Experience in Research, Development, Construction and Commissioning of Normal Conducting Accelerating Structures.

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Content

1. Construction of the accelerating system for high energy part of the Moscow Meson Facility.

2. Methodical developments

3. Implementation of developed methods

4. New developments

High Energy Part of INR Linac, 100-600 MэВ

DAW structure, invented by V.G. Andreev [1972], for INR linac was developed and tested in RTI AS USSR.

Accelerating cavities in the tunnel. 27 four-section Disk And Washer (DAW) cavities, f_0= 991 MHz. ~2400 DAW modules, diameter (450-410) mm. The total length ~ 300 m

Frame work technology was established:
- **hot sludge to 500 mm blanks from 170 mm OFC rods;**
- **pre-forming with stamping;**
- **draft mechanical treatment;**
- **fine mechanical treatment;**
- **RF tuning for tanks;**
- **tanks brazing;**
- **………**

The initial three steps were done in industry with INR and RTI monitoring.

Construction of accelerating structure - starting from fine mechanical treatment and to structure commissioning has been performed by INR in-house.

Tasks (to be solved)

- **reasonable and motivated tolerances for mass production;**
- **precise and fast procedure for RF tuning of tanks;**
- **HOM removal from the vicinity of operating point;**
- **brazing, vacuum tests and RF tuning after brazing;**
- **cavity assembling and RF tuning;**
- **cavity matching with waveguide;**
- **cavities RF commissioning.**

Final mechanical treatment was performed with standard lathe and milling machines with using diamond lathe tool at the last step.

RF tuning of DAW tanks

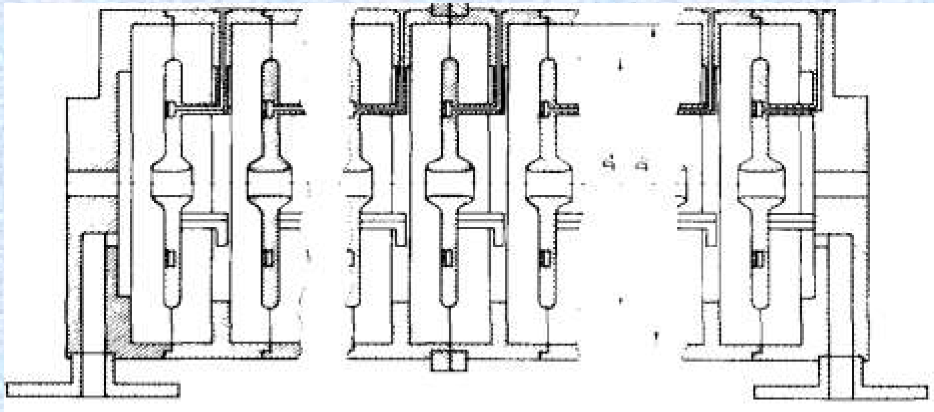


Fig.1. The disk and washer accelerating tank.

Steps

- *operating frequency adjustment;*
- *stop band removing;*
- *field distribution tuning;*
- *HOM displacement.*

Due to extra high coupling coefficient in DAW structure, kc~45%, individual cells tuning is not required. Structures with the high coupling coefficient allow frequency tuning for the total tank 'in average', ensuring required $\sigma_E \sim 1\%$ for the accepted precision of mechanical treatment.

Stop band removing

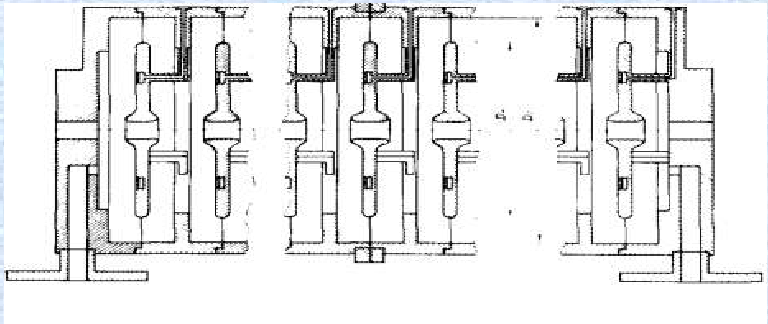
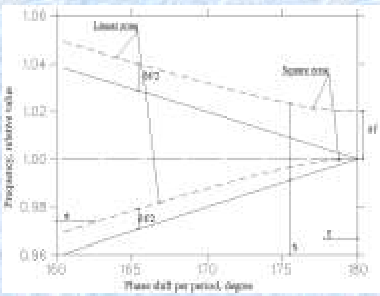


Fig.1. The disk and washer accelerating tank.

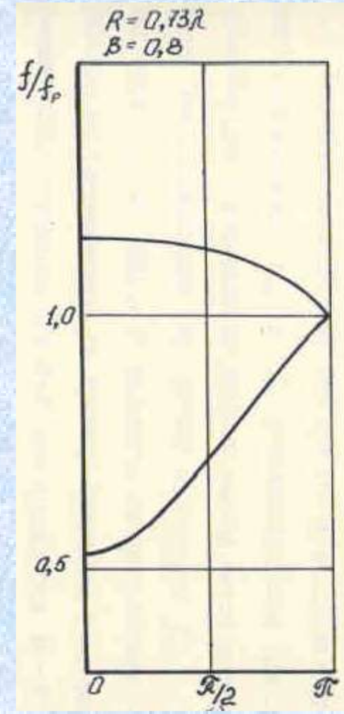
Due to boundary conditions at the tank ands just accelerating mode with f_a can be excited. But the stop band $\delta f = f_c - f_a$ should be removed for maximal stability.

With k_c=0.4 DAW dispersion curve is nonlinear even in the vicinity of operating point.

The linear approximation, used before, $\delta f = f_u + f_d - 2f_a$, provides big errors.



Operating point vicinity.



Total DAW dispersion curve

$$f^t_m, f^b_m \qquad \theta_m = \frac{(N-m)\pi}{N}, \quad \theta_0 = \pi, \quad \xi_m = \theta_0 - \theta_m$$

$$\delta f = \frac{m^2\Delta F_n - n^2\Delta F_m}{m^2 - n^2} = \frac{j^2\Delta F_n - n^2\Delta F_j}{j^2 - n^2} = \frac{m^2\Delta F_j - j^2\Delta F_m}{m^2 - j^2}.$$

Without limitation on k_c it is valid for all compensated structures.

Some methods for the stop band evaluation in the compensated accelerating structures. 1895.

Field distribution tuning.
Methodical error for bead pull measurements

The classical Slater formula $df/f \sim E^2R^3/V$ is just first approximation valid for infinite uniform field. For measurements in big DTL and DAW cavities, when R is comparable with gap length … Calibration is not possible.

Extra precise 2D simulation to fix frequency shift ~ 10^{-4} with the precision 10^{-3}

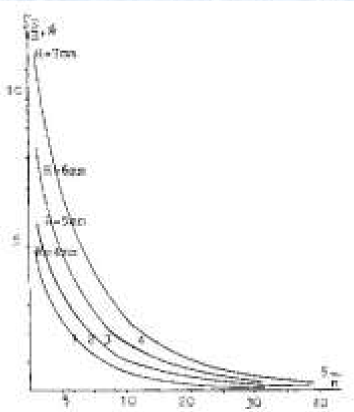


Fig. 4. Systematic error of the field distribution measurements in first DTL tank. n – number of the accelerating gap.

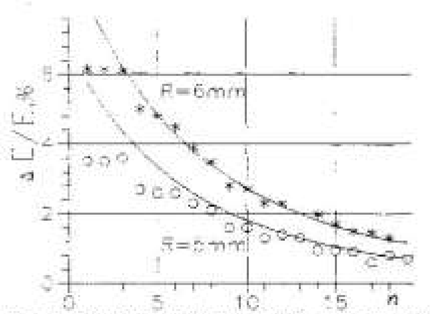


Fig. 1. Calculated (solid lines) and experimentally estimated (points) systematic error of the field distribution measurements in first DTL tank. n – number of the accelerating gap.

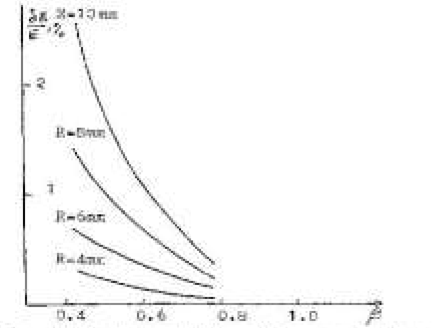


Fig. 2. Dependence of δE/E vs β for measurements in the DAW structure. Perturbing sphere is in the center of the accelerating gap.

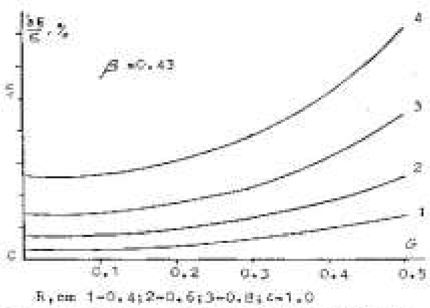
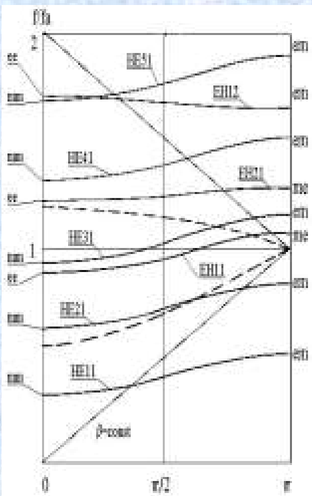


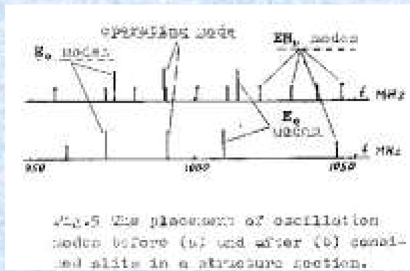
Fig. 3. Dependence of δE/E vs displacement of the bead sphere from the center of the accelerating gap in the DAW structure. G is the length of the gap.

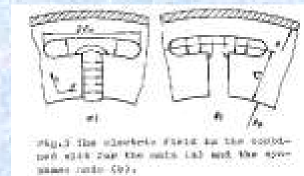
A systematic errors study for bead pull measurements. 1987.

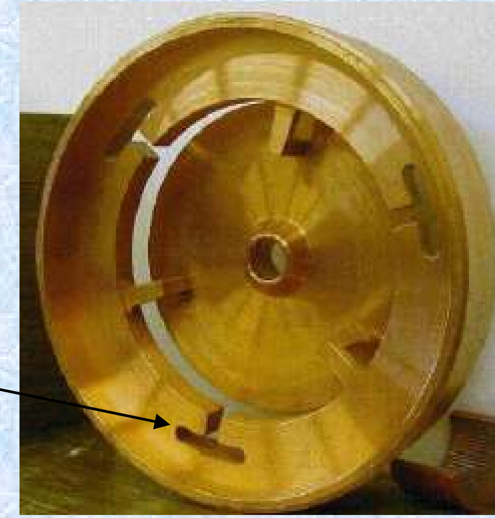
HOM displacement

High Order Modes with azimuth field dependence in DAW operating point vicinity were found in experiments and later sort out in simulations.
Several solutions for HOM displacements were developed.









Complete DAW dispersion diagram, β=0.43

T-slots is the selective resonant element, tuned near operating frequency, and has no coupling with operating mode, a very weak coupling with TM_{0n} modes and strong coupling with EH_{mn} modes.
Parameters extended in INR DAW construction.

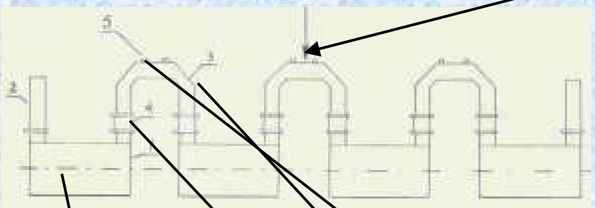
Beam blow-up effect is not possible – high threshold.
Cumulative emittance growth is less than originated by quads misalignments.

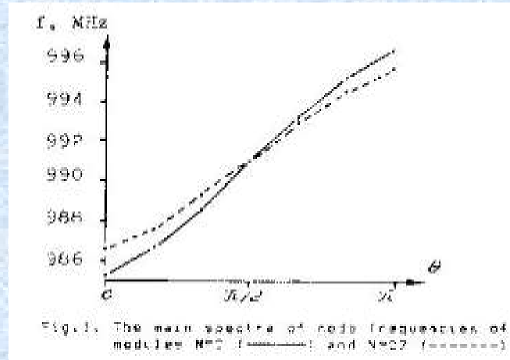
Parasitic modes removal out ….1983
Beam break-up in multi sectional …1984
The bunched beam interaction … 1985

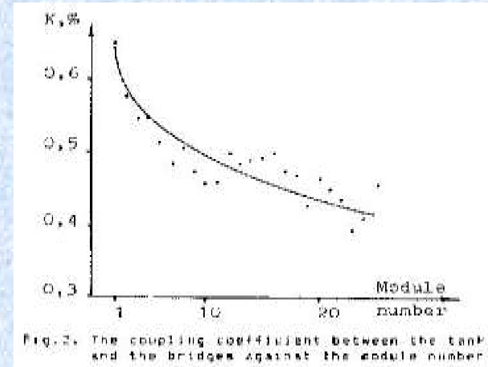
DAW cavities tuning

Cavity scheme. 1-DAW tanks, 2 – shorts,3-bridge cavities, 4 –bellows, 5-tuners

RF input

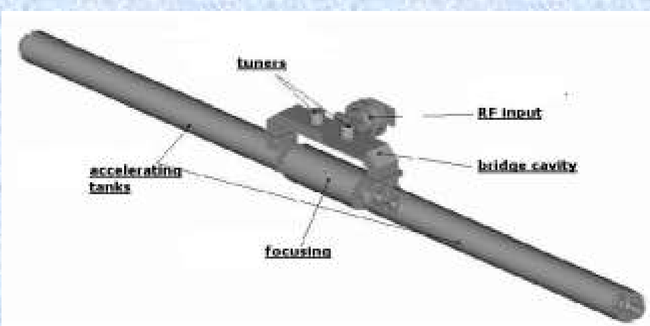






All DAW cavities are tuned at operating frequency, symmetrical cavity curve and field σ_E<1%.

DAW tanks and bridge cavities form coupled structure. Operating is π/2 mode. RF input is in coupling cell.

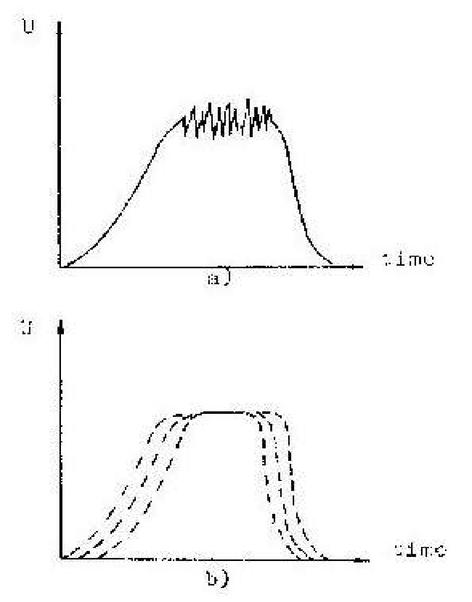


Such bridge cavities are compatible with all accelerating structures, are effective and cheap. Longest RF bridge ~7 m is used in INR linac.

Adjustment of the meson factory 991 MHz linac …1990

DAW cavities matching and conditioning

DAW were matched with waveguide system, taking into account beam loading.
The cavities were conditioned for higher, as designed, field and RF power values. The experience in the passage zones of the multipactor discharge was developed in conditioning of 27 DAW cavities.



The RF field pulse at the moment
a) multipactor discharge
b) electrical breakdown
U - signal from detector in the module

The mentioned tasks were generated by practice and results were implemented in practice immediately, leading to better quality of the system under construction. Definitely it was a part of big joint work.

All steps and problems, arising in the construction of such big accelerating system were overcame.

Accelerating system of the high energy part for INR linac was constructed, tuned and conditioned to design parameters.

The beam with energy up to 540 MeV was accelerated.

The practical experience for such system construction has been collected.

Results of DAW tuning … 1988
Acceleration… 1991

Software development and improvement

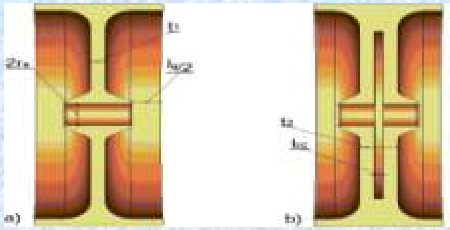
In the research, development and construction of accelerating structures appropriate software is the cost-effective tool for numerical experiments.

1 Fast and precise 2D FEM, MULTIMODE, in collaboration with IHEP and JINR (1980-1988).

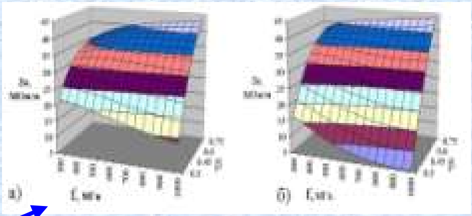
2. Simulations of multipactoring discharge .

3. Closed chain – RF – RF losses – Fluid analysis – Thermal deformations – RF, based on ANSYS software. For complete analysis of cavities operating with the high heat load.

4. Optimizing add-in .. For data library storage



Model

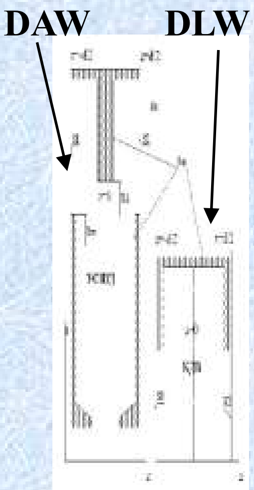


Results

Equivalent in efficiency to the 'carpet bombing'.

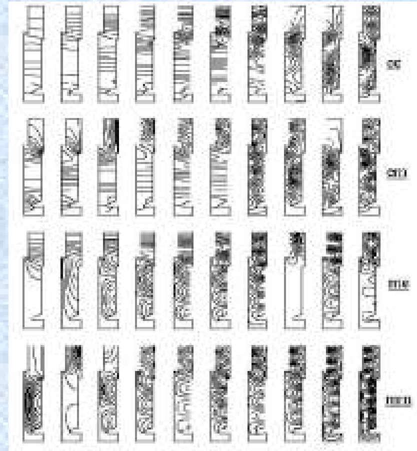
2D FEM software… 1988,
Complete 3D Thermal ..2002,
Data library … 1996

Common description of periodical structures.



One period

Considering just one period of the structure, let us compute with existing software and store fields for 0 and π modes in simple boundary conditions, …



Basis for expansion

Let us represent the traveling wave field in the structure as the set over calculated 0 and p modes.

$$\Re e\vec{E} = \sum_{n}^{N_{ee}} c_n^{ee}\vec{E}_n^{ee} + \sum_{n}^{N_{em}} c_n^{em}\vec{E}_n^{em}, \quad \Im m\vec{E} = \sum_{n}^{N_{me}} c_n^{me}\vec{E}_n^{me} + \sum_{n}^{N_{mm}} c_n^{mm}\vec{E}_n^{mm}.$$

Applying Floquet boundary conditions z-0, z=d, and using variational approach

$$(\vec{\nu}(\vec{E}e^{i\theta/2} + \vec{E}^{*}e^{-i\theta/2}))_{z=d/2} = 0, \quad (\vec{\nu}(\vec{E}e^{-i\theta/2} + \vec{E}^{*}e^{i\theta/2}))_{z=-d/2} = 0,$$

$$\omega^2 = \frac{\int_{V_d} \frac{1}{\mu_0} rot\vec{E}^{*} rot\vec{E}\, dV + I_S}{\int_{V_d} \epsilon_0 \vec{E}^{*}\vec{E}\, dV},$$

$$I_S = 2\int_{S_1} \vec{\nu}[(\vec{E}e^{-i\theta/2} + \vec{E}^{*}e^{i\theta/2})\frac{1}{\mu_0}(rot\vec{E}^{*}e^{i\theta/2} + rot\vec{E}e^{-i\theta/2})]dS +$$
$$+2\int_{S_2} \vec{\nu}[(\vec{E}e^{i\theta/2} + \vec{E}^{*}e^{-i\theta/2})\frac{1}{\mu_0}(rot\vec{E}e^{i\theta/2} + rot\vec{E}^{*}e^{-i\theta/2})]dS,$$

Come to symmetrical generalized eigen value problem,

$$AC - k^2 BC = 0,$$

$$\mathbf{A} = \begin{pmatrix} A_{ee}^{ee} & A_{ee}^{em} & 0 & A_{ee}^{mm} \\ A_{ee}^{em} & A_{em}^{em} & A_{em}^{me} & 0 \\ 0 & A_{em}^{me} & A_{me}^{me} & A_{me}^{mm} \\ A_{ee}^{mm} & 0 & A_{me}^{mm} & A_{mm}^{mm} \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} B_{ee}^{ee} & B_{ee}^{em} & 0 & 0 \\ B_{ee}^{em} & B_{em}^{em} & 0 & 0 \\ 0 & 0 & B_{me}^{me} & B_{me}^{mm} \\ 0 & 0 & B_{me}^{mm} & B_{mm}^{mm} \end{pmatrix}$$

where

$$(A_{ee}^{ee}, A_{em}^{em}, A_{me}^{me}, A_{mm}^{mm}), a_{ij} = \delta_{ij}k_i k_j, \quad (B_{ee}^{ee}, B_{em}^{em}, B_{me}^{me}, B_{mm}^{mm}), b_{ij} = \delta_{ij},$$

$$(B_{ee}^{em}), b_{ij} = \frac{\epsilon_0}{W_0}\int_{V_1} \vec{E}_i^{ee}\vec{E}_j^{em} dV, \quad (B_{mm}^{me}), b_{ij} = \frac{\epsilon_0}{W_0}\int_{V_1} \vec{E}_i^{mm}\vec{E}_j^{me} dV,$$

$$a_{ij} = \frac{\epsilon_0}{W_0}\int_{V_1} rot\vec{E}_i^{em} rot\vec{E}_j^{ee} dV + \frac{2\epsilon_0(1+\cos\theta)}{W_0}\int_{S_2} \vec{\nu}[\vec{E}_i^{em}, rot\vec{E}_j^{ee}]dS,$$

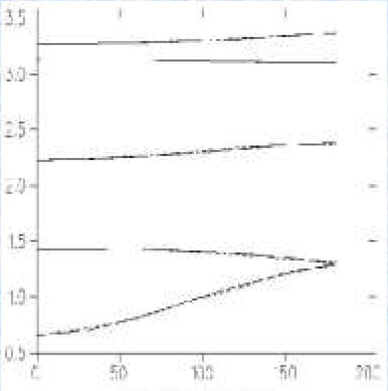
Method of field description… 2000

General dispersion equation

$$AC - k^2 BC = 0,$$

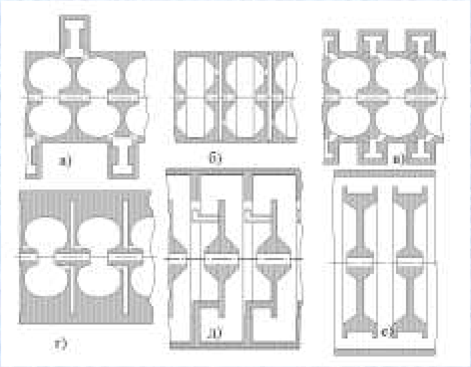
The eigen value problem in formulation ***det (A-k²B)=0*** *is the* ***dispersion equation of the structure.***

High energy structures SCS (a), OAS (b), ACS ©, DAW (f)



Instead of quite different design and different particular propertied, all high energy compensated (bi-periodical) structures have the common dispersion equation.

$$det \begin{vmatrix} k_1^2 - k^2 & 0 & I_1^k + I_2(1+cos\theta) - I_1^\varepsilon k^2 & 0 \\ 0 & k_2^2 - k^2 & I_3^k + I_4(1+cos\theta) - I_3^\varepsilon k^2 & 0 \\ a_{13} & a_{23} & k_s^2 - k^2 & I_5 sin\theta \\ 0 & 0 & a_{34} & k_c^2 - k^2 \end{vmatrix} = 0$$



DAW TM0n dispersion curves, directly calculated (2D solid lines) and reconstructed from general dispersion equation (dotted lines).

The differences are in the ‘details’

$$I_1^\varepsilon = \frac{\varepsilon_0}{W_0}\int_{V_1} \vec{E}_1^{\pi} \vec{E}_s^{*m} dV; \quad I_1^k = \frac{\varepsilon_0}{W_0}\int_{V_1} rot\vec{E}_1^{\pi} rot\vec{E}_s^{*m} dV;$$

$$I_2 = \frac{2\varepsilon_0}{W_0}\int_{S_2} \vec{n}[\vec{E}_s^{*m}, rot\vec{E}_1^{\pi}]dS; I_3^\varepsilon = \frac{\varepsilon_0}{W_0}\int_{V_2} \vec{E}_2^{\pi} \vec{E}_s^{*m} dV;$$

$$I_3^k = \frac{\varepsilon_0}{W_0}\int_{V_2} rot\vec{E}_2^{\pi} rot\vec{E}_s^{*m} dV; I_4 = \frac{2\varepsilon_0}{W_0}\int_{S_2} \vec{n}[\vec{E}_s^{*m}, rot\vec{E}_2^{\pi}]dS;$$

$$I_5 = \frac{2\varepsilon_0}{W_0}\int_{S_2} \vec{n}[\vec{E}_s^{*m}, rot\vec{E}_c^{*m}]dS.$$

Extension to the family of structures is done …

General dispersion equation… 2002

Operating point vicinity. Local dispersion equation.

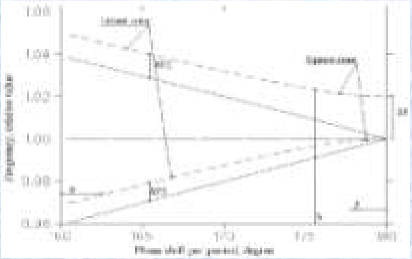
For practice the vicinity of operating point θ_0 is more interesting and important. The common dispersion equation is reduced to local equation, just for two modes, E_a and E_c, interaction.

$$(k_a^2 - k^2)(k_c^2 - k^2) - [I_{5,6} sin\xi]^2 = 0, \quad \xi = \theta_0 - \theta$$

$$I_5 = \frac{2\epsilon_0}{W_0}\int_{S2} \vec{\nu}[\vec{E}^{em}, rot\vec{E}^{me}]dS, \quad \theta_0 = \pi,$$

$$I_6 = \frac{2\epsilon_0}{W_0}\int_{S2} \vec{\nu}[\vec{E}^{mm}, rot\vec{E}^{ee}]dS, \quad \theta_0 = 0,$$

In the vicinity of operating point all – field structure, frequencies, influence of deviations, for neighbor modes is defined just with two parameters – stop band width δf *and group velocity* β_g *value.*



From CC model, $\gamma_{ac}=k_c$

$$\beta_g = \beta\frac{\pi\gamma_{ac}}{4\sqrt{(1-\gamma_{aa})(1-\gamma_{cc})}},$$

$$\beta_g = \left|\frac{\pi\beta\int_{V_1}(\epsilon_0\vec{E}_a\vec{E}_c - \mu_0\vec{H}_a\vec{H}_c)dV}{4W_0}\right|,$$

Completely different results are

for open stop band *and* *for closed stop band.*

For open stop band:

$$f^{a,b}(\xi) \approx f_a + \frac{\delta f}{2} \pm \frac{\beta_g\xi}{\pi\beta} + \frac{\partial^2 f^a}{\partial\xi^2}\frac{\xi^2}{2} \pm \frac{\partial^3 f^a}{\partial\xi^3}\frac{\xi^3}{6} + \frac{\partial^4 f^a}{\partial\xi^4}\frac{\xi^4}{24} \pm .. + .. \pm .. + .. = \frac{\delta f}{2} + f_0^{a,b}(\xi)$$

$$E_{sw}^b = \frac{E_a\cos j\theta_m - \frac{\xi}{\chi}E_c\sin j\theta_m}{\sqrt{(1+\frac{\xi}{\chi}^2)}}, \quad E_{sw}^a = \frac{\frac{\xi}{\chi}E_a\cos j\theta_m + E_c\sin j\theta_m}{\sqrt{(1+\frac{\xi}{\chi}^2)}}.$$

For closed stop band:

$$f_0^{a,b}(\xi) = f_a \pm f_a\frac{\beta_g\xi}{\pi\beta} + \frac{\partial^2 f^a}{\partial\xi^2}\frac{\xi^2}{2} \pm \frac{\partial^3 f^a}{\partial\xi^3}\frac{\xi^3}{6} + \frac{\partial^4 f^a}{\partial\xi^4}\frac{\xi^4}{24} \pm .. + .. \pm .. + ..$$

$$E_{tw}^b = \frac{E_a - \iota E_c}{\sqrt{2}}, \quad E_{sw}^b = \frac{E_a\cos j\theta_m - E_c\sin j\theta_m}{\sqrt{2}},$$

And so on … for all measurable parameters of neighbor modes, f, Δf, Q, E(z) and structure behavior.

Description of processes in accelerating structures.

1. Coupling mode excitation. **Common electro-dynamical approach.**

1a) Due to RF losses and beam loading. To define field attenuation α – the common case and case of small beam loading.

$$\frac{\beta_g Q_a(1-e^{-4N_1\alpha_s d})}{2\pi\beta_p} = \frac{I_b U_a N_1(1+e^{-2N_1\alpha_s d})}{2N_1\alpha_s d P_a} + \frac{N_1}{8}\left(\frac{(1-e^{-4N_1\alpha_s d})(Q_a+Q_c)}{N_1\alpha_s d Q_c} + 4\frac{(Q_c-Q_a)e^{-2N_1\alpha_s d}}{Q_c}\right).$$

$$N_1\alpha_s d \approx \frac{1+\frac{I_b U_a}{P_a}}{\frac{2\beta_g Q_a}{N\pi\beta_p}+2+\frac{I_b U_a}{P_a}} \approx \left(1+\frac{I_b U_a}{P_a}\right)\frac{N_1\pi\beta_p}{2\beta_g Q_a}$$

Differs in physical conclusions with the results from Coupled Circuits (CC) model.

1b) Due to transient.

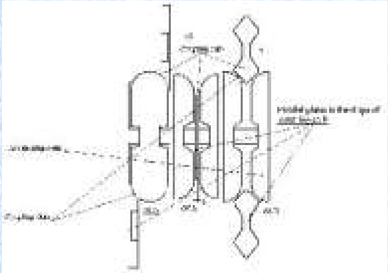
$$W_c^{(tr)} = W_a^{(s)}\left(\frac{8N\beta(Q_a+Q_c)}{\pi\beta_g Q_a Q_c}\right)^2.$$

.

1c) Due to frequency errors of accelerating cells.

$$\sqrt{W_{c_j}^{(dt)}} = \frac{8\beta}{\pi\beta_g f_a}\sqrt{W_{a_1}^{(s)}}\left|\sum_{m}^{j}\delta f_{a_m}\right|,$$

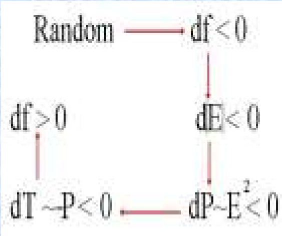
It are limitations to the structure design, because miltipactoring and even discharge in coupling cells are possible, if not foreseen ..



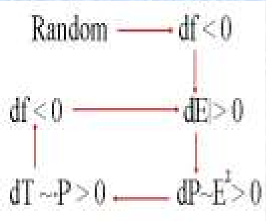
Stability of Normal Conducting Structures for Operation with High Average Heat Loading.

Stability and sensitivity are different properties.

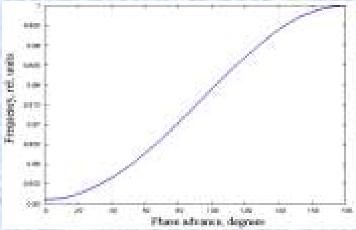
Dispersion

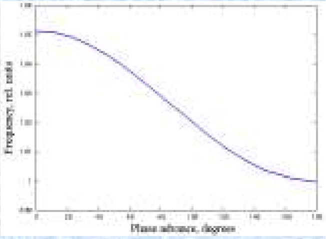


Stable



Not stable



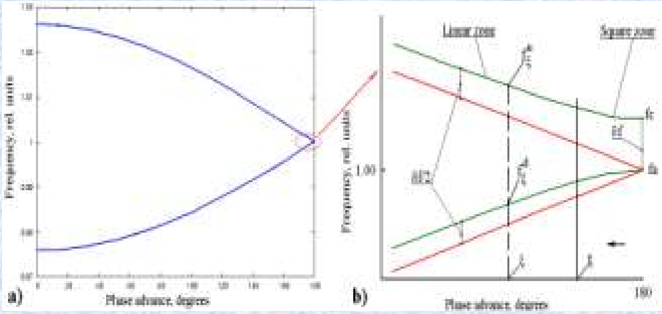


Critical is df – d|E| relation.

Table 1: Thermal stability of simple structures

Operating mode	Dispersion	Thermal stability
0 (2π)	positive	No
0 (2π)	negative	Yes
π	positive	Yes
π	negative	No

Compensated structures



$\delta f = fc - fa > 0$ **stable**

$\delta f = fc - fa < 0$ **not stable**

These theoretical and methodical developments are valid for a wide family of accelerating structures and provide complete set of approaches, recommendations and limitations in the research, development and improvement of accelerating structures.

Joint with understanding of practical problems, it provides the reliable base for another developments.

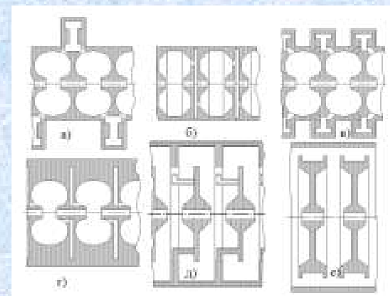
Coupling coefficient increasing at the expense of minimal Ze reduction.

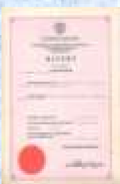
$$\beta_g = \left|\frac{\pi\beta\int_{V_1}(\epsilon_0\vec{E}_a\vec{E}_c - \mu_0\vec{H}_a\vec{H}_c)dV}{4W_0}\right|,$$

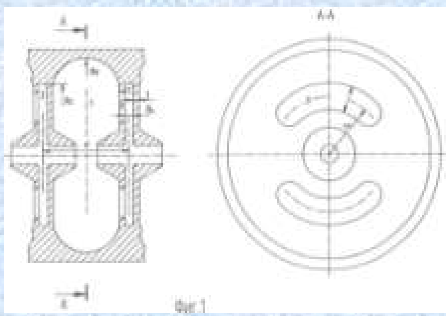
Structures can be distinguished as with localized (k_c~5%) and distributed (k_c>20%) interaction of accelerating E_a and coupling modes E_c.

Slot coupled structures –localized interaction. Set of recommendations to improve k_c..

$$\gamma_{ac} \sim \frac{h l_s^3 H_{as} H_{cs}}{t\sqrt{W_a W_c}},$$







Leading idea – work with accelerating mode for RF efficiency and with coupling mode for coupling improvement.

k_c~0.05-0.15

Now this OAS geometry is usual ..

Coupling coefficient increasing 1996

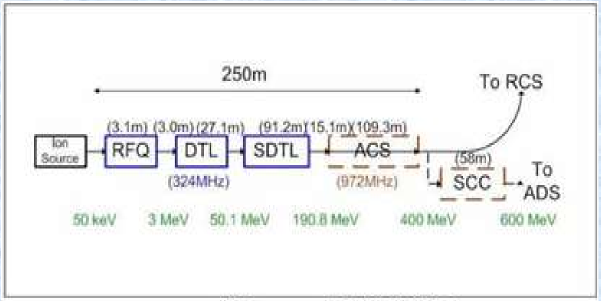
Applications of developed methods

In frames of SNS-INR collaboration the knowledge's and experience in the structures construction and commissioning have been implemented during construction and commissioning of the warm part of the SNS linac.

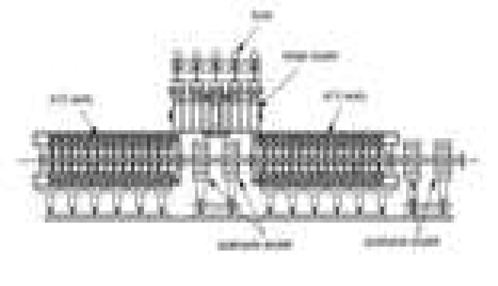
In frames of KEK-INR collaboration the physical design for Annular Coupled Structure (ACS) has been developed for J-PARC linac .

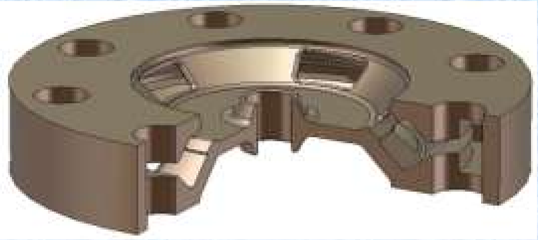
ACS, invented and first time tested in USSR (RTI), was essentially improved during IHP R&D program for f=1296 MHz.

For J-PARC, f=972 MHz, ACS was essentially reconsidered and optimized.



Scheme of J-PARC Linac.

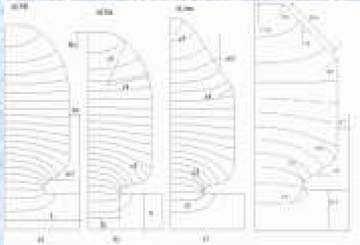

Layout of a ACS module

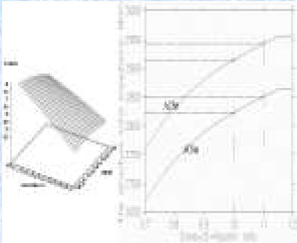

ACS cells for J-PARC

ACS optimization … 2000

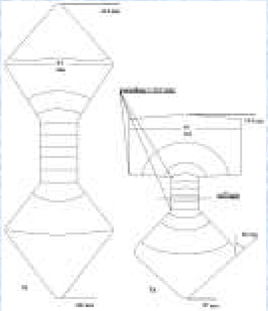
ACS optimization for J-PARC

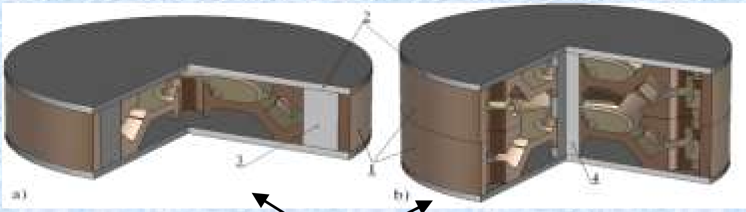
The total set of developed methods, approached and recommendations has been applied. All components of ACS module were reconsidered.



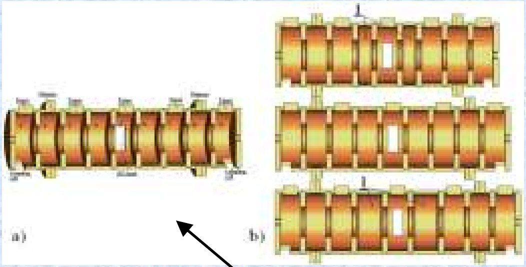


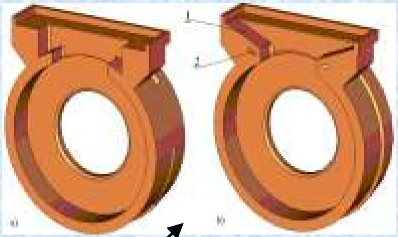
Cells optimization.



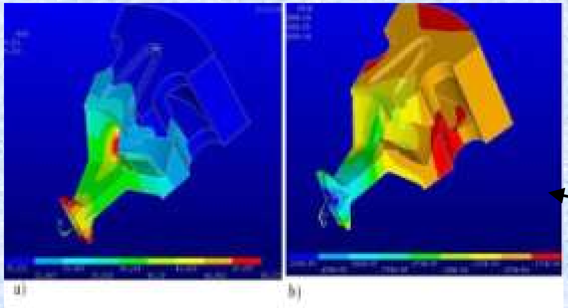


Individual cells tuning

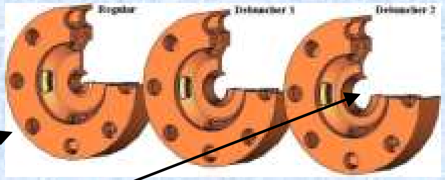




Bridge couplers and RF input



Thermal stress analysis.

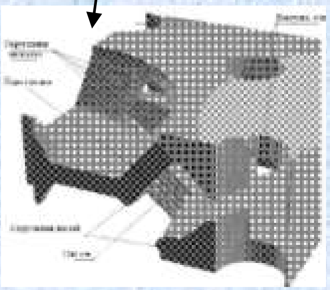


Regular ACS cells and ACS for debunchers, aperture diameter 85 mm.

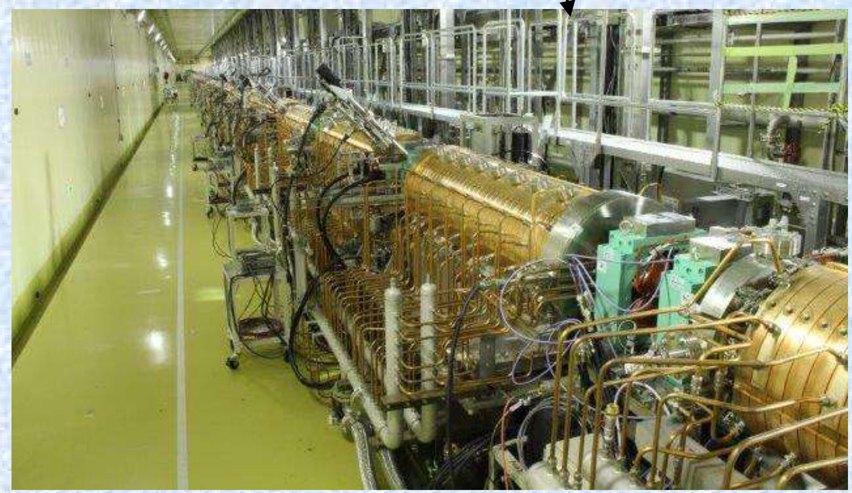
As the result, optimized ACS overlaps prototype in all parameters and was accepted for J-PARC

It was a long work of the joint ACS group

2000



2013

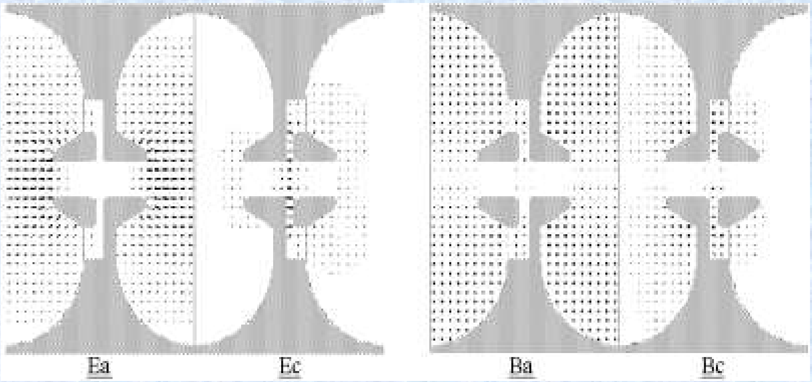


Installed and commissioned by J-PARC in 2013-2014, ACS is now operating in J-PARC linac

ACS in the tunnel of the J-PARC linac.

H.Ao et. al.,

INR development –the Cut Disk Structure - CDS



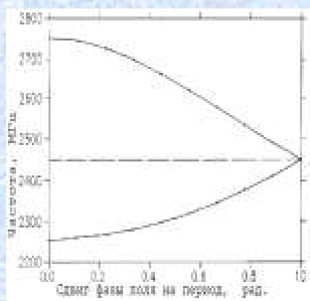
Fields distributions for accelerating and coupling modes.

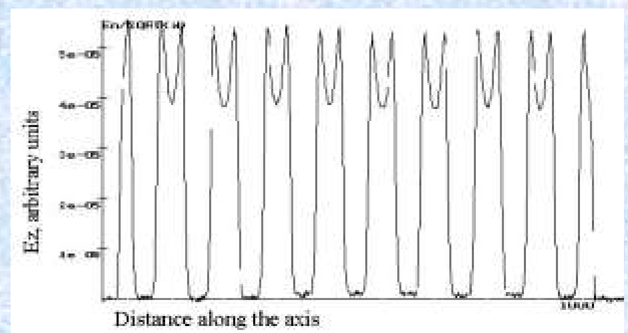
$$\beta_g = \left|\frac{\pi\beta \int_{V_1}(\epsilon_0 \vec{E}_a \vec{E}_c - \mu_0 \vec{H}_a \vec{H}_c)dV}{4W_0}\right|,$$

CDS concept – the accelerating cell is formed for higher Z_e. Coupling cell is formed than there are no own space for magnetic field H_c, with the necessity is extruded in the accelerating cell, providing high β_g value.

CDS particularities – compact, high β_g, for moderate β_g - Z_e value is higher than for cells without coupling windows.

CDS cold model

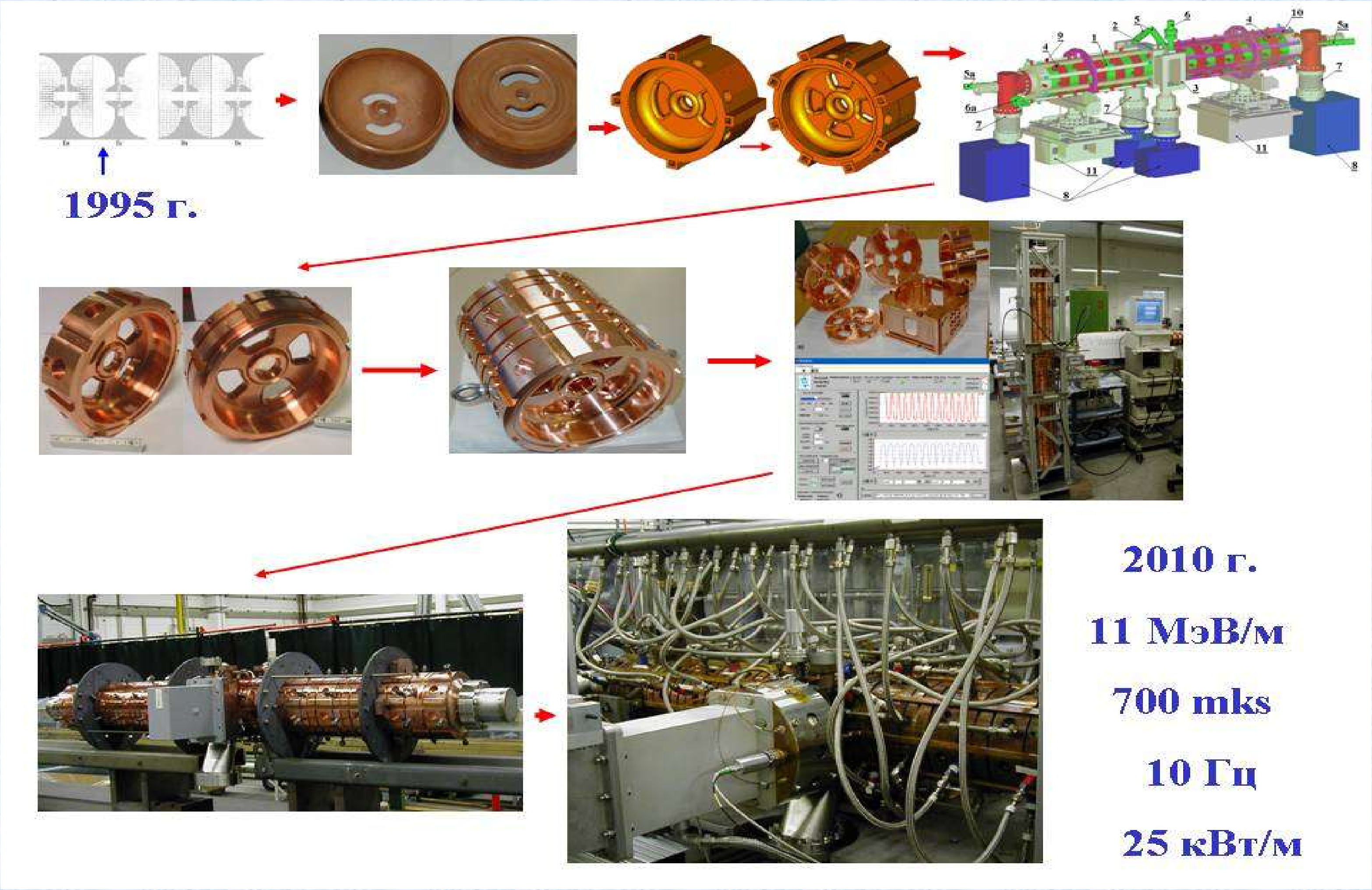




k_c=22%, Ze =0.98 Ze_{2D}

CDS concept– 1996,
CDS cold model - 1998

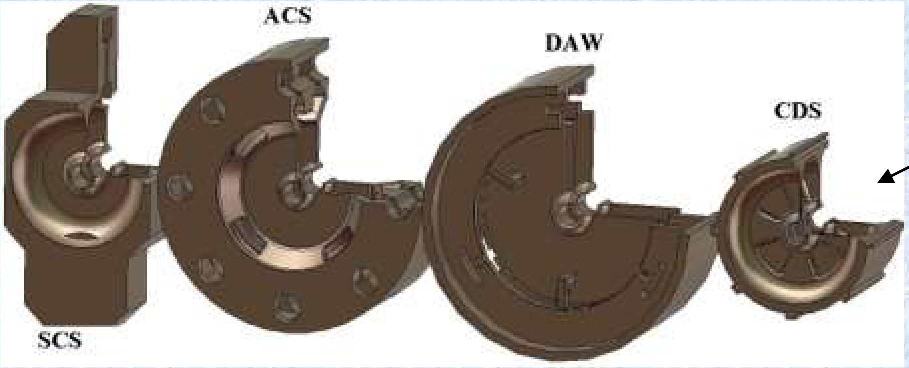
INR CDS development and construction (DESY-INR) for PITZ booster cavity.



All steps in CDS development were done and now it is operating at PITZ, β=1, f=1300 MHz

Structures comparison in parameters

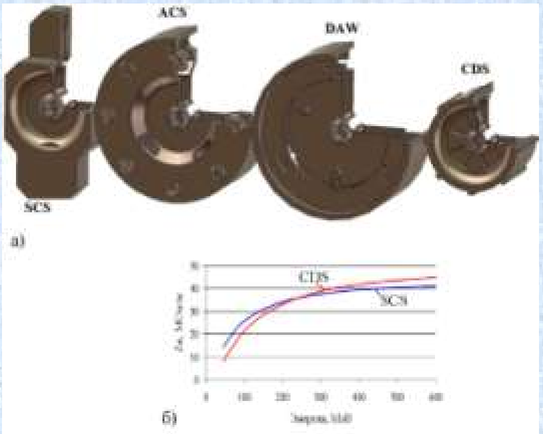
	SCS	DAW	ACS	CDS
Ze	100%	96%	98%	85%-107%
kc	0.04	0.45	0.05	0.15
Ph, kW/m	8-10	3-4	<60	<30
Vacuum conduct.	4	1	3	2
HOM	2	night mare	3	1
R/l	~0.7	~0.7	~0.7	~0.37
RF tuning	3-4	1-2	3-4	1-2
Tuning after brazing	ac	nn	nn	a ?
Brazing water/vacuum	yes	yes	yes	no!



Transverse dimensions comparison for the same frequency

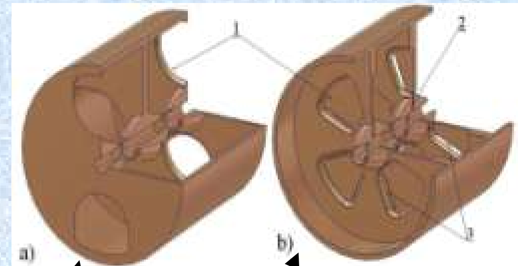
Current CDS investigations

Low β~0.43 region, high frequency f=991 MHz, for INR linac.

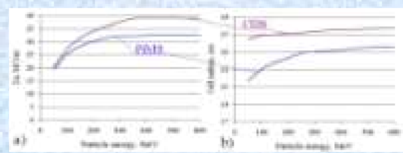


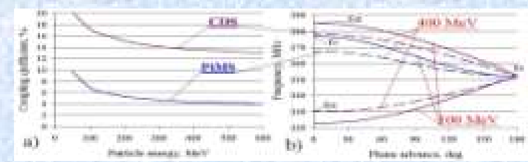
Z_e decreasing at low β was a sequence of original CDS formation. Proposals to improve Z_e are developed. Will be reported at next Conference.

Low frequency f=352 MHz, β~0.43=0.7, for future projects (see poster THPSC07)



PiMS and CDS - possible structures for low frequency application.





CDS has higher Z_e value and qualitative advantage in field stability, looks more labour-intensive in construction, but it is easy in tuning.

In the INR research activity in normal conducting accelerating structures the complete set of methods, approaches for investigation, development and construction of accelerating structures was developed. Results of this activity are realized in the constructed, tuned, commissioned and operating accelerating system of the INR hadron linac,

are implemented in the design, construction and commissioning of similar linacs in foreign laboratories. Guiding this basements results, attractive proposal for different future application is generated, investigated and tested.

Research and developments are in progress!

ACKNOWLEDGMENT

The authors warmly tank a lot of our colleagues in INR, MRTI, DESY, KEK, J-PARC, SNS for fruitful collaborations in accelerating structures development and construction.

Thank you for attention!