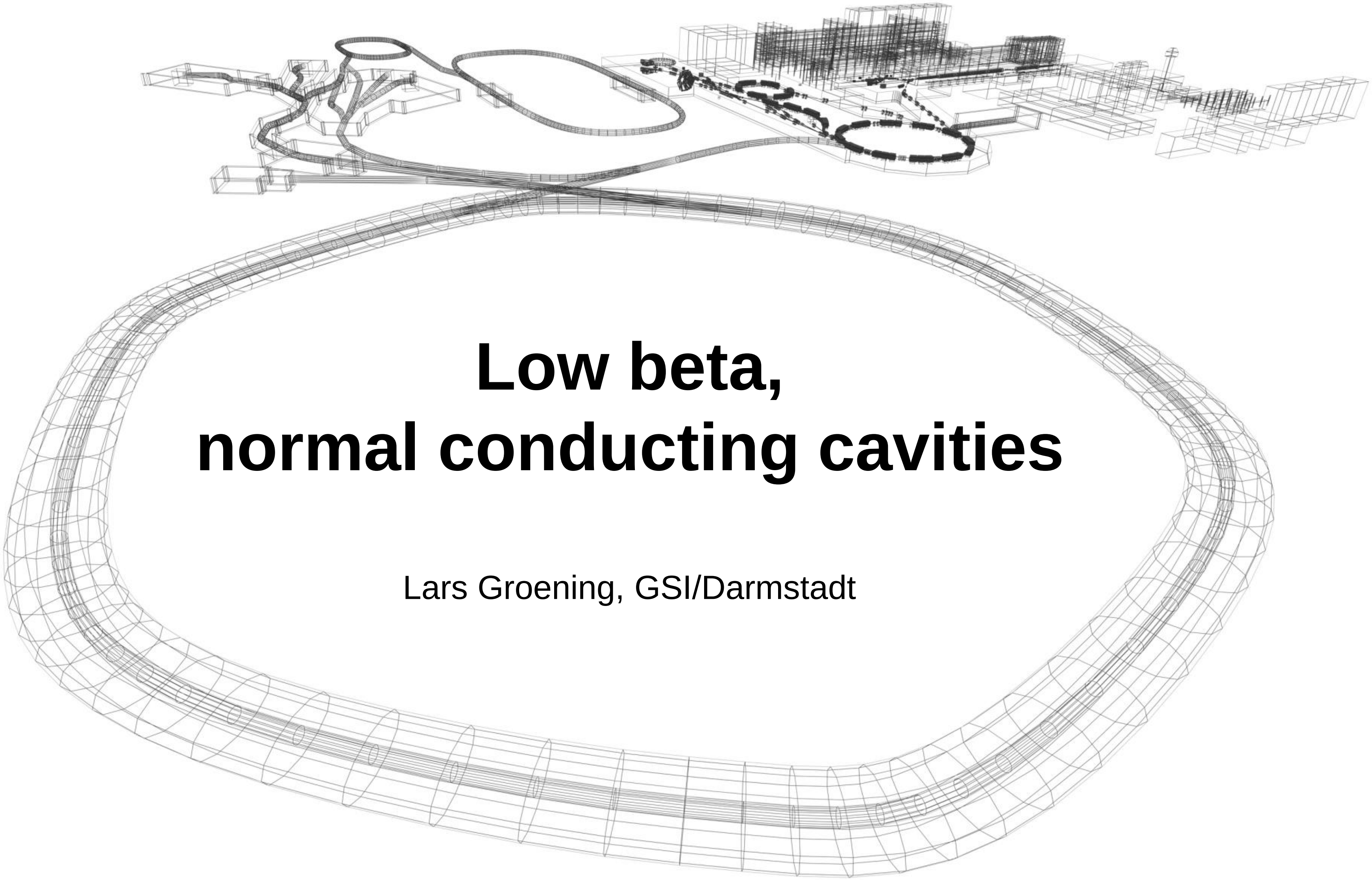


Low beta,
normal conducting cavities

Lars Groening, GSI/Darmstadt

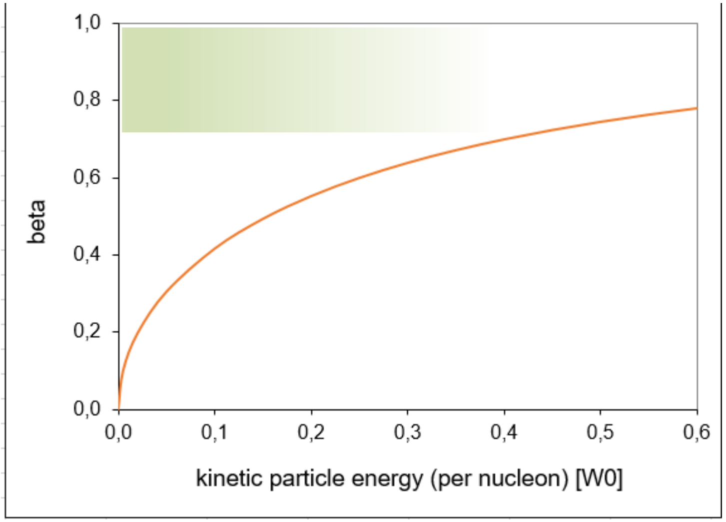
Outline

- Impact of *low beta* and normal *conducting*
- Types of cavities (selection!)
- Choosing best type for the project
- Production issues
- Copper plating
- Rf-conditioning

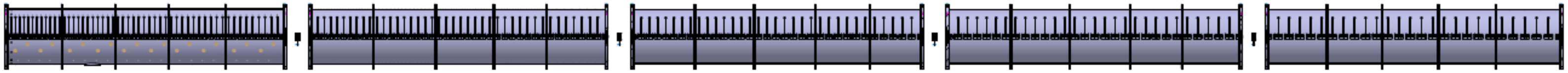
Impact of *low beta* and *normal conducting*

low beta:

- space charge forces may be an issue during acceleration
- beam velocity significantly depends on beam energy:



the local cavity geometry (on axis) must match the local beam energy, in order to preserve the synchronous rf-phase:



$E = 0.0015\ W_0$
$\beta = 0.055$

$E = 0.012\ W_0$
$\beta = 0.15$

Impact of *low beta* and *normal conducting*

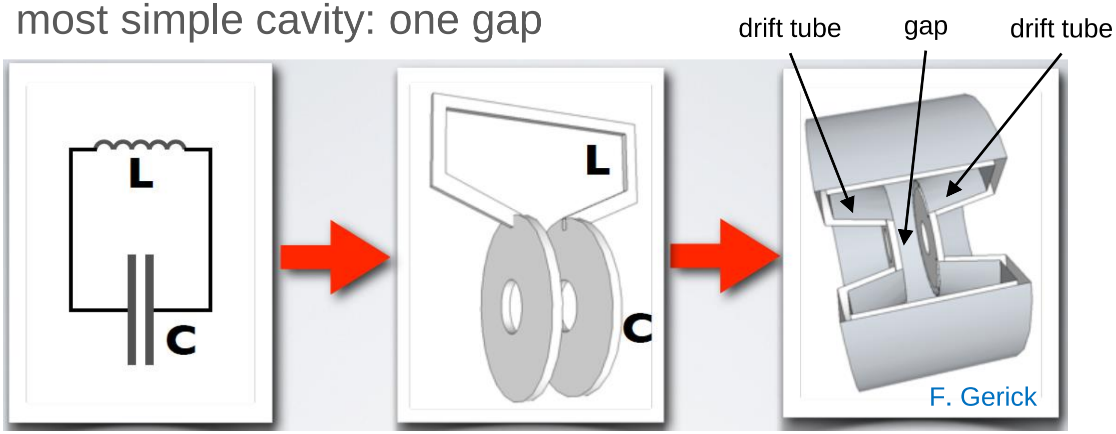
normal conducting:

- relevant part of rf-power heats the cavity and does not accelerate the beam:
    - increases cost for wall plug power
    - local heating -> to be limited to avoid de-tuning / damage

- resonance width of cavity is about 10^4 times broader w.r.t. (quasi loss free) super conducting cavity:
    - accordingly lower $Q, R/L$ values
    - shorter rise / decay times
    - allow to change design cavity voltage within some milliseconds
        - -> switch ion species between pulses
    - no need to deal with infrastructure for liquid helium / nitrogen, thermal shielding, …

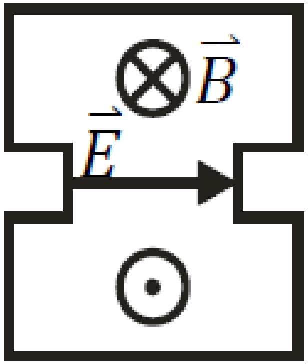
Types of cavities:
Pill box

- most simple cavity: one gap



F. Gerick

$$f = \frac{1}{2\pi\sqrt{LC}}$$



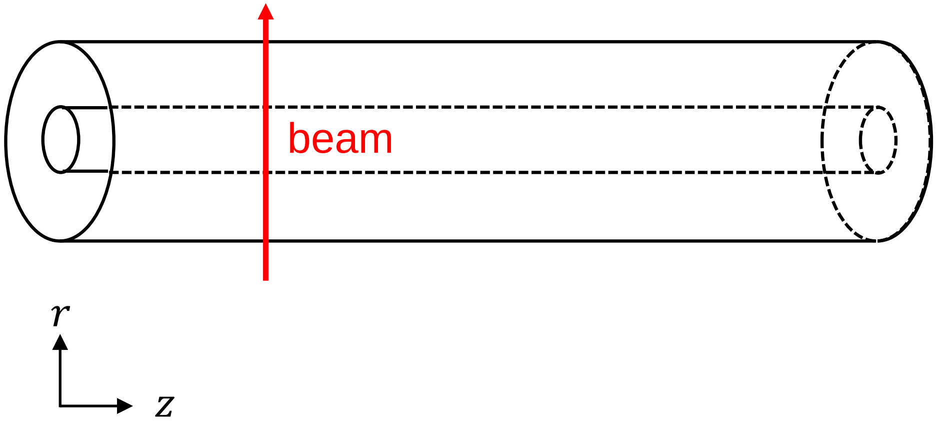
TM$_{010}$ mode

- used as bunchers, or for moderate energy correction
- drift tubes may be filled with quadrupoles for focusing
- example: 10 independent pill boxes for energy tuning & bunching at GSI UNILAC (≈ 1 MV/gap)

Types of cavities:
λ - resonators

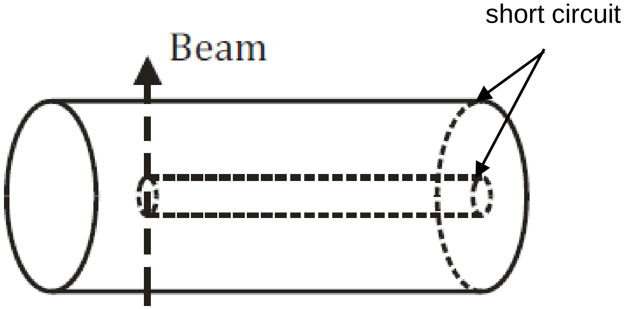
- (very) low frequency at reasonable size, i.e., not some meters
- very few gaps: bunching or few acceleration per cavity

principle: a coax line is passed transversely by the beam; acceleration by E_r :



Types of cavities:
λ - resonators

$\lambda/4$ – resonator :

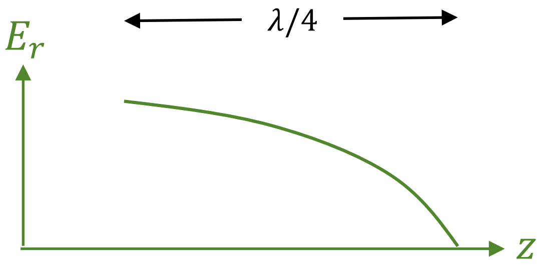


boundaries:

$$E_r(z = L) = 0 \rightarrow L = (2n - 1) \cdot \frac{\lambda}{4}$$

$$\downarrow$$

$$f = 75MHz \cdot \frac{2n - 1}{L[m]}$$

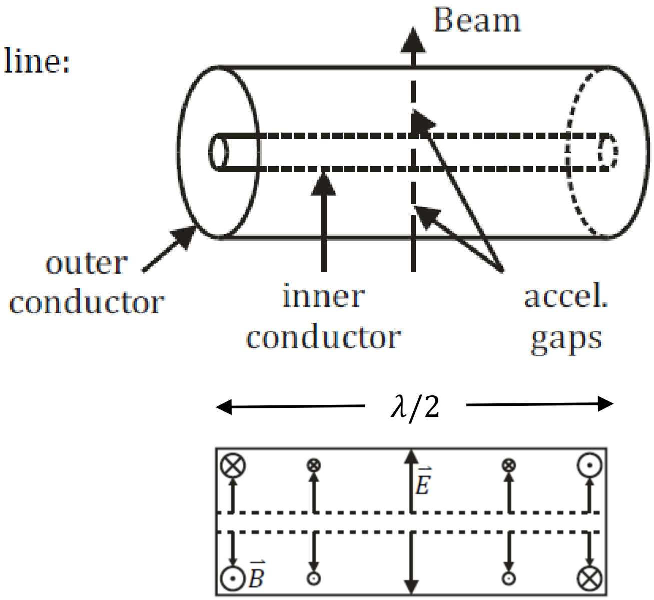


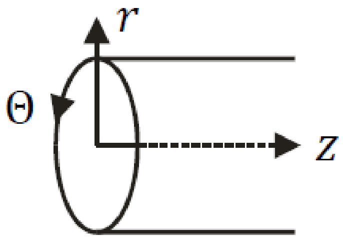
- Saclay, SPIRAL-2
- peak field: 6.5 MV/m
- frequency (n=1): 88 MHz

Types of cavities:
λ - resonators

$\lambda/2$ – resonator:

coaxial line:





boundaries:

$$E_r(z=0) = E_r(z=L) = 0, \quad L = n \cdot \frac{\lambda}{2}$$

$$\downarrow$$

$$f = 150MHz \cdot \frac{n}{L[m]}$$

- FZ Jülich prototype
- peak voltage: 0.8 MV/gap
- frequency (n=1): 160 MHz

Types of cavities:
Spiral resonators

- low frequency at reasonable size, i.e., not some meters
- few gaps: bunching or moderate acceleration
- principle:
  - low frequency calls for large radius R, but a short cavity should have small R
  - compensating small R with large inductivity L

    $f \sim \frac{1}{\sqrt{LC}} \sim \frac{1}{\sqrt{L}\,R}$
  - prolonging (spiraling) the drift tube suspension

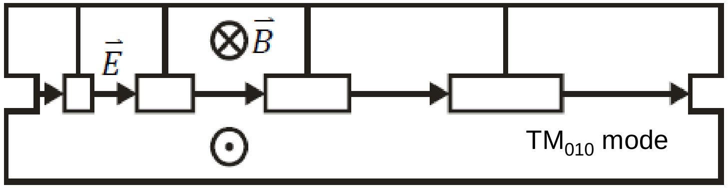
TM$_{010}$ mode

- GSI Darmstadt UNILAC buncher
- peak voltage: 0.18 MV/gap
- frequency: 108 MHz

Types of cavities:
Alvarez

- few to many gaps: regular acceleration, strong periodic transverse focusing
- gap & drift tube lengths increase with particle velocity (energy)
- principle:
  - attach many pill boxes to each other
  - place quadrupoles (or diagnostic devices) inside drift tubes

Luis Walter Alvarez
1911 - 1988



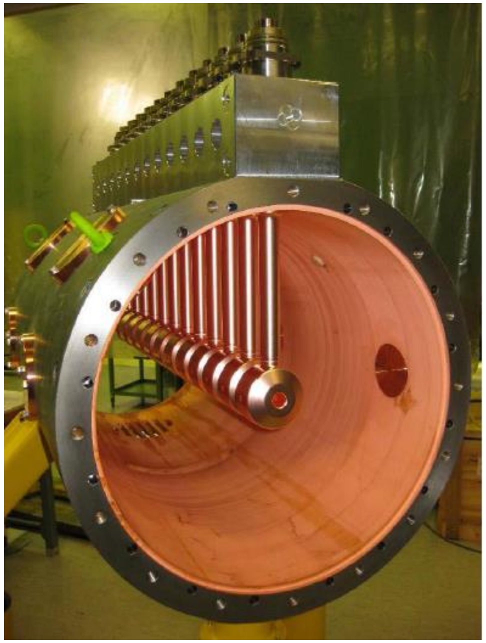
$\vec{E}$ in 2π – mode

$\vec{E}$ longitudinal

$\vec{B}$ transverse

Drift Tube Linear Accelerator

- CERN Linac-4, 1st DTL cavity
- 28 gaps
- peak voltage: ≤ 0.31 MV/gap
- frequency: 352 MHz

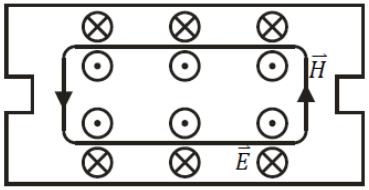


TDR Linac-4, CERN, (2006)

Types of cavities:
Inter-digital H-mode (IH)

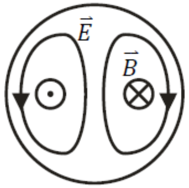
- few to many gaps: high voltages, some transverse focusing, few drift tubes with quadrupoles
- gap & drift tube lengths increase with particle velocity (energy)
- principle:
  - create longitudinal magnetic field $\vec{B}$
  - place drift tube supports along $\vec{E} = \vec{\nabla} \times \vec{B}$ in order to charge drift tubes

from top:



TE_{111}mode

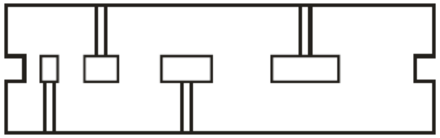
from entrance:



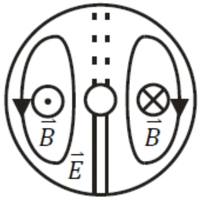
no $E_{\parallel}$ for acceleration

insert drift tubes:

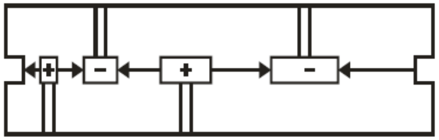
from side:



from entrance:

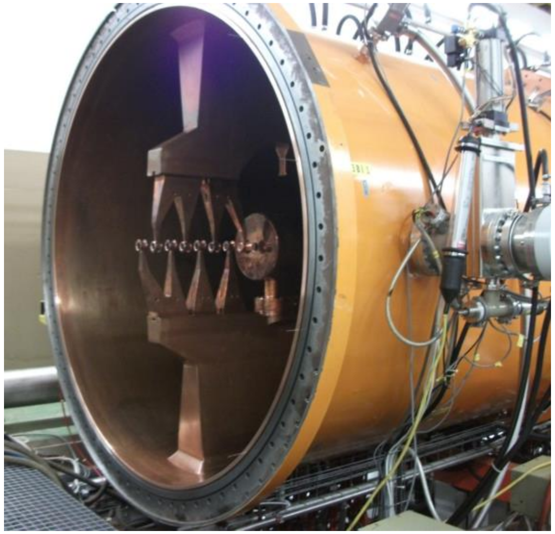


E charges drift tubes



π-mode

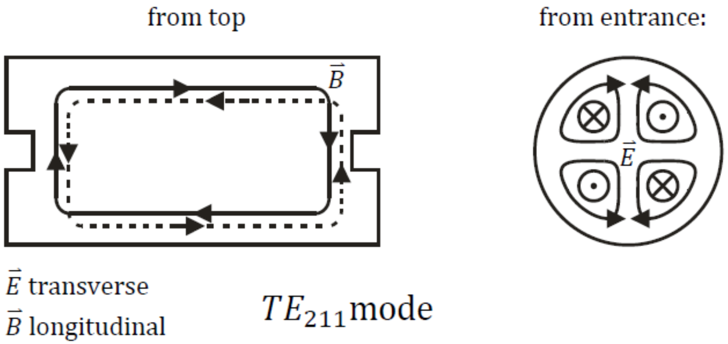
- GSI Darmstadt, 1st HSI cavity
- 53 gaps
- peak voltage: ≤ 750 kV/gap
- frequency: 36 MHz

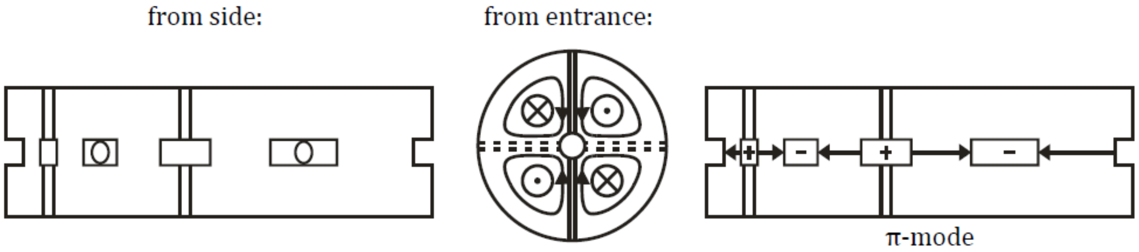


U. Ratzinger, Proc. Linac Conf. 1996

Types of cavities:
Crossed-bar H-mode (CH, “spoke“)

- few to many gaps: high voltage, no transverse focusing
- gap & drift tube lengths increase with particle velocity (energy)
- principle:
  - create longitudinal magnetic field $\vec{B}$ (higher mode w.r.t. IH-cavity)
  - place drift tube supports along $\vec{E} = \vec{\nabla} \times \vec{B}$ in order to charge drift tubes



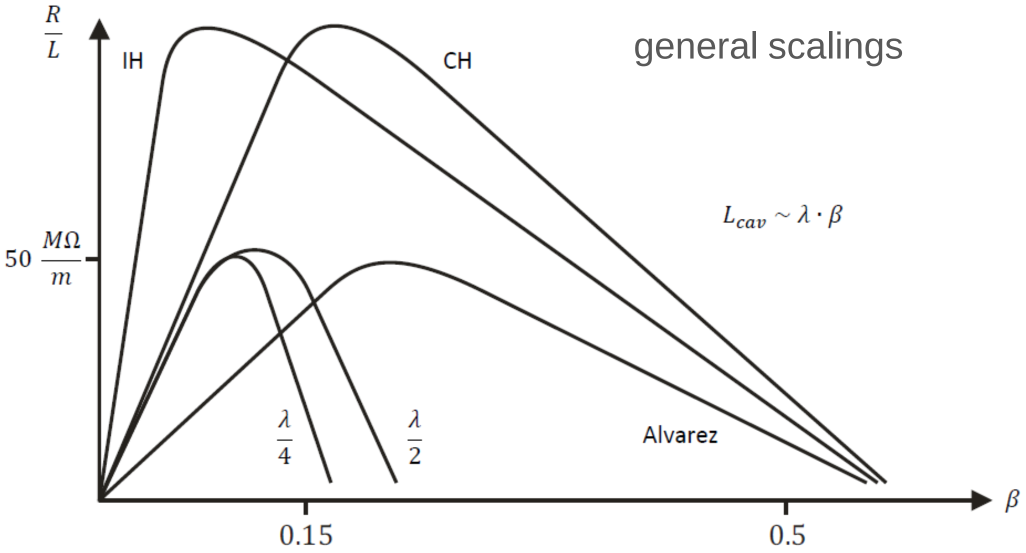


- GSI Darmstadt, 1st p-Linac cavity
- 21 gaps
- peak voltage: ≤ 330 kV/gap
- frequency: 352 MHz

G. Clemente, PRAB, **14**, 110101 (2011)

Types of cavities:
Figures of merit and comparison

- shunt impedance per length R/L:
  (gap voltage)^2 per input power
- Q: width of resonance $f/\Delta f$ ->
  rise / decay time, scales with R/L
- $(\frac{R}{L})\ /\ Q$:
  concentration of cavity energy at gap
- maximum electric surface field
- preservation of beam quality
- size (H-mode is smaller than Alvarez)
- cost



general scalings

<u>dt-distance short</u>

- E_z on axis lower, because:

too high E_r

- higher $dt \leftrightarrow dt$ Capacity
- more I needed to get U $[\int I dt = C \cdot U]$
- more P_{loss} from residual resistivity

more P_{loss}, less $E_z \rightarrow$ lower $\frac{R}{L}$

<u>dt-distance long</u>

- E_z on axis higher

- I needs longer path to dt
  $\rightarrow$ more P_{loss}
- cavity longer

netto: $\frac{R}{L}$ lower

Types of cavities:
Radio Frequency Quadrupole (RFQ)

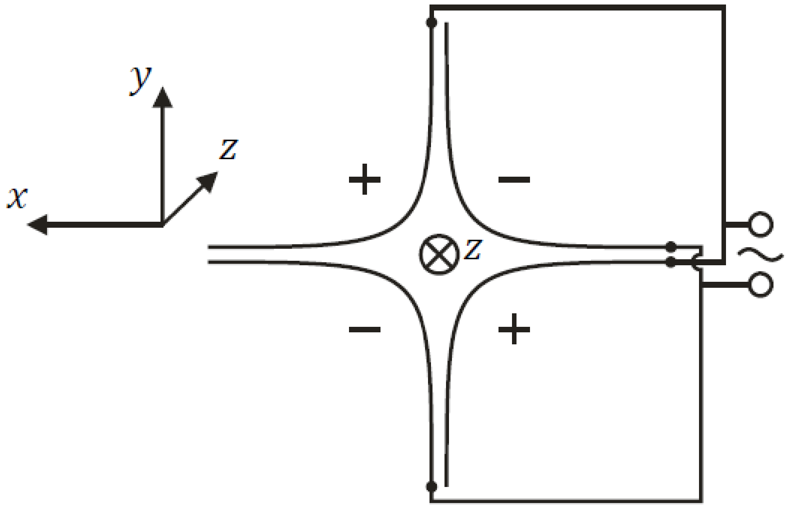
- transform dc-beam into bunched beam, keep beam focused
- starts w/o gaps -> ends with many “effective“ gaps, called cells
- effective gap lengths increase with beam energy
- principle:
  - create electric field that simultaneously bunches, accelerates, and focuses
  - once built: almost everything fixed; just field amplitude can be varied

- SARAF / Israel
- peak voltage: 56 kV
- frequency: 176 MHz

A. Perry et al. Proc. Linac Conf. 2018

Types of cavities:
Radio Frequency Quadrupole (RFQ)

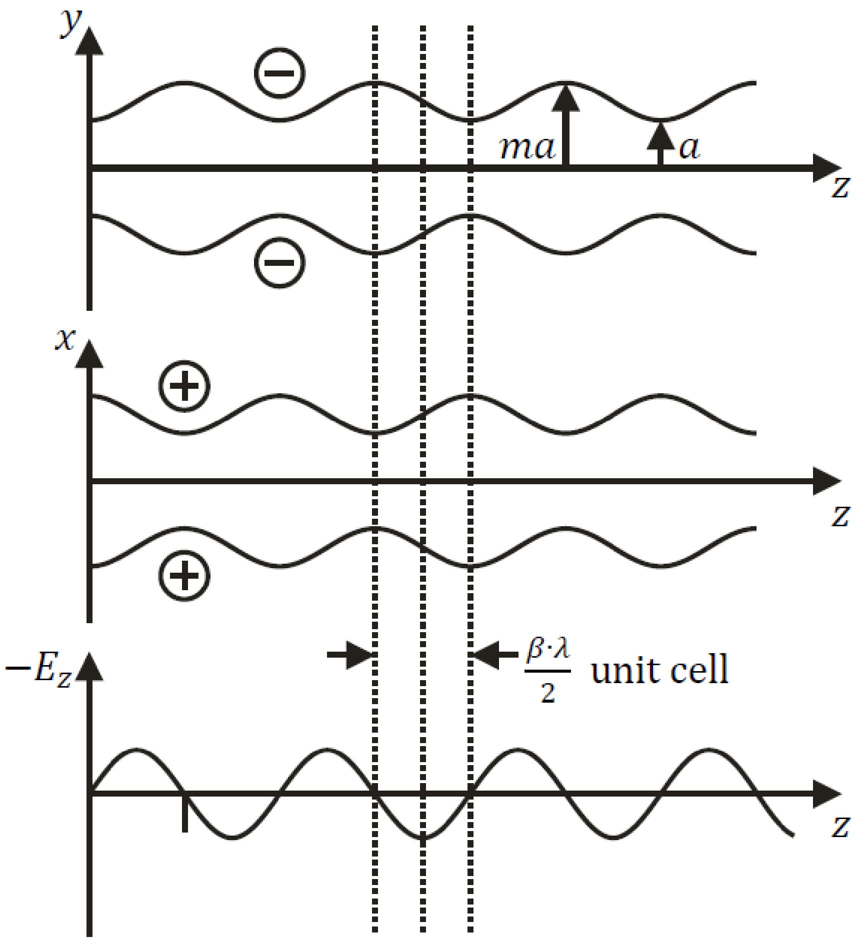
bunching + focusing device:



4 Poles, rf-driven → RFQ

- focusing in each plane changes with time
- particles move along z
- focusing varies along z

→ net focussing like F0D0

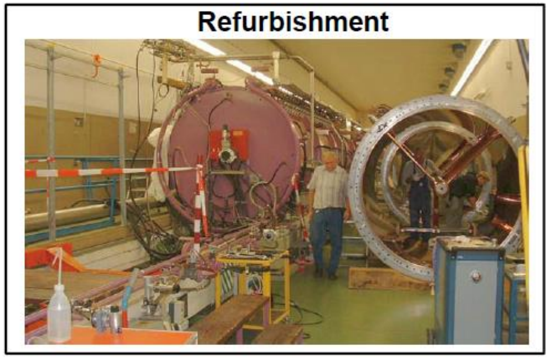


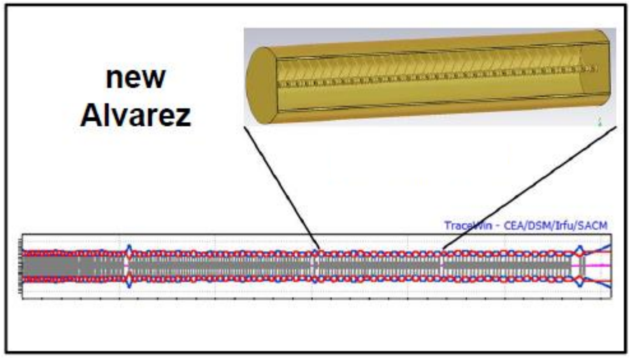
Choice of cavity type:

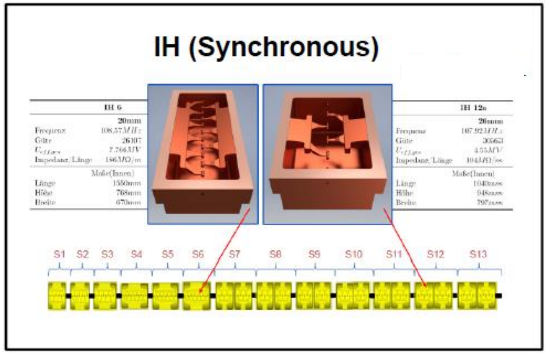
- cavities and their rf-power units are the main cost driver of a linac project (≥ 50%)
- choice is about millions of $, €, CHF, ₤, ...
- it takes a systematic analysis of the specific projects needs:
  - “must have“ criteria w.r.t. target beam parameters
  - on-campus expertise (today and following 10 years)
  - tight budgets limitations
  - on-site building limitations
  - schedule restrictions
- options, that are not excluded <u>from first principles</u> should be worked out and quantitatively benchmarked w.r.t.:
  - above criteria
  - construction cost & risks
  - operation cost & flexibility
  - output beam quality
  - needs for maintenance (amount of spares, competences of staff, ext. suppliers)
  - experiences with potential partners

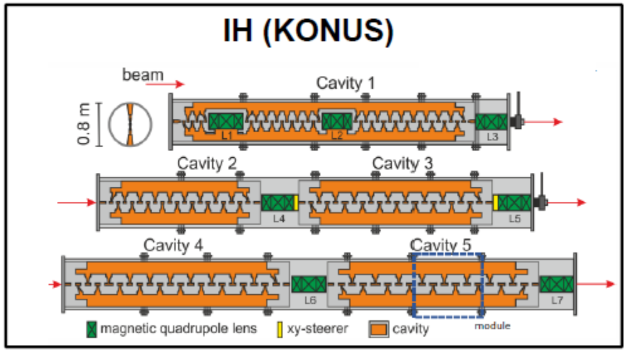
Choice of cavity type:
Benchmarking for uranium DTL

- GSI replaces a DTL for intense uranium beams: 1.4 – 11.4 MeV/u of acceleration, 50 m long
- four options proposed in 2016:
  1. refurbish existing DTL
  2. new DTL from Alverez-type cavities
  3. new DTL from IH-cavities w/o quadrupoles inside drift tubes, cavities separated by triplets
  4. new DTL from IH-cavities with quadrupoles inside few prolonged drift tubes


Refurbishment


new Alvarez


IH (Synchronous)


IH (KONUS)

Choice of cavity type:
Benchmarking for uranium DTL

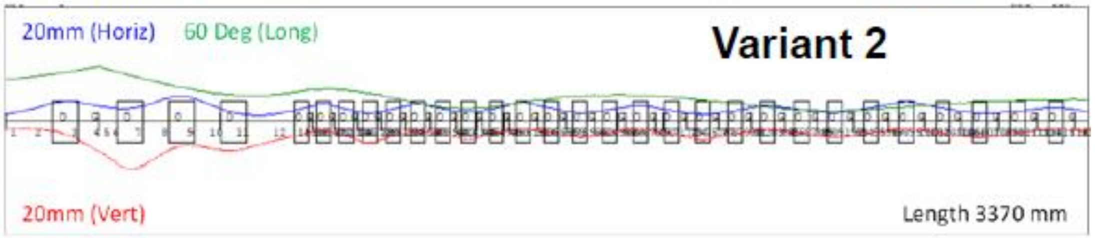
- criteria:
    - operational flexibility & ease (beam set-up procedure, needs for instrumentation, …)
    - operational risks (surface fields, tolerances)
    - feasibility of construction and copper plating
    - detailed lists with required components & spares incl. mechanical designs
    - cost for each option estimated by same(!) experts of corresponding technical departments
    - -> cost book of 40 pages
    - beam quality: options 2-4 simulated with six different beam scenarios (same person and code)
    - … many more
- total of 34 criteria per option have been collected into a table
- options described in dedicated proposals each (≈ 30 pages) by respective proposers
- options presented to dedicated international expert review committee by respective proposers
- committee evaluated proposals and delivered final report
- final choice by host lab

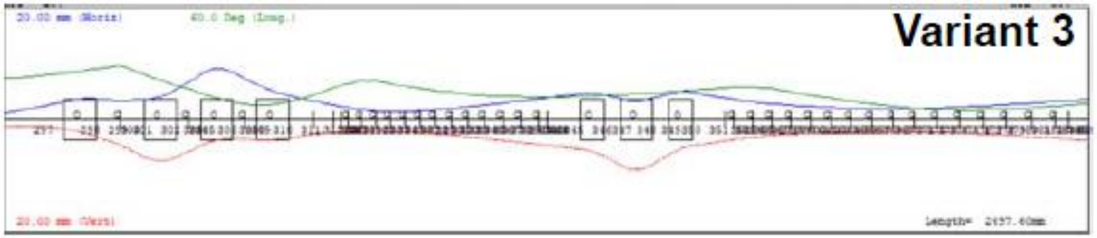
Choice of cavity type:
Benchmarking for proton DTL

- TRIUMF proton linac for neutron source: 3 – 10 MeV of acceleration, moderate current

- seven options are considered:
  - two Alvarez-cavity options: different scenarios for beam matching before/within DTL
  - five CH-cavity options: different number of cavities, # gaps, rf-phases, # focusing quads

Parameter	**Variant 1**	**Variant2**	**Variant3**	**Variant4**	**Variant5**	**Variant6**	**Variant7**
Type	Alvarez	Alvarez	CH-DTL	CH-DTL	CH-DTL	CH-DTL	CH-DTL
Tanks	1	1	2	3	4	3	5
Drift tubes	25	25	12,15	11,8,11	8,7,9,11	13,10,14	4,4,5,5,6
Eo (MV/m)	3.4	3.4	6.6	6	5	5	6
Synch. Phase φ_s	-30	-30	0, -60, 0	-25, -25, -25	-27, -25, -25, -25	-28, -27, -28	-25





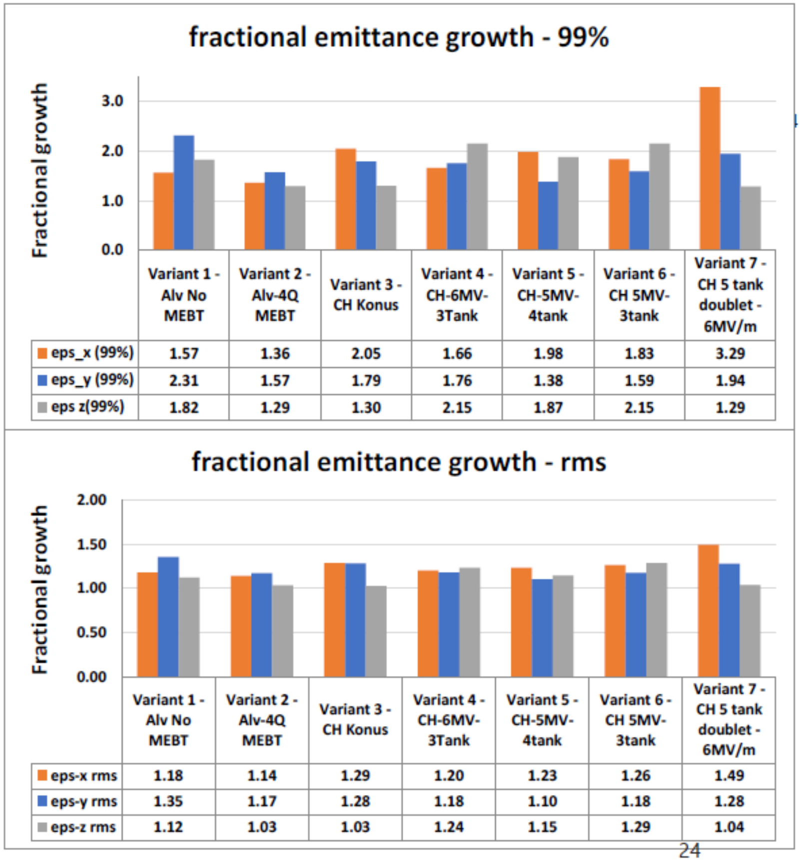
M. Abbaslou
LINAC Conf.
2022

Choice of cavity type:
Benchmarking for proton DTL

- criteria:
  - growth of rms-emittance & beam halo (same person, two codes)
  - low beam transmission loss
  - long. & transv. DTL acceptance
  - power consumption (rf-power and focusing quads)
  - total construction cost
  - ease of operation
  - robustness of design

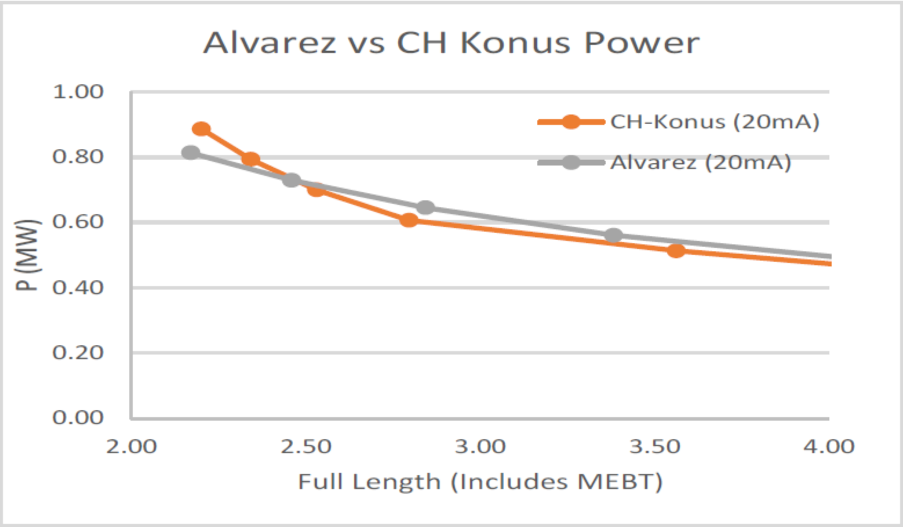
- final choice at TRIUMF

M. Abbaslou
LINAC Conf.
2022



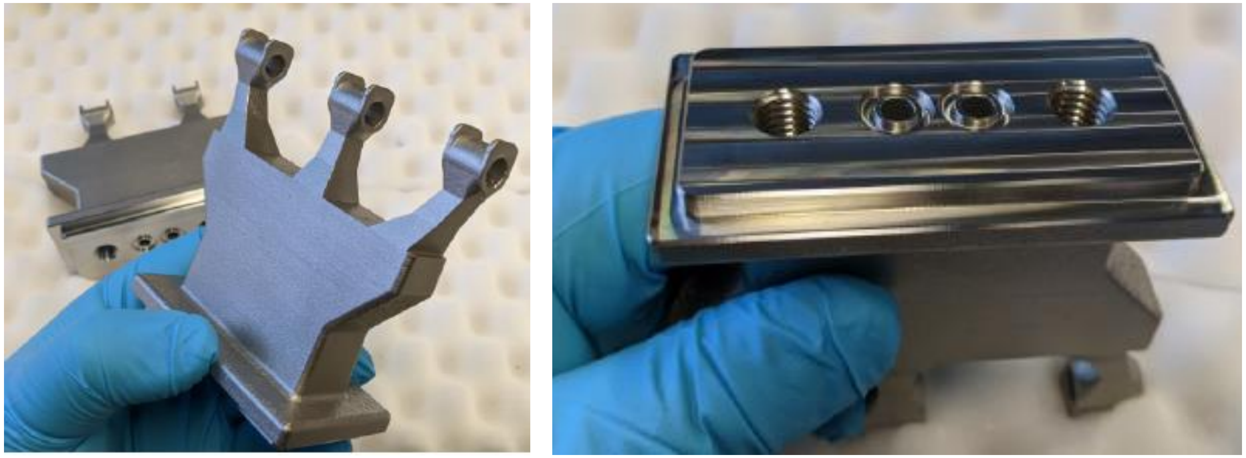
	Variant 1 - Alv No MEBT	Variant 2 - Alv-4Q MEBT	Variant 3 - CH Konus	Variant 4 - CH-6MV-3Tank	Variant 5 - CH-5MV-4tank	Variant 6 - CH 5MV-3tank	Variant 7 - CH 5 tank doublet - 6MV/m
🟧 eps_x (99%)	1.57	1.36	2.05	1.66	1.98	1.83	3.29
🟦 eps_y (99%)	2.31	1.57	1.79	1.76	1.38	1.59	1.94
⬜ eps z(99%)	1.82	1.29	1.30	2.15	1.87	2.15	1.29

	Variant 1 - Alv No MEBT	Variant 2 - Alv-4Q MEBT	Variant 3 - CH Konus	Variant 4 - CH-6MV-3Tank	Variant 5 - CH-5MV-4tank	Variant 6 - CH 5MV-3tank	Variant 7 - CH 5 tank doublet - 6MV/m
🟧 eps-x rms	1.18	1.14	1.29	1.20	1.23	1.26	1.49
🟦 eps-y rms	1.35	1.17	1.28	1.18	1.10	1.18	1.28
⬜ eps-z rms	1.12	1.03	1.03	1.24	1.15	1.29	1.04



Practical issues:
Dimensions

- cavity radius should allow on-site handling: $R \leq 1\ m$
- dimensions to be accessible by tools and humans: $10\ cm \leq \beta\lambda = \frac{\beta c}{f} \leq 50\ cm$
  - β from input energy
  - f according to:
    - rf-power sources available on the market (cost !)
    - frequencies already used at the lab
- the lower limit may change considerable in near future, in regard of remarkable progress being made in additive machining (3d-printing)



H. Hähnel, HIAT Conf. 2022

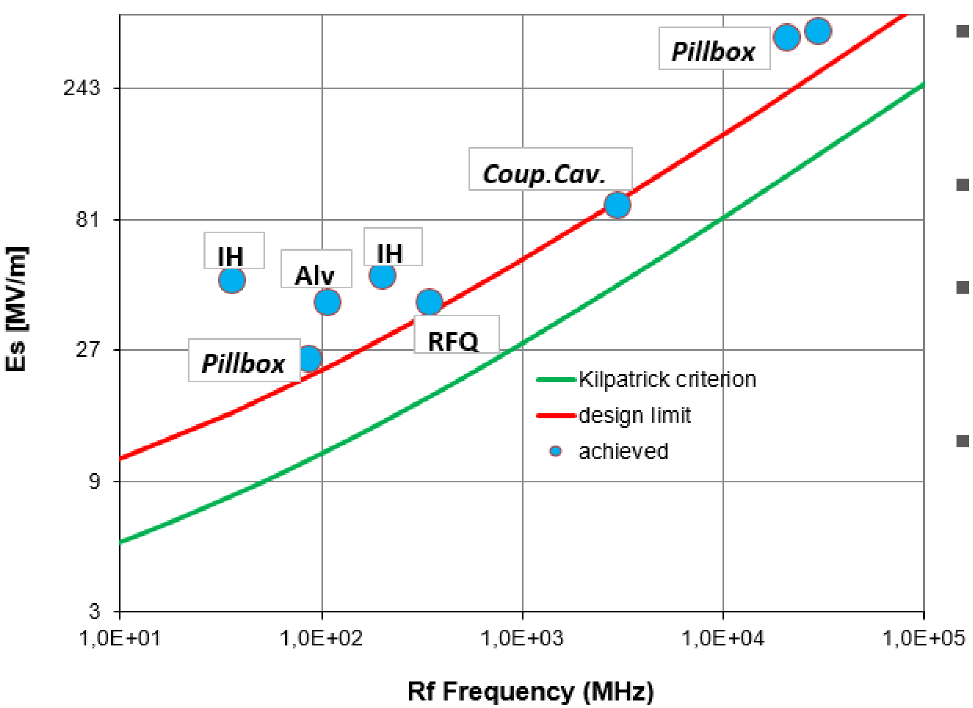
BEVATECH

Practical issues:
Maximum surface field strength

surface field strength E_s should permit reliable long-term operation including ≈ 5% margin:

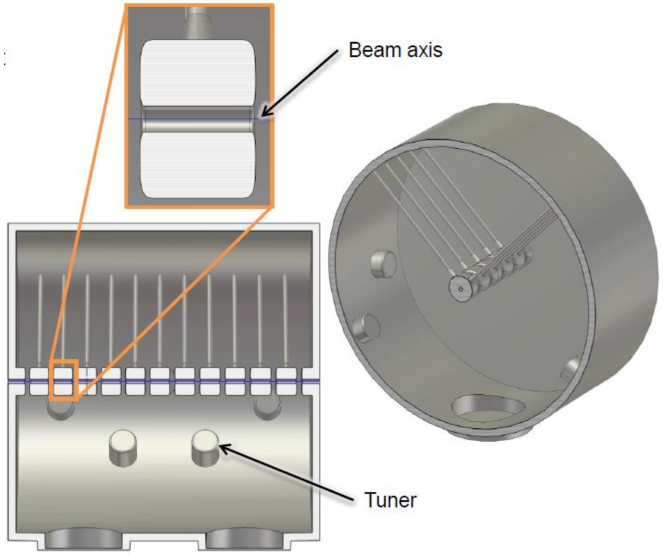
- in general, reasonable field strength increases with f
- the Kilpatrick criterion (late 40ies, empirical) is well known, but respected differently in practice

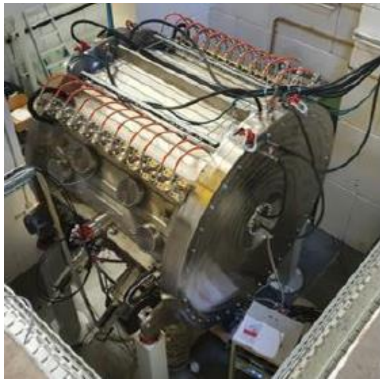
$$f\,[MHz] = 1.64\,E_K^2\,e^{-\frac{8.5}{E_K}}$$



- modern designs for many-gap cavities vary from $1.0\,E_K \leq E_s \leq 1.7\,E_K,\quad f \geq 100$ MHz
- at lower frequencies, the factor is larger
- it depends a lot on how conservative or agressive the actual design is
- larger overall surface & duty cycle -> more conservative

Practical issues:
From MWS file to operating cavity



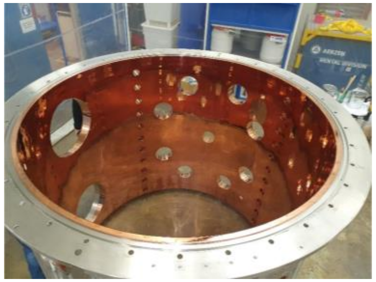


- very long way, picked with surprises (negative and positive)
- is often underestimated as “engineers‘ and/or mechanics‘ job, will be done some way“
- several years, many meetings, calculations, trials & fails at workshops/suppliers, consulting experts from other labs, … → <u>prototyping prior to launch series production!</u>
- in the following, just few issues are sketched briefly

Practical issues:
Material

- inner cavity surface to be plated with copper to minimize Ohmic surface losses, i.e., maximize shunt impedance R

  -> very few steel types remain, that can be plated adequately



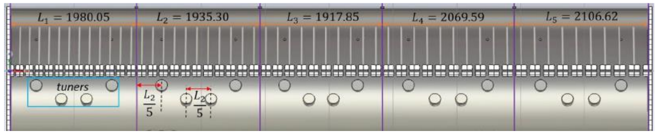
- for long time, mild steel has been chosen for its twice larger heat conductivity

- nowadays, stainless steel is widely preferred:
  - much less trouble with erosion inside water cooling channels
  - hardly more expensive
  - workshops must seperate strictly machining of stainless from mild; many do so by waving mild
  - most Cu-plating workshops do not like working with mild as it spoils the basins

Practical issues:
Critical tolerances

- natural relative bandwidth of rf-power sources is about 10^{-3}

- TM-cavities (f dominated by radius):
    - f very sensitive to outer radius and roundness of the mantle
    - rel. error in radius is rel. error in frequency
    - mean outer radius should deviate from design by ≤ 0.3 mm
    - corresponding f-shift can be corrected by so-called plungers
        - they reduce effective cavity volume (radius)
        - they cannot augment the volume !!!
          -> cavity design assumes plungers moved half way in
        - <u>plungers do practically not change voltage distribution along gaps</u>
    - quads inside drift tubes: transverse positioning of drift tubes to precision of about 0.1 mm



C. Xiao et al., NIM **A** 1027 166295 (2022)

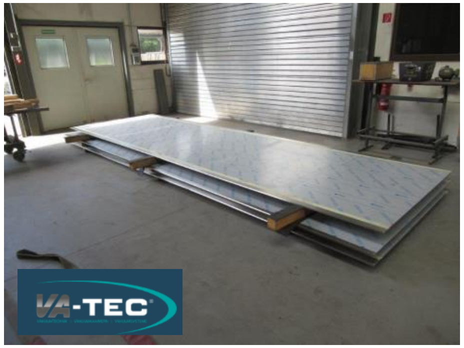
- TE-cavities (f dominated by capacity between drift tubes)
    - f very sensitive to gap widths
    - corresponding f-shift can be corrected by so-called plungers
        - they reduce effective cavity volume (radius)
        - they cannot augment the volume !!!
          -> cavity design assumes plungers moved half way in
        - <u>plungers do significantly change voltage distribution along gaps</u>

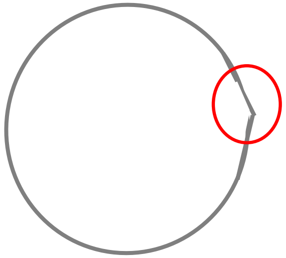
Practical issues:
Critical tolerances

- quantification of tolerances by dedicated analytical calculations or even FEM simulations -> values depend on specific project; tight tolerances -> high cost, small market

- way to produce a round cavity mantle depends on what tolerances can be accepted

    - rolling causes residual pear-shape at the weld

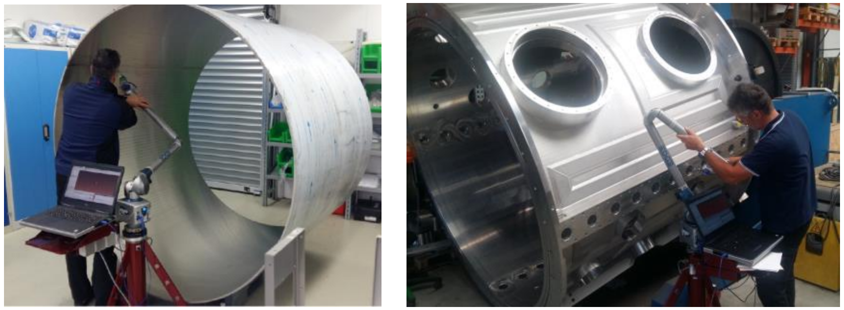




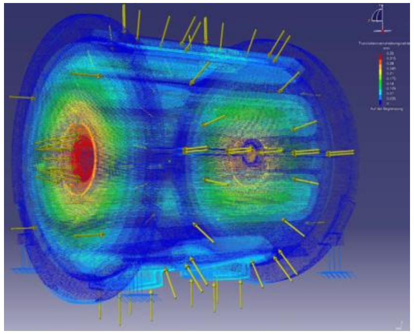
    - drilling (from inside) gives very good roundness but is much more expensive (especially for large r)

Practical issues:
Critical tolerances, intrinsic deformation

- tolerances to be checked during/after production and at delivery on-site (after transport !!)
- dedicated devices probe the piece by touching it (e.g. FARO-arm)
- alternatively, laser scanners are used



- cavities may deform significantly by:
    - own mass and gravity (0.x mm)
    - pressure from outside after evacuation (0.x mm)
    - insufficient cooling or room temperature regulation



- deformations may change resonance-frequency and/or voltage distribution along gaps
- should be evaluated during design phase and anticipated into production drawings

Practical issues:
Alignment

- most sensitive: magnetic axis of the quads “as built“ (if any) inside the drift tubes. Accordingly, internal quads augment alignment efforts significantly ! $|\Delta\vec{r}| \leq 0.1$ mm

- alignment is from inside (beam/quad axis) towards outside (reference marks on cavity mantle)

- quad as “built“ inside drift tube $\rightarrow$
  - measuring its magnetic axis, i.e., $\vec{B} \coloneqq 0$
  - storing/marking this information for each drift tube individually
  - aligning each drift tube, such that magnetic axis coinsides with design beam axis even …
  - … at expense of twisted/rotated drift tubes afterwards
  - misaligned E-fields are much less harmful w.r.t. misaligned B-fields

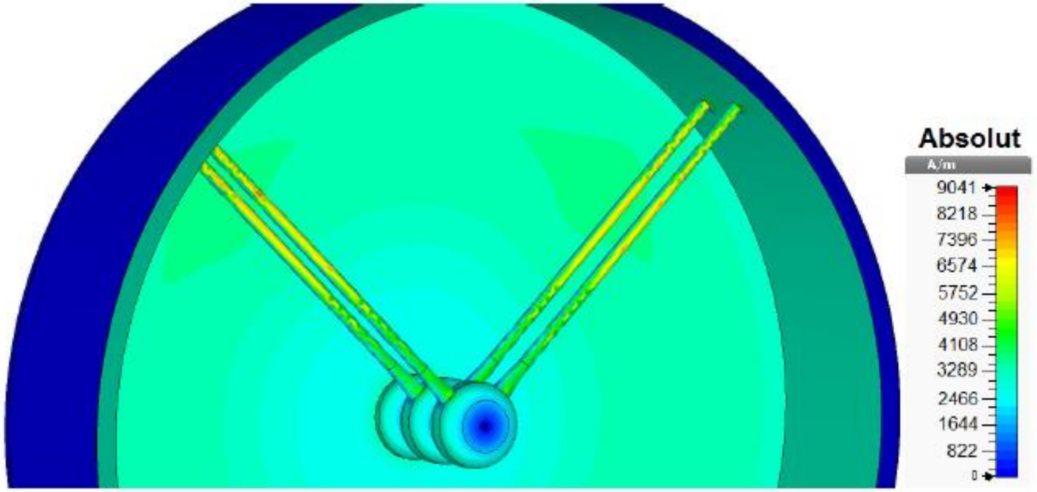
example: alignment of tubes for new Alvarez cavity / GSI

- alternative to manual alignment: tight machining tolerances such that it must fit (Alvarez of Linac-4 / CERN)

- each project may have its individually optimized alignment solution

Practical issues:
Cooling

- power to be cooled away is given by residual shunt impedance $P_c = \frac{U_{cav}^2}{2R_s}$
- generally, power is absorbed by water at room temperature
- a rule-of-thumb states:
  - 1 l/sec of water increases temperature by 1°C during absorption of 4.2 kW
  - rules works very fine and is confirmed by various simulations, albeit different schemes of water flow, channel geometries, etc.
- power dissipation is not homogeneously distributed along inner cavity surfaces
- scales with the square of induced surface current, i.e., with surface B-field amplitude (squared)
- dedicated simulations can provide for “surface current“ or “heat“ map



Practical issues:
Cooling

- codes, that simulate cooling by using the full geometry of cavity and cooling channels are commercially available

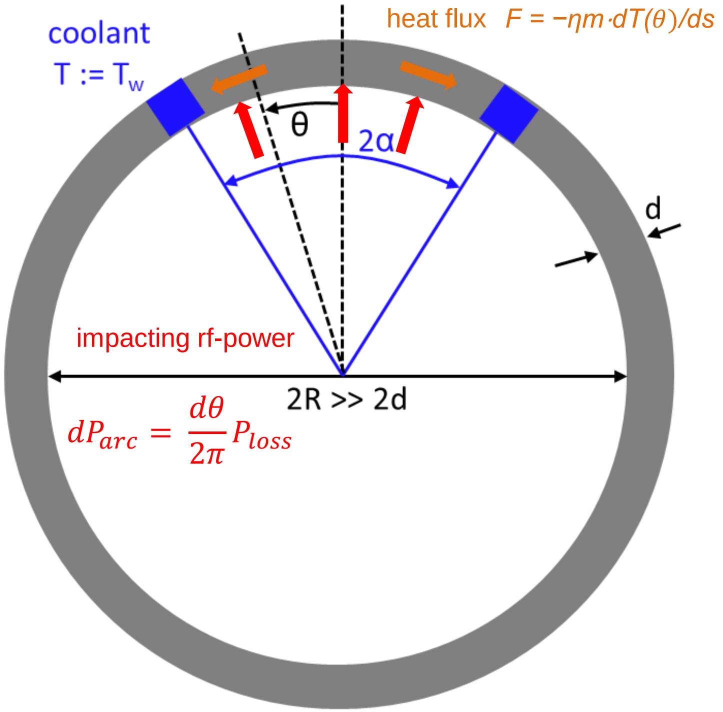
- however, their use is very hard, time consuming, and expensive (up to 10^5 €/$/CHF/£ per licence / y)

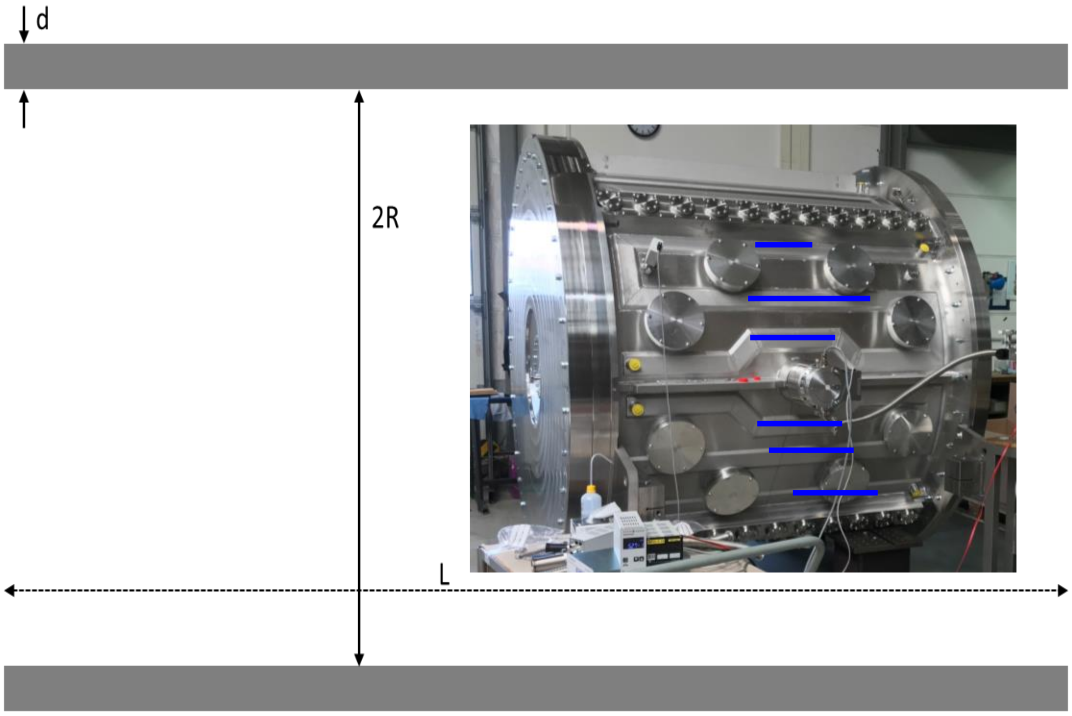
- for practical application, it may be sufficient to use simple theoretical models:

    - assumption of constant temperature at location of cooling channels
    - using basic equations of heat conduction
    - adapting equations to specific geometry

- in the following, examples for cooling the cavity mantle and the drift tube end caps are given

Practical issues:
Cooling of cavity mantle



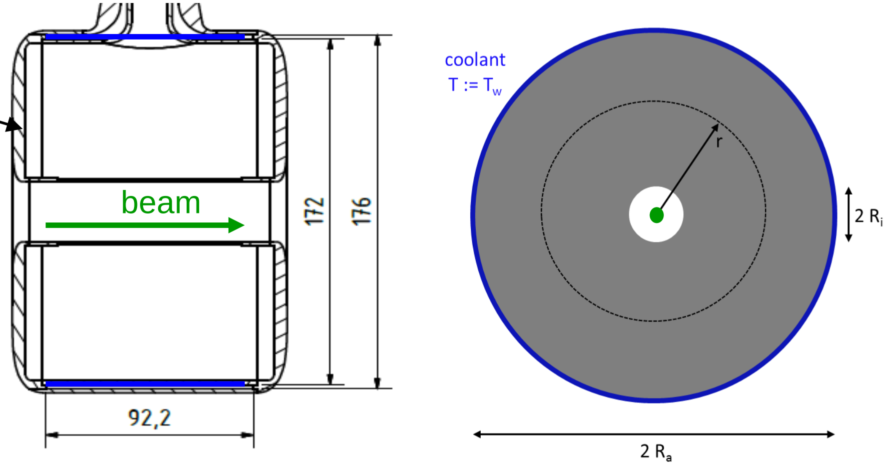


- at each θ: local flux towards channel augments by $dF = dP_{arc}\frac{1}{d \cdot L} = \frac{P_{loss} d\theta}{2\pi\, d \cdot L}$
- total flux from integrating dF and using $F(0) = 0$
- plugging result for $F(\theta)$ into equation for heat flux
- integration of $dT(\theta)$: $T(\theta) = -\frac{P_{loss}\, R\, \theta^2}{4\pi\, \eta_m\, d \cdot L} + T(\theta = 0),\ T_{max} := T(\theta = 0)$
- finally: $T_{max} = T_w + \frac{P_{loss}\, R\, \alpha^2}{4\pi\, \eta_m\, d \cdot L}$ → required α to limit temperature to T_{max}

credits to S. Ramberger for proposing this approach

Practical issues:
Cooling of drift tube end plate

same considerations & equations serve to calculate temperature on indirectly cooled drift tube end plate:



- scaling of rf-power at cap with r from:

$$\vec{\nabla} \times \vec{B} \sim \dot{\vec{E}}, \quad \oiint (\vec{\nabla} \times \vec{B}) d\vec{A} \sim \dot{E} r^2, \quad B \sim \dot{B} \sim I$$

$dP \sim I^2 \sim r^2$, i.e., $dP = a \cdot r^2$

- eqs. for power/heat flux to be adapted to geometry
- factor a from comparing surface of endplate (P_{plate}) to total in inner surface of cavity ($P_{loss, tot}$)
- integrations …
- $T(r) = -\frac{a}{b\eta_p}\left[\frac{1}{12}r^4 - \frac{1}{2}r^2R_i^2 + \frac{2}{3}rR_i^3\right] + T_0$
- $T_0 = T_w + \frac{a}{b\eta_p}\left[\frac{1}{12}R_a^4 - \frac{1}{2}R_a^2R_i^2 + \frac{2}{3}R_aR_i^3\right]$

seems long and ugly, but it is faster and cheaper than a FEM simulation

Copper plating:
Motivation

- specific resistance of stainless $\rho \approx 0.72\,\Omega\,\frac{mm^2}{m}$
- specific resistance of copper $\rho \approx 0.017\,\Omega\,\frac{mm^2}{m}$
- reduction of power loss by factor of 40 through plating inner surface of cavity
- layer thickness should be well beyond the skin depth, i.e., $1/e$-penedration depth of rf-wave:

$$\delta = \sqrt{\frac{\rho}{\pi \mu_0 f}}$$

  - 10 MHz → δ = 21 µm,   1 GHz → δ = 2.1 µm
  - in practice layer thickness ≥ 15 δ, mainly due to achievable homogeneity

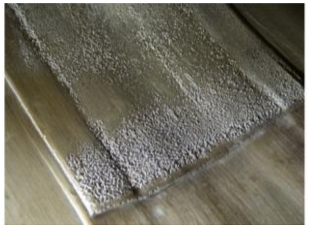
- alternatively, whole cavity may be produced from bulk copper → issues with:
  - cost
  - meachnical stability

Copper plating:
Requirements to/for plating

- plating for accelerators is a complex task, number of experts around the world is very sparse

- there are many commercial plating facilities everywhere. But many focus on making surfaces look pretty (cars, dishes, accessories, etc …), rather on conductivity

- inside of a cavity operated under incoming rf-power it needs:
    - very clean copper, i.e., $\rho \leq 0.0171\ \Omega\ \frac{mm^2}{m}$
    - copper surface roughness $R_a \leq 1.0$ µm (mean of bump heights $< |hi| >$ from mean (even) surface)
    - strong adhesion (no peeling off)
    - no bubbles

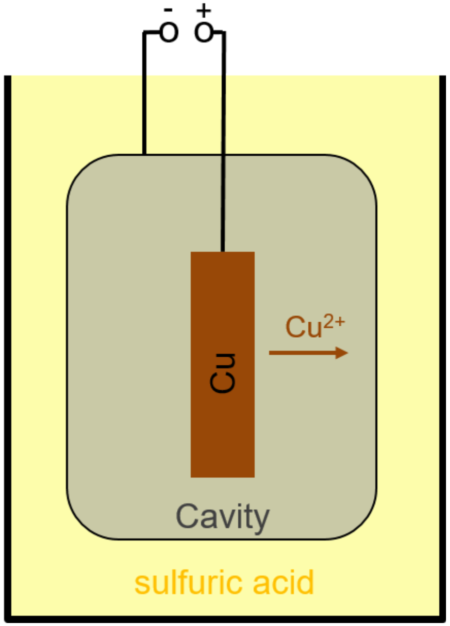


- steel to be plated should feature:
    - $R_a \leq 0.3$ µm
    - preferably of type stainless: 1.4404, 1.4301, 1.4306, 1.4307 (304L)
    - no voids

Copper plating:
Procedure

- surface pre-processing (days):
  - cleaning (chemicals!), removing bumps (partially by hand!)
  - masking of surfaces not to be plated (outer part of cavity, sealing surfaces)
  - closing holes, to which Ni/Cu must not enter (bores, cooling channels)
  - degreasing (chemicals!)
  - surface activiation

- plating (hours):
  - plating with very thin Ni surface (link between stainless steel and Cu)
  - plating with Cu surface
- surface post-processing (days):
  - water rinsing
  - removing bumps and blisters
  - final polishing
  - applying pre-vacuum or N-atmosphere in case of long storage afterwards



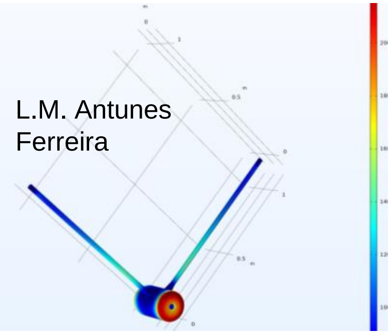
Copper plating:
Procedure

- tayloring of anodes is lengthy procedure requiring key expert knowledge:
  - a large number of individual anodes to be distributed inside the cavity
  - to arranged around stems, drift tubes, flanges → tailoring
  - some parts need to be “shadowed“ to avoid over-plating and blisters

- anode distribution and geometry determines homogeneity of layer thickness

- requires trials (& errors) with dummy geometries

- even dedicated FEM simulation tools are used to predict the current flow



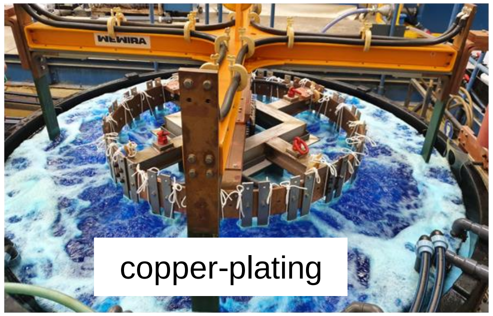
L.M. Antunes Ferreira

- applied currents during plating range up to 10^4 Amps

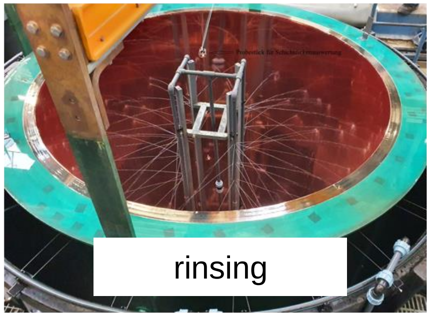
masked

anodes

nickel-plating



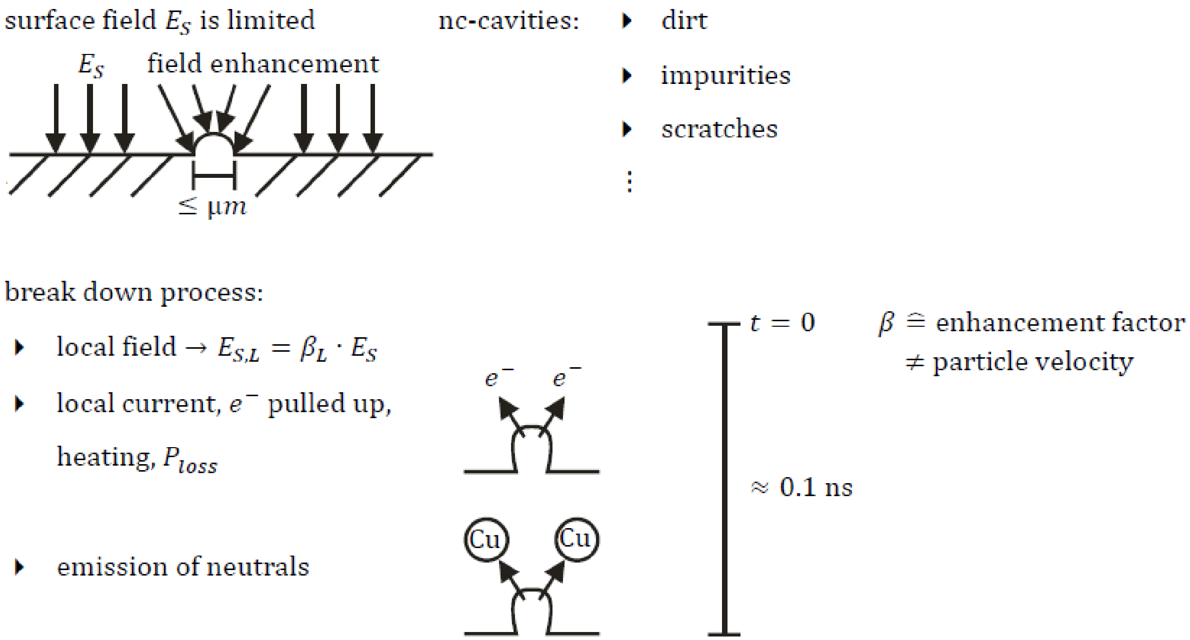
copper-plating



rinsing

Rf-conditioning

- although new cavity has been cleaned and re-polished, its surface is full of tiny dirt / dust particles and material spikes / scratches
- cause local surface field peaks → local field emission → melting of these perturbations
- melting causes further spreading of perturbation and strong pressure increase → rf-breakdown → de-tuning → reflection of incoming rf-power



surface field E_S is limited

nc-cavities:
- dirt
- impurities
- scratches
- ⋮

break down process:
- local field → $E_{S,L} = \beta_L \cdot E_S$
- local current, e^- pulled up, heating, P_{loss}
- emission of neutrals

$t = 0$

≈ 0.1 ns

$\beta \mathrel{\widehat{=}}$ enhancement factor $\neq$ particle velocity

Rf-conditioning

- initial perturbations are “conditioned“ away, starting from very low
  - rf-power level P
  - rf-pulse length τ
  - rf-repetition rate η

- initial time-averaged rf-power $P \cdot \tau \cdot \eta$ is some 10^5 lower w.r.t. design value

- first conditioning of a new cavity up to design operation parameters: weeks to months

- re-conditioning time for cavity already operated at design values:
  - after breaking the vacuum: days to weeks
  - after some operation below design: hours to days

Rf-conditioning:
General procedure

- rf-conditioning is like cooking; each expert has individual recipe

- common features:
  - diagnostics: pressure, heat sensors, cooling water temperature, *cameras, X-ray det., res. gas spectrometer, …*
  - rf-signals: coupled-in / coupled-out / reflected rf-power
  - while watching vacuum, reflected power, *and …*:
    - increasing smoothly(!) one of the parameters P, τ, or η
    - if pressure beyond approx. 10^{-5} mbar or breakdown of coupled-out power →
      - reduction of input rf-power, waiting for recovery of vacuum to some 10^{-7} mbar
      - recovery of mean input rf-power
    - increasing the chosen parameter
    - increasing the other parameters

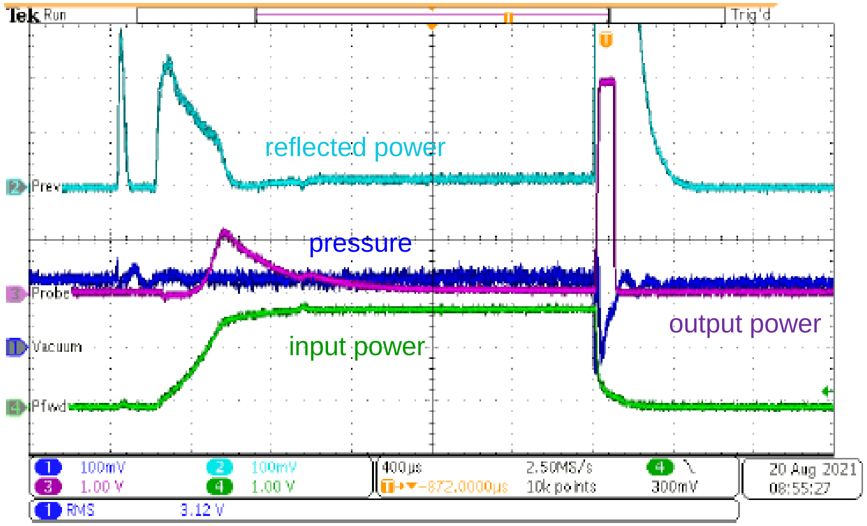
- cavity should be conditioned with some n·10% margin beyond design parameters

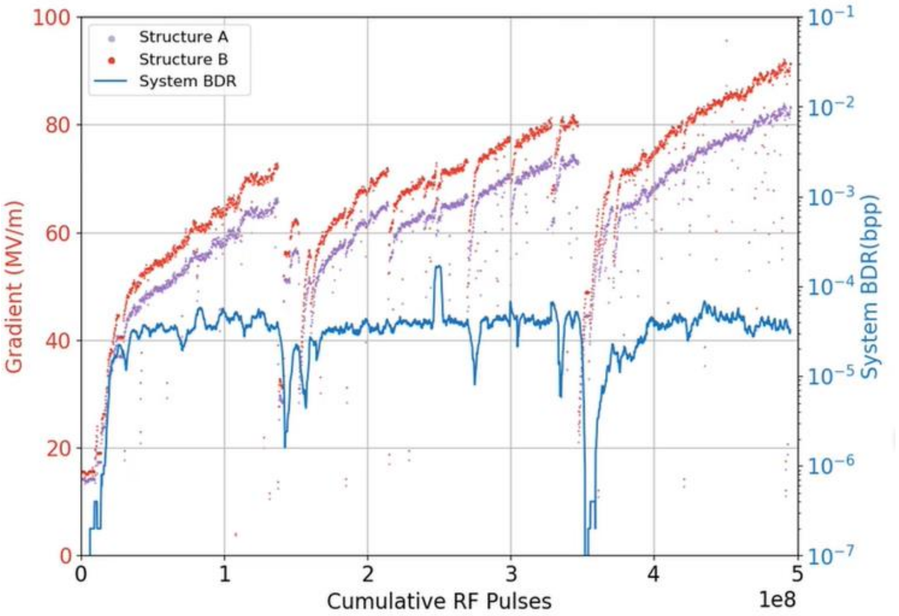
- cavity should perform long-term run (some days) at these parameters

- w/o operation, cavity will become untrained and needs re-conditioning

Rf-conditioning:
General procedure

- several trials have been made to fully automate rf-conditioning
- doing so, it has been realized empirically, that surfaces are conditioned by rf-pulses that do <u>not</u> cause rf-beakdowns, i.e., during the recovery periods
- a good example can be found in: L. Millar, Proc. of the 2020 Linac-Conf.





Material taken from and thanks to …

F. Gerigk, P. Gerhard, X. Du, U. Ratzinger, G. Clemente, H. Podlech, R. Laxdal, M. Abbaslou, H. Hähnel, A. Perry, M. Heilmann, S. Mickat, M.S. Kaiser, H. Dewid, C. Xiao, S. Ramberger, NTG, VA-TEC, GSI-workshop, T. Dettinger, E. Merz, M. Taborelli, L.M. Antunes Ferreira, BEVATECH,

and many more …