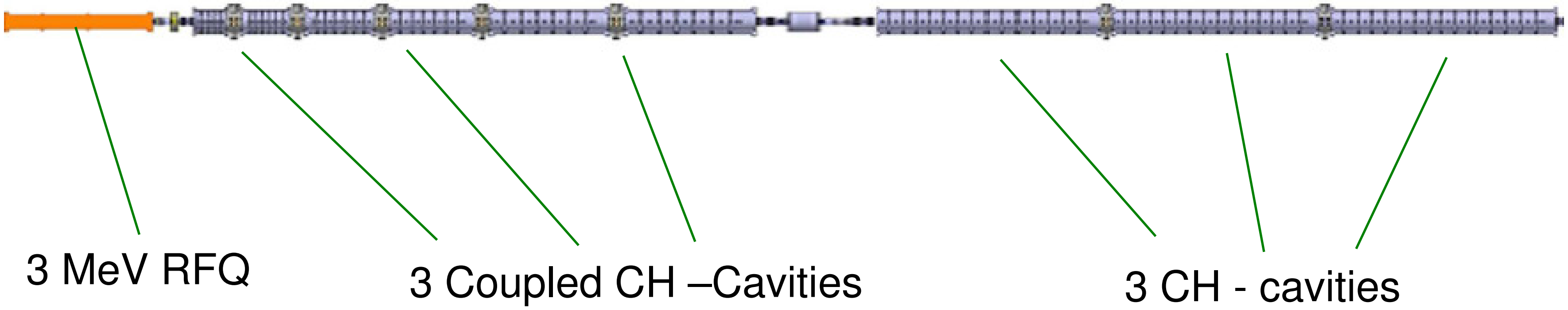
- Cern Linac4 project to replace LINAC2 and lateron possibly to serve as a front end for a 2 GeV superconducting linac SPL.

  LINAC4 is under construction (M. Vretenar, LINAC12)



Some linac projects

- FAIR Proton injector, 70 MeV, 35 (70) mA
  325 MHz, prototyping underway



Some linac projects

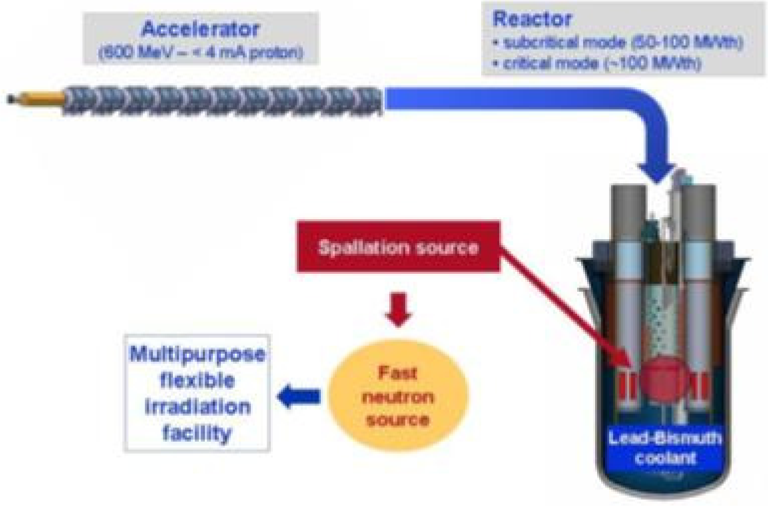
Accelerator Driven Systems ADS

The European MYRRHA Project

MYRRHA Project

**Multi-purpose hYbrid Research Reactor for High-tech Applications
At Mol (Belgium)**

*Development, construction & commissioning of
a new large fast neutron research infrastructure
to be operational in 2023*



SCK•CEN
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

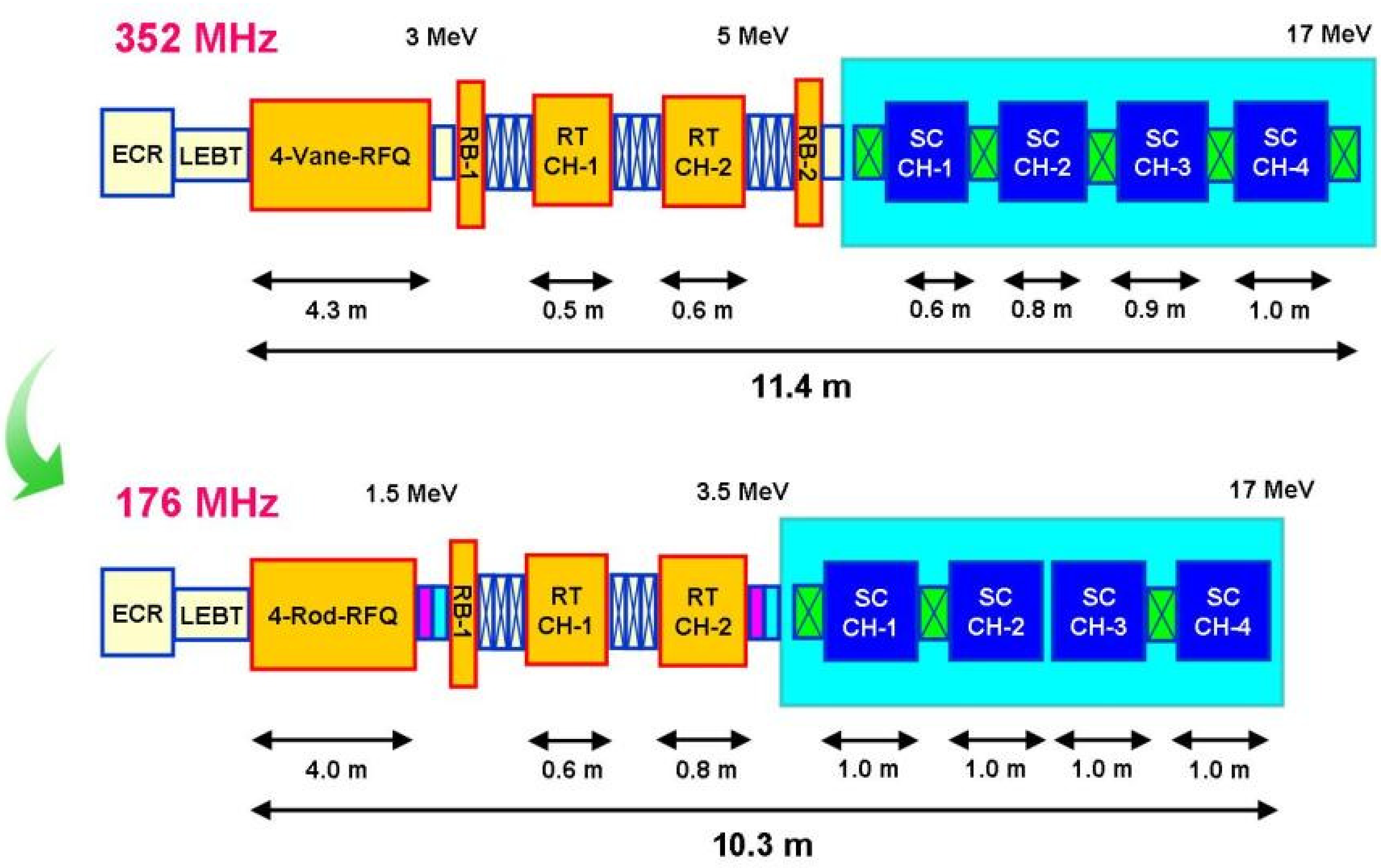
ADS demonstrator

Fast neutron irradiation facility

Pilot plant for LFR technology

Accelerator Driven Systems ADS

Layout of the 17 MeV section designed by IAP



Some linac projects

European Spallation Neutron Source ESS, Lund

Technical Design Report TDR will be presented soon.
Envisaged is a proton beam power of up to 6 MW,
no accumulator ring. Basic RF frequency 352 MHz.

A Chinese Neutron Source will be realized in steps

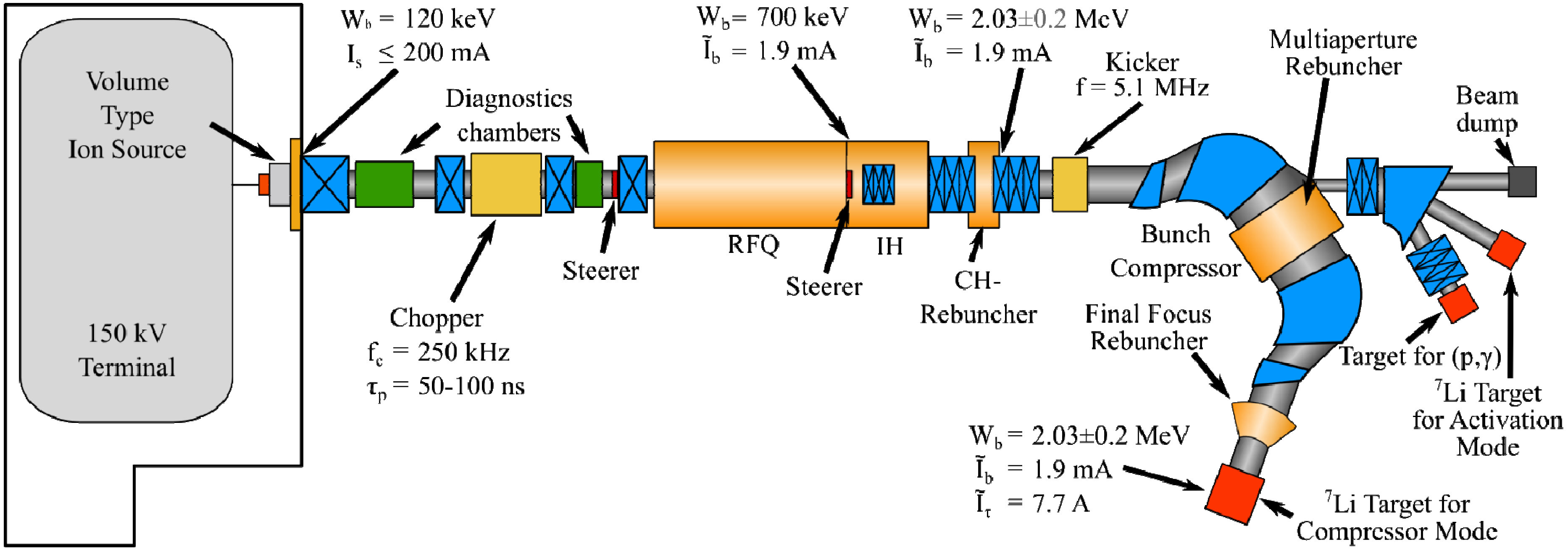
ADS activities at several places worldwide.

The IFMIF – EVEDA phase for the development of a
250 mA 40 MeV d – beam under construction in Italy and
France, to be tested in Japan.

Some linac projects

Frankfurt Neutron Source FRANZ

Overview



- Extracted source current : 50 mA …..(200 mA dc)
- Pulsed beam target : some 10^6 n / cm^{2}s at l=0.8 m
- ‘Straight’ beam target : 10^{10} n / cm^{2}s

Allows experiments for nuclear astrophysics (stellar element burning by s - process

Beam losses, activation studies

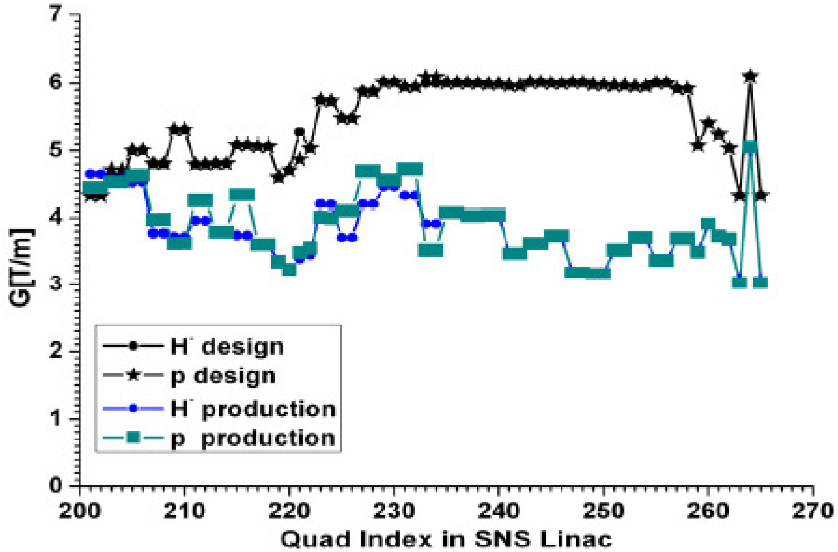
The dominant effect for beam losses along the SC linac of SNS is not beam halo formation as was expected, but intra-beam Scattering:

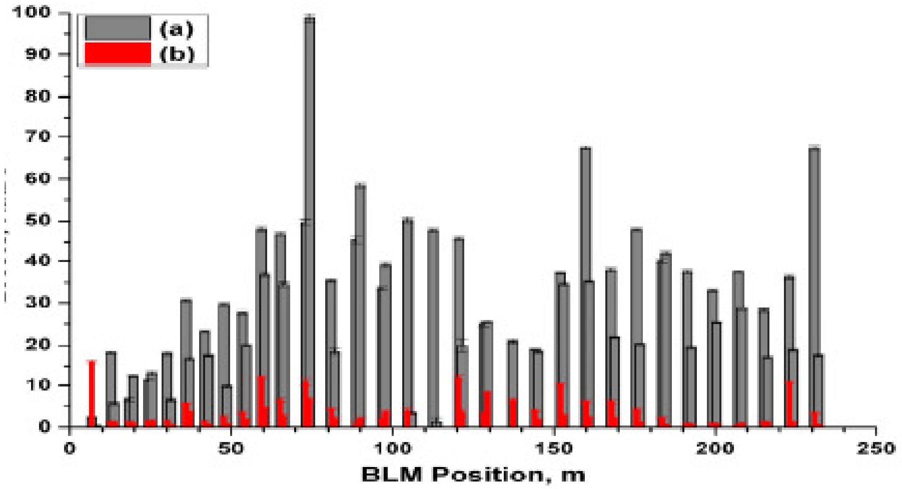
$$H^- + H^- \rightarrow H^- + H^0 + e$$

Significantly reduced quadrupole settings resulted in minimum beam losses.

This effect and the comparison with proton beam operation confirm the dominance of intra beam scattering leading to losses by charge exchange.

Beam losses, activation studies





J. Galambos et al., IPAC 2012, New Orleans

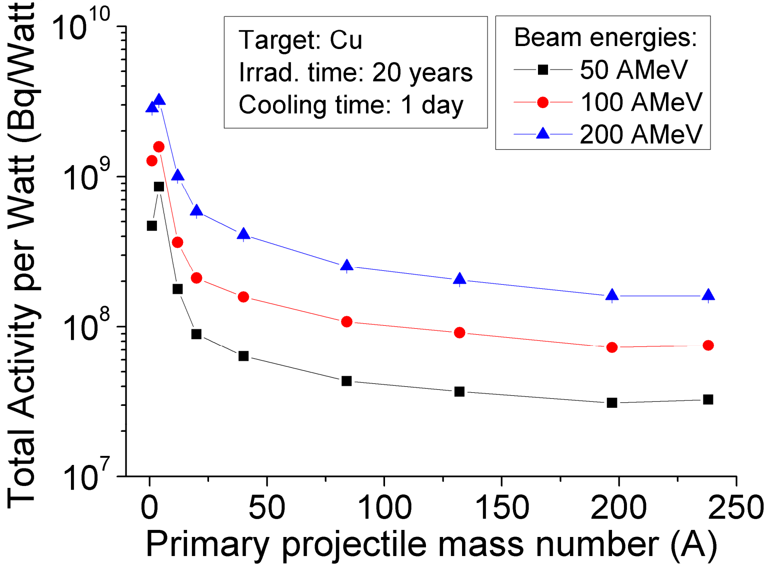
This means that high current proton linacs show significantly less beam losses then H^- linacs at comparable beam parameters.

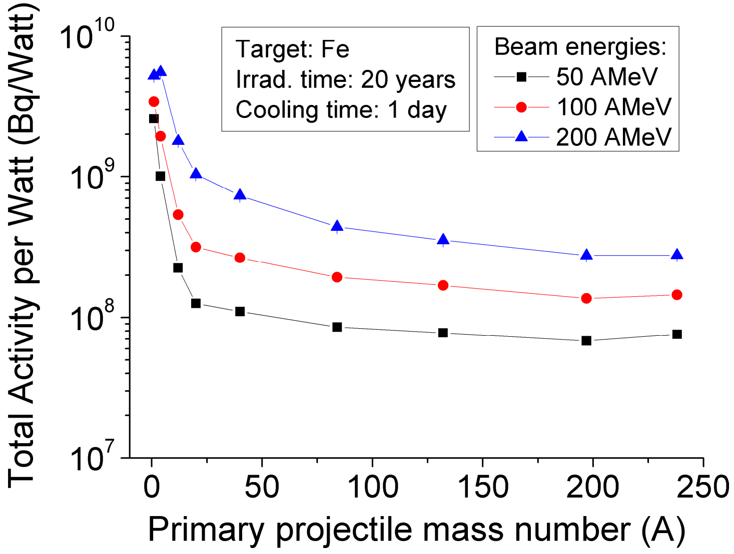
Beam losses, activation studies

Finally, differences in activation between proton and heavy ion beams are considered:

Short summary of results from simulations with FLUKA mainly as performed at GSI and documented by the thesis of V. Chetvertkova (Frankfurt, 2012).

Beam losses, activation studies





The 1 W/m beam loss limit used for the design of proton linacs is relaxed towards heavier masses and towards lower beam energies.
This is important, as heavy ion linacs are more complex and tend towards higher beam losses.

For example losses around 200 W/m can be tolerated for 50 AMeV uranium beams.
At 200 AMeV this number goes down to about 50 W/m.

Conclusions

- Many activities wordwide in improved linac development for fundamental research and for applications
- Better performance of linac key components is one direction to go
- Completely new approaches like Laser acceleration techniques and plasma wake fields have to demonstrate there potential
- Activation levels have to be watched carefully for the envisaged high current projects