IAEA Coordinated Research Project on *Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems*

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on behalf of the CRP team

Nuclear Power Technology Development Section

IAEA

International Atomic Energy Agency

Paper Presented on Behalf of the CRP Participants

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Coordinated Research Project (CRP) Framework

- **Technical Working Group on Fast Reactors (TWG-FR) providing considerable leverage for IAEA activities**
  - Promotes in-depth scientific and technical information exchange on advances in fast spectrum systems research and technology development
  - Stimulates and facilitates collaborative R&D (CRPs)
  - Coordinate activities with other Agency projects, and international organizations (EC, OECD/NEA)

Framework for IAEA Activities, cont'd

- **Membership of the TWG-FR**

  Belarus, Brazil, China, France, Germany, India, Italy, Japan, Kazakhstan, Republic of Korea, the Netherlands, Russia, Switzerland, Ukraine, United Kingdom, and United States of America; EU (EC), and OECD/NEA

  Observers: Belgium, Sweden

Background of the CRP

- Initiated in December 2005, ending in 2010
- Participation from 25 institutions in 17 IAEA Member States: Argentina, Belarus, Belgium, Brazil, China, Germany, Greece, Hungary, Italy, Japan, the Netherlands, Pakistan, Poland, Russia, Spain, Ukraine, and the USA

Objectives of the CRP

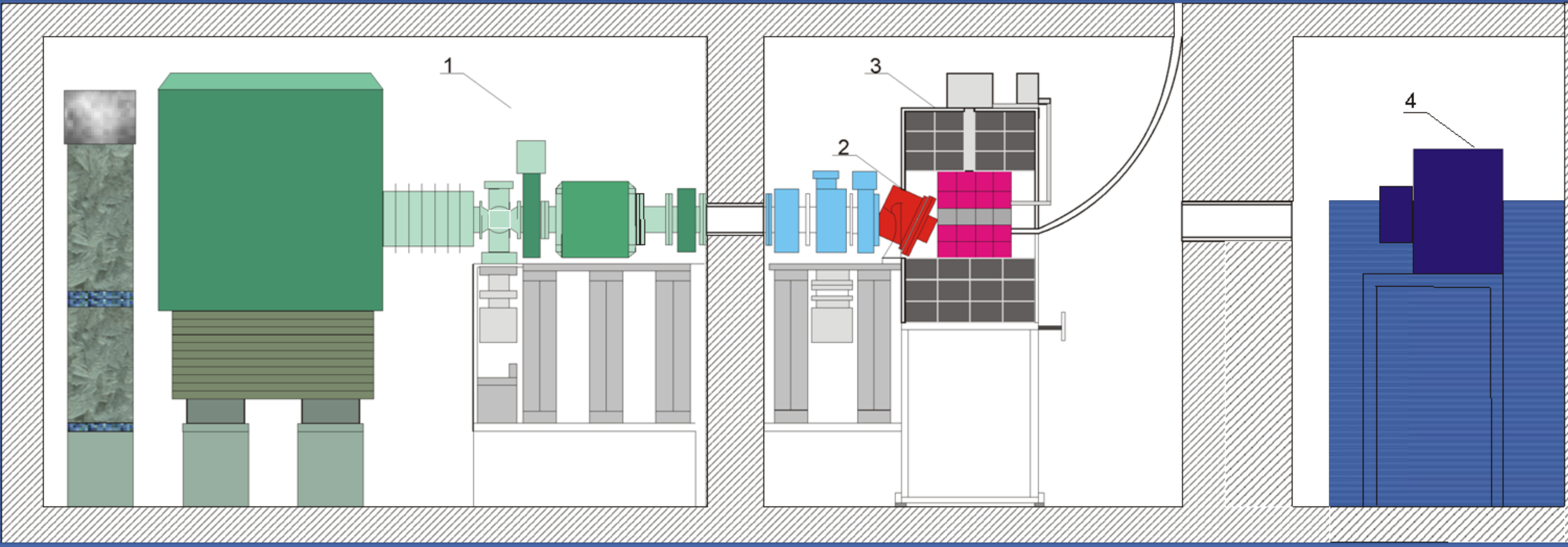
- Improve **physics understanding** of coupling an external neutron source with a sub-critical assembly
- Provide international information exchange and collaborative R&D framework for **data and code V&V&Q** → participants are performing computational and experimental benchmark analyses using integrated calculation schemes and simulation methods

Scope of the CRP

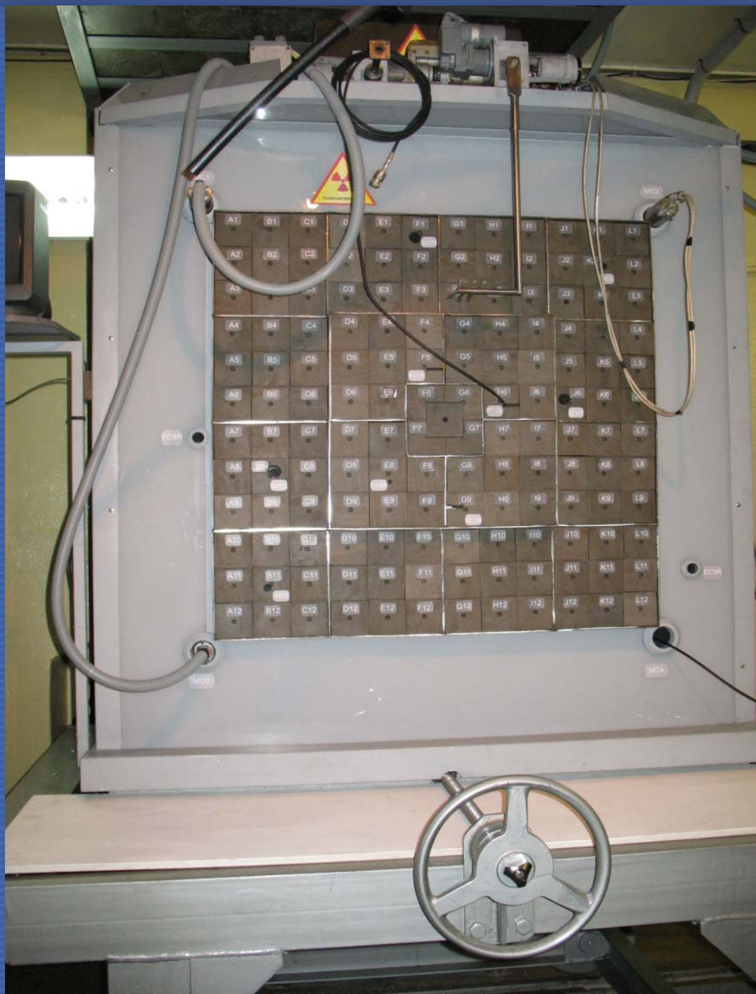
- Computational and experimental benchmarking
- ADS and non-spallation neutron source driven sub-critical systems
- Work domains
  - YALINA Booster
  - Kyoto University Critical Assembly (KUCA)
  - Pre-TRADE
  - FEAT (First Amplifier Tests)
  - TARC (Transmutation by Adiabatic Resonance Crossing)
  - ADS kinetics analytical benchmarks
  - Spallation targets

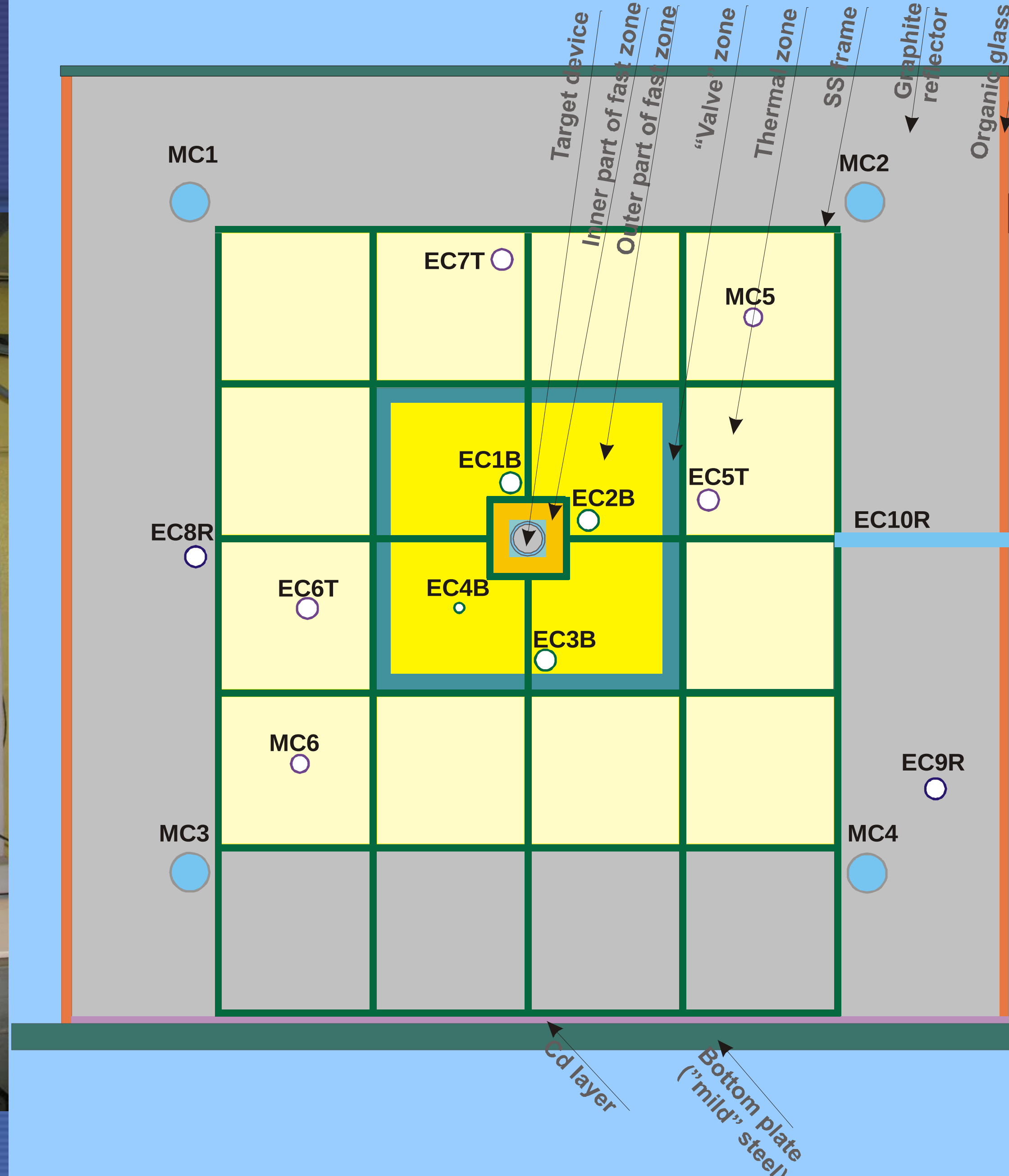
YALINA Booster (JIPNR, Minsk, Belarus)

(1) d-accelerator; (2) neutron source: Ti-d (or Ti-t) target
(3) sub-critical assembly; (4) γ-spectrometer

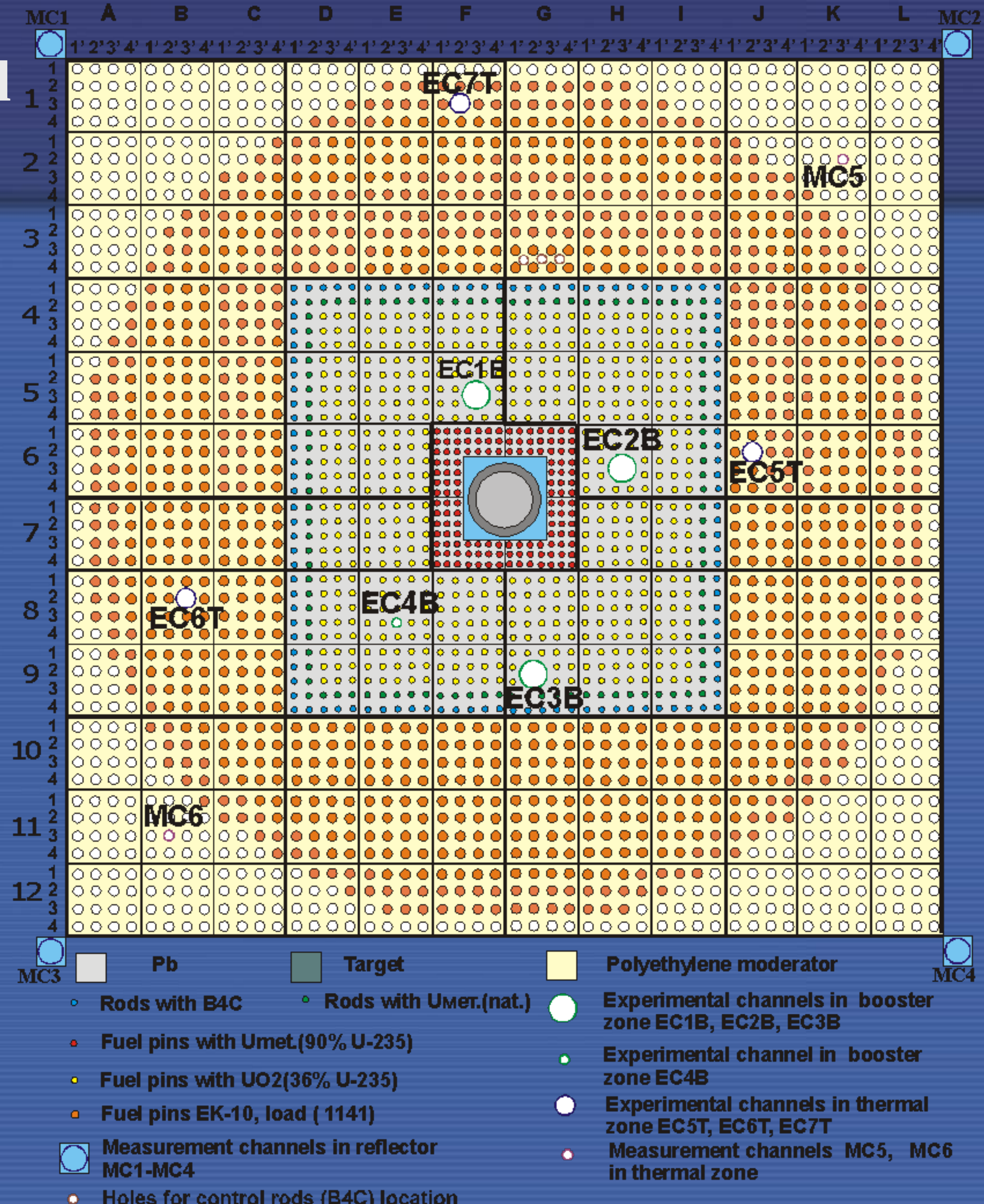


YALINA Booster Facility





YALINA Booster, 1141 Al clad UO_2 fuel rods (10% ^{235}U)



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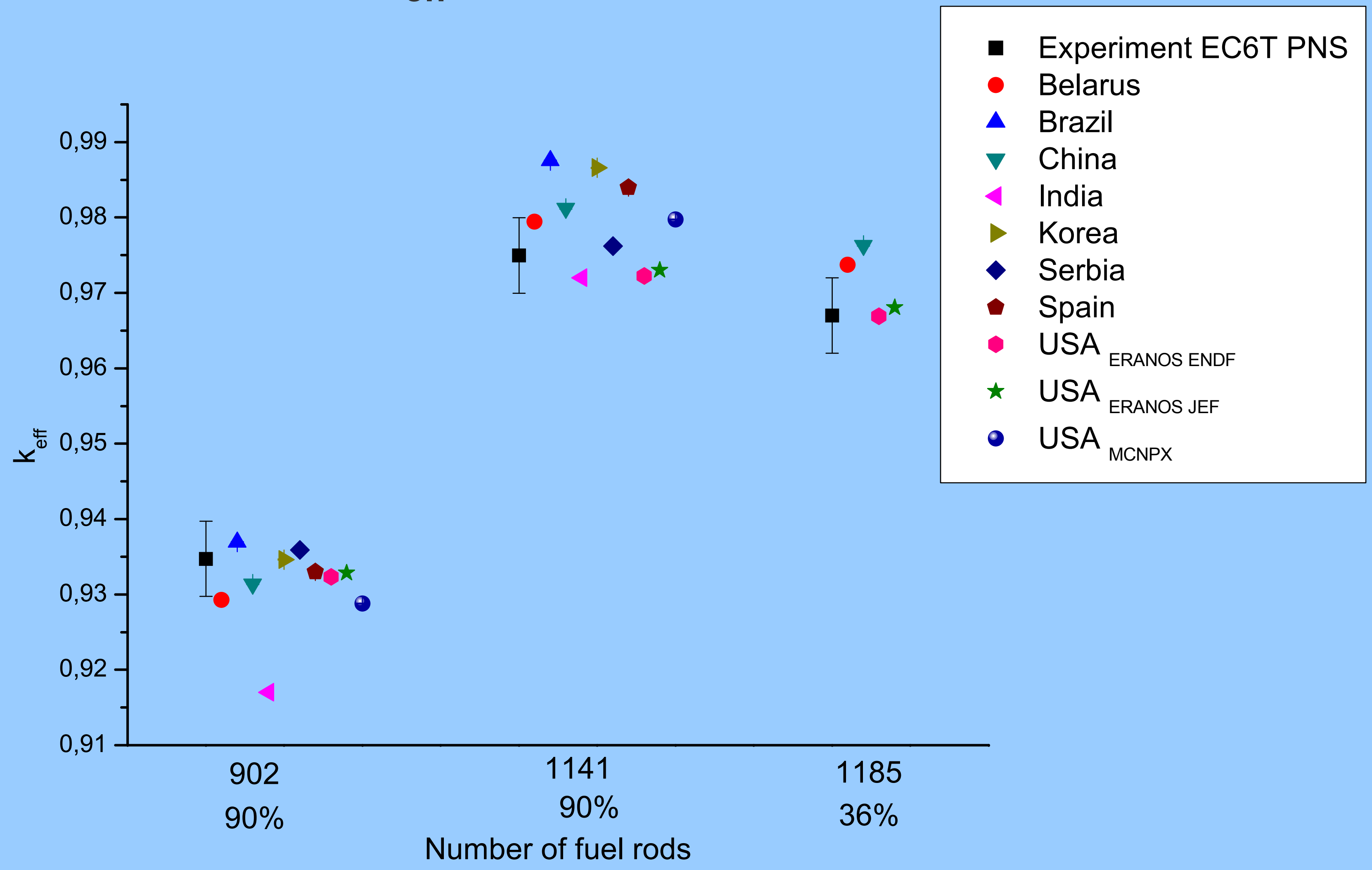
YALINA Booster, cont'd

- Various configurations with different number of 10% ^{235} U enriched UO_2 fuel rods in the thermal zone
- Various neutron sources (Cf, d-d, d-t)
- Criticality and neutron source studies (k_{eff}, k_{source})
  - Pulsed neutron source (d-d, d-t) experiments
  - Sub-criticality level measurements with the help of time-dependent detector (^{235}U and ^{3}He) responses in various locations
- Neutron flux distributions and spectra
- Reaction rate distributions [^{235}U(n,f), ^{3}He(n,p), ^{55}Mn(n,γ), ^{115}In(n,γ), ^{197}Au(n, γ)]
- Kinetic parameters (β_{eff} , Λ_{eff})

YALINA Booster, cont'd

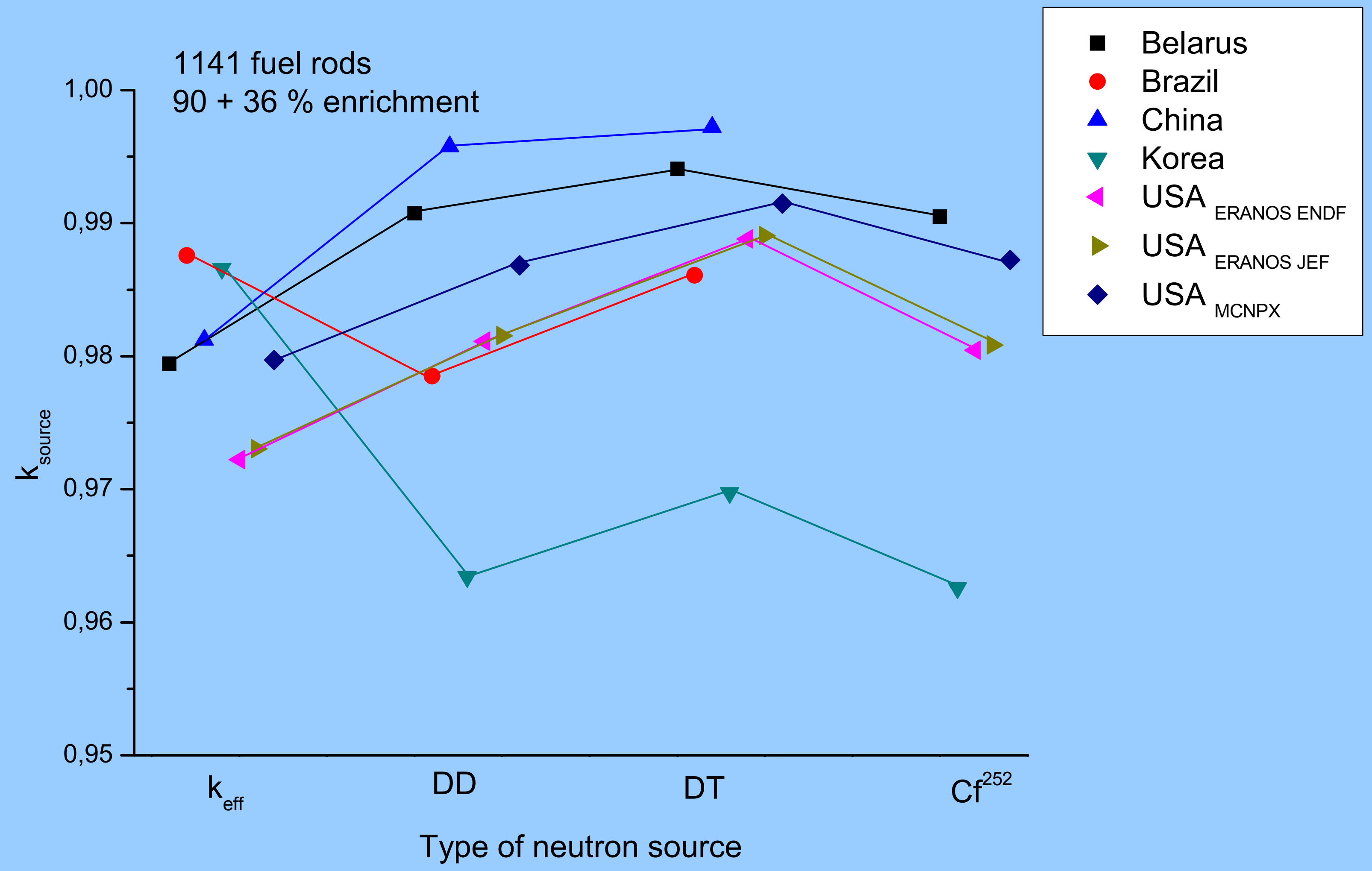
- Deterministic (ERANOS, ATES3) and Monte-Carlo (NCNP4c, MCNP5, MCNP5.1.2, MCNP5.1.4, MCNPX, MCNPX2.6, McCARD, MONK) codes
- Different nuclear libraries (WIMS, JEF 2.2, JEF 3.1, ENDF/B-VI.0, -VI.6, -VI.8, -VII.0)

YALINA Booster, k_{eff}



Sadovich ,4th RCM, Feb 2010

YALINA Booster, k_{source}



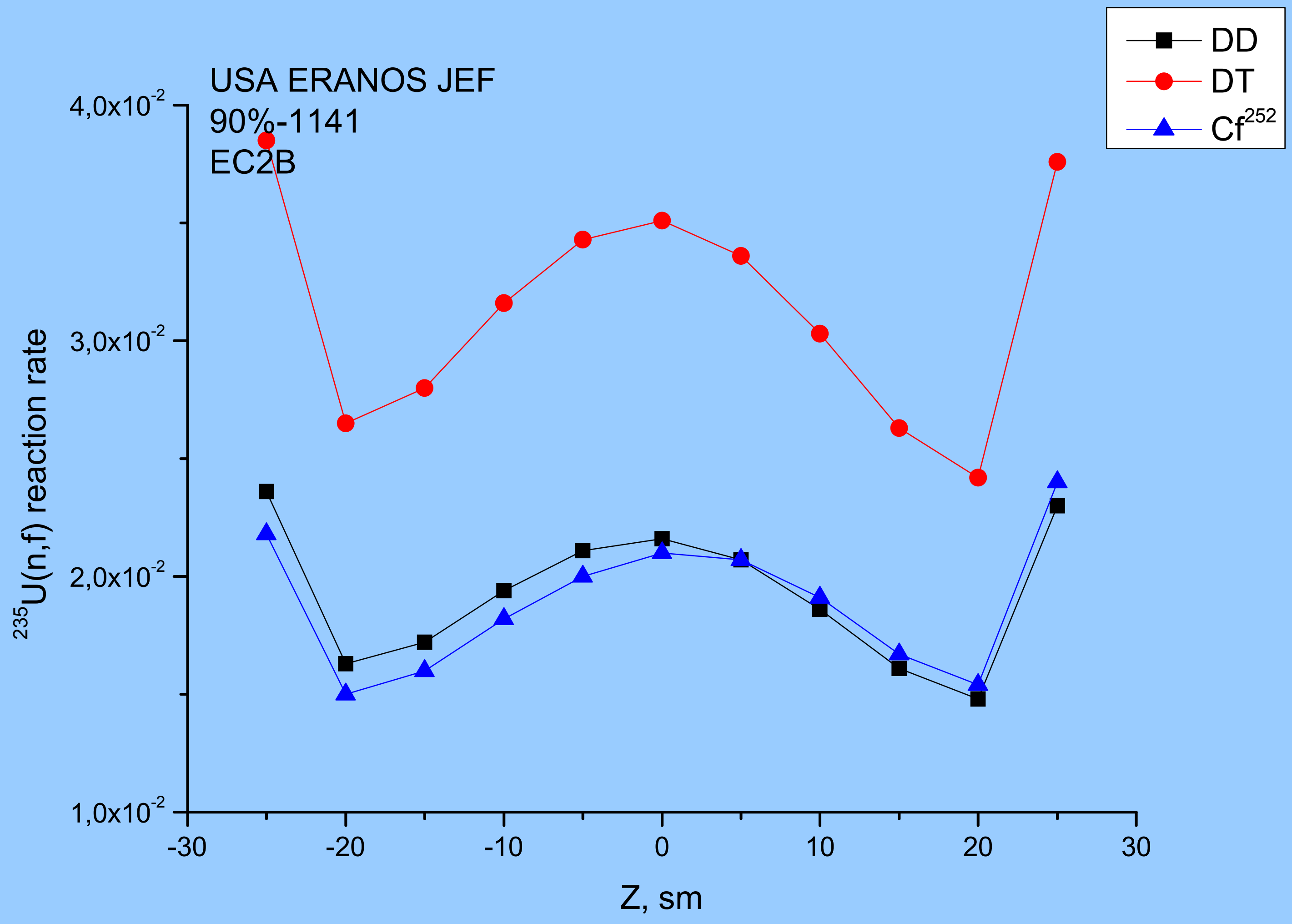
Sadovich ,4th RCM, Feb 2010

YALINA-Booster, configuration 1141
ERANOS-JEF3.1 reactivity corrections for area ratio method measured reactivity, using ^{3}He detector responses to a d-d pulsed neutron source

Detector	Measured by Area Ratio	Corrected Values
EC5T	0.973180 (-2756 pcm)	0.973527 (-2719 pcm)
EC6T	0.975133 (-2550 pcm)	0.973345 (-2738 pcm)
EC7T	0.975347 (-2528 pcm)	0.972690 (-2808 pcm)

Gohar, 4th RCM, Feb 2010

YALINA Booster, axial reaction rate distribution



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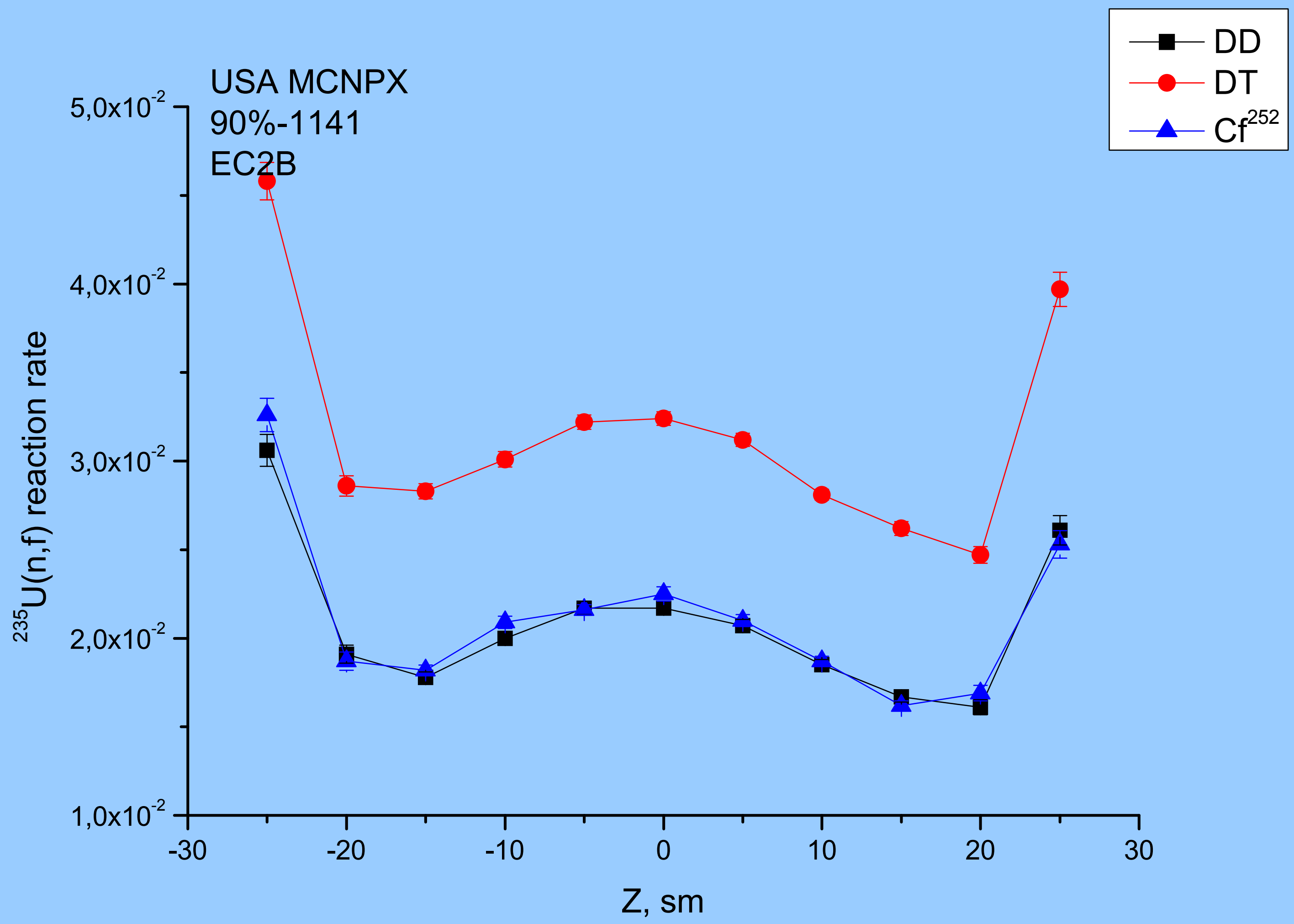
YALINA Booster, axial reaction rate distribution



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YALINA Booster, Preliminary Conclusions

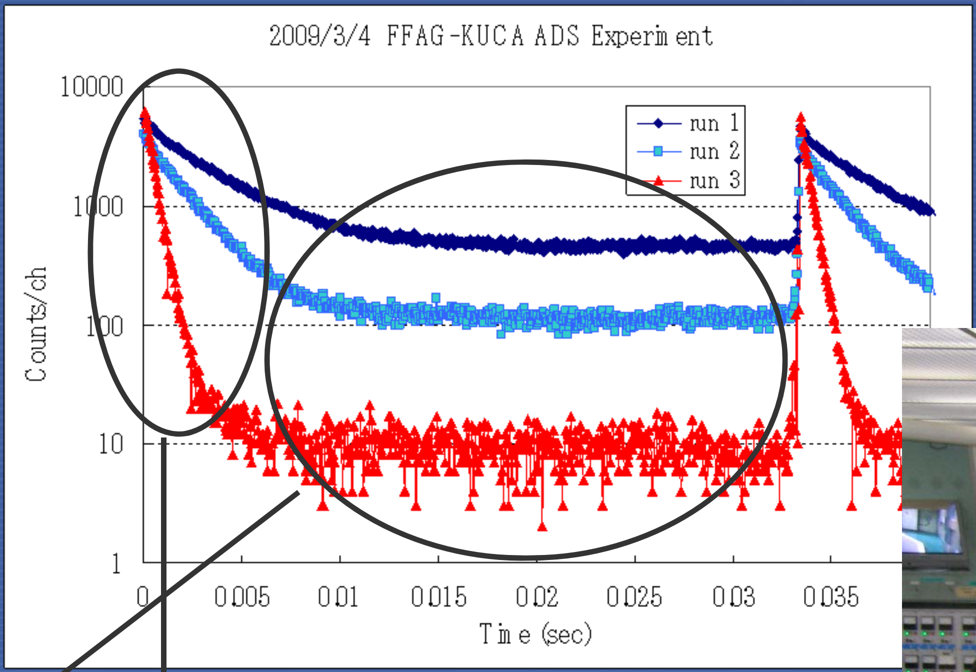
- Detector responses used to measure sub-criticality levels with the help of slope and area ratio methods depend on the type of source, its geometry, and location → correction factors needed, analyses are ongoing
- Importance of normalization procedure for energy spectra and reaction rate distributions
- Satisfactory agreement between calculation (based on transport codes and current nuclear data files) and experiments

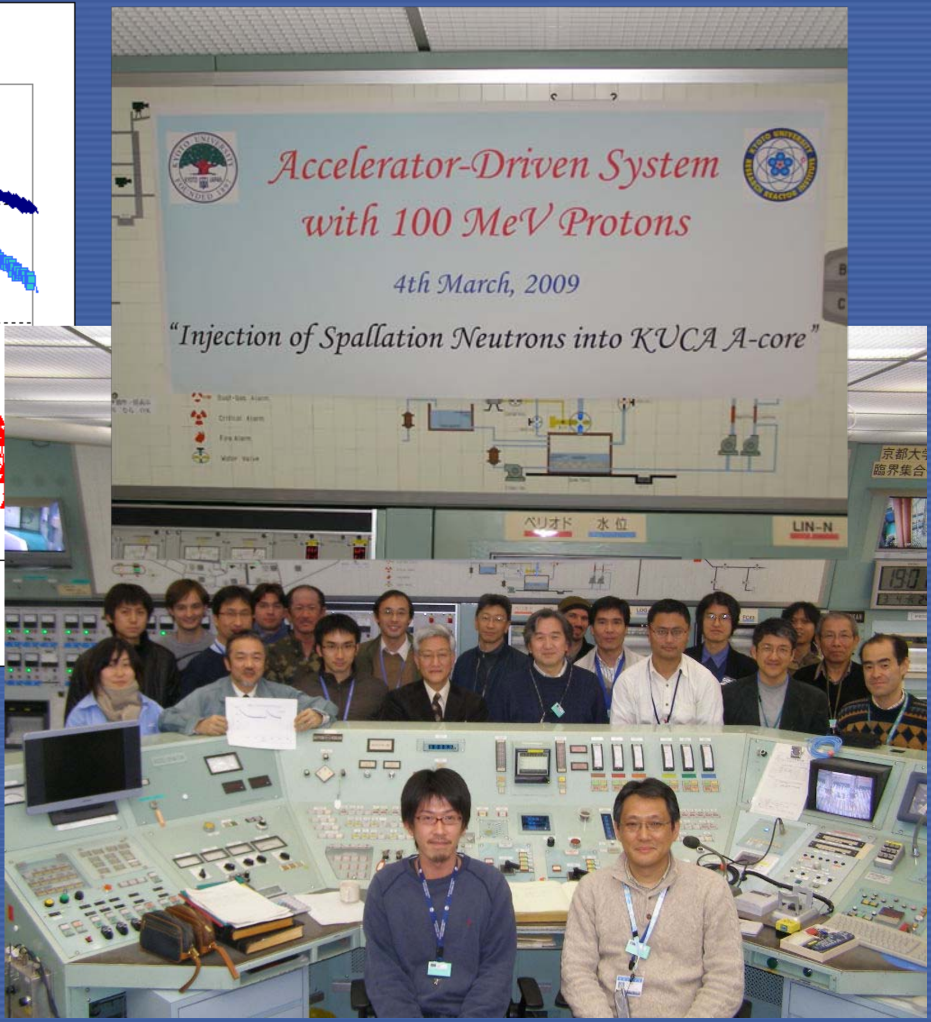
KUCA Sub-critical Experiments

- First stage: 14.1 MEV (d,t) pulsed neutron source
- Sub-criticality satisfactorily evaluated by pulsed neutron source measurements
- Strong dependency on the (BF_3) detector location of the E/C discrepancy (-7% to +21%) for sub-criticality levels measured by the source (^{252}Cf) multiplication method
- Foil activation measurements [$^{115}In(n,n')^{115m}In$, $^{56}Fe(n,p)^{56}Mn$, $^{27}Al(n,\alpha)^{24}Na$, and $^{92}Nb(n,2n)^{92m}Nb$] at various sub-criticality levels
- For all sub-criticality levels, agreement within 10% / 26% for ^{27}Al reaction rates in the core / close to t-target
- Very large discrepancies and strong dependency on sub-criticality level for all other reaction rates

Sub-critical Experiments at Kyoto University Critical Assembly (KUCA)

C.H. Pyeon, Kyoto University Research Reactor Institute





Spallation neutrons from target

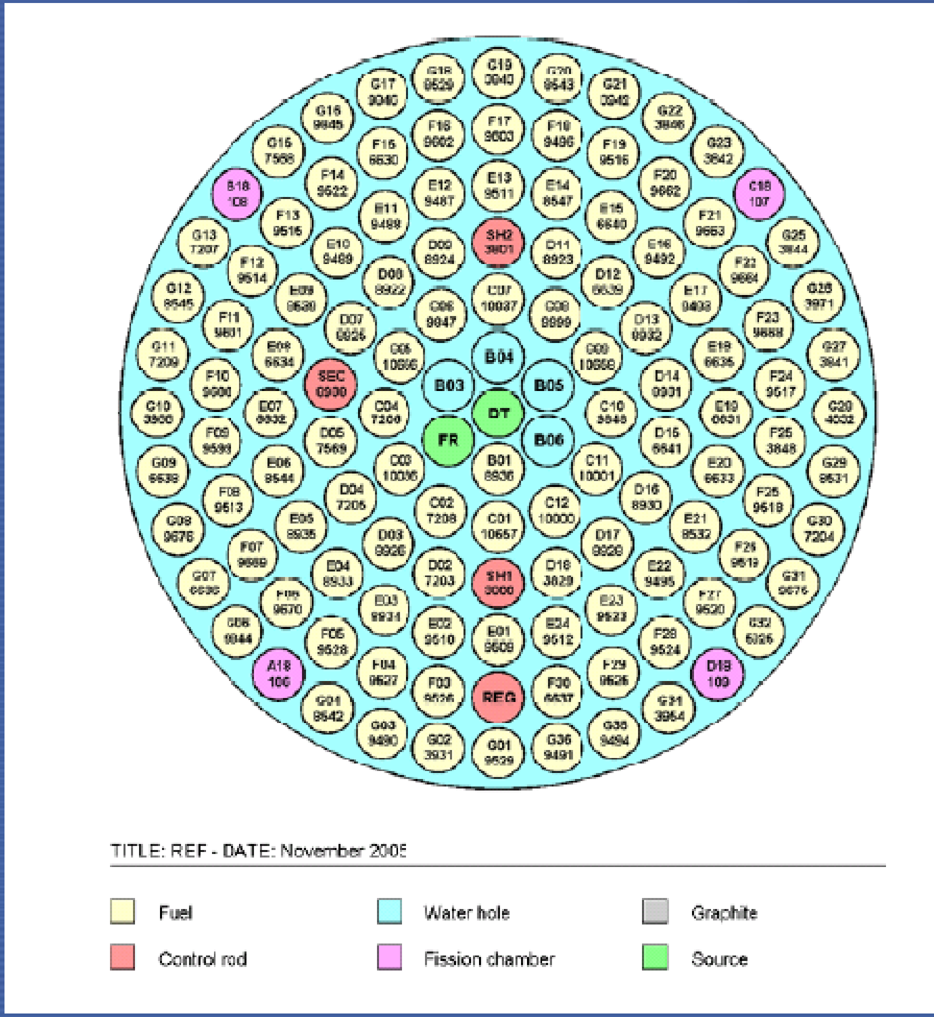
Delayed neutrons in core

IA

Spallation neutrons (gen. by 100MeV p) multiplied in KUCA

Pre-TRADE Experiments

- TRIGA RC-1 Pre-TRADE sub-crit. reactivity measurements (-500, -2500, -5000 pcm)
- Understanding the spatial/energy correction factors with different experimental sub-criticality measurement techniques:
  - MSM (MSA) [^{252}Cf source in B02]
  - PNS area-ratio [(d,t) neutron generator]
  - Evaluation, via computation, of the correction factors to be applied to the PNS area-ratio and MSA results



Pre-TRADE Experiments, Conclusions

- Strong under-estimation (up to -4$ for the deepest sub-critical level) of the experimental reactivity level due to uncertainties in actual burnup distribution of the reactor (in spite of efforts to reconstruct the burnup history)
- Large spread (up to 1$ standard deviation for the deepest sub-critical level) of experimental raw reactivity results obtained by PNS area-ratio and MSA methods, depending on the method and on the detector position
- Satisfactory clustering of experimental results after applying calculated correction factors for both PNS area-ratio and MSA methods

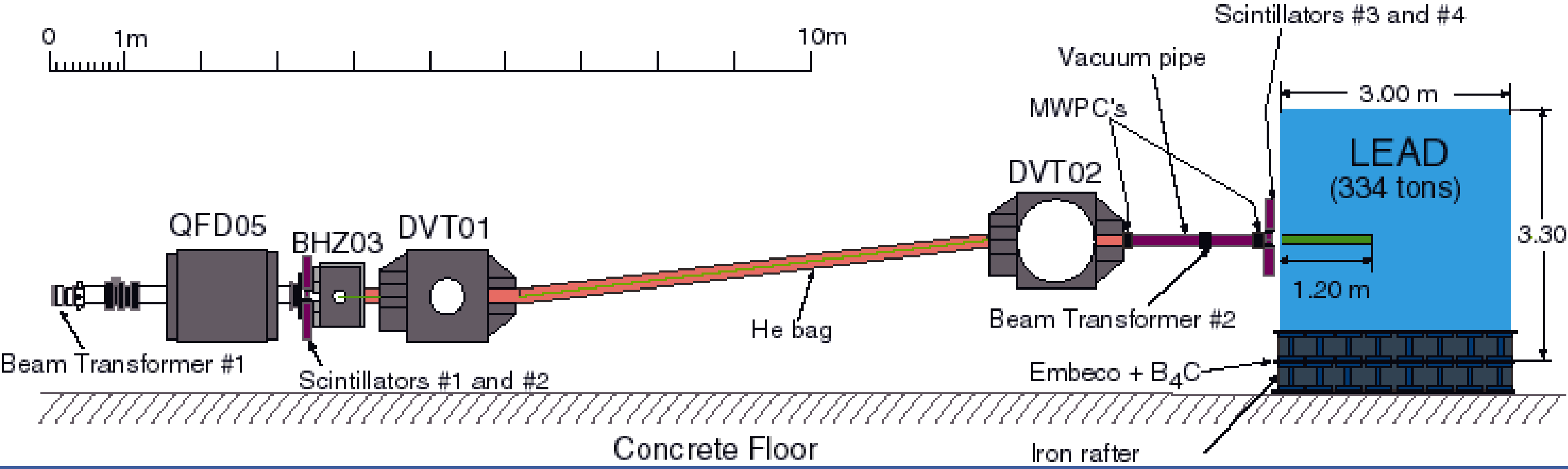
FEAT (First Energy Amplifier Tests)

- **Experimental determination of the energy generated in nuclear cascades by a high energy beam**
- **CERN sub-critical natural uranium array and low intensity proton beams**
- **Criticality, energy gain, power density, fission rates and flux values have been calculated for nine different proton energy beams, from 600 MeV to 2.75 GeV**
- **Neutron production per proton is still missing**
- **Analyses of discrepancies between calculations experimental data ongoing**

Álvarez-Velarde, 4th RCM, Feb 2010

TARC (Transmutation by Adiabatic Resonance Crossing)

- **TARC used the CERN Proton Synchrotron**
- **Spallation neutron production by GeV protons hitting a large lead volume**



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TARC cont'd

- **Complementary techniques employed to measure neutron fluence from thermal up to a few MeV**

[redacted]

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TARC cont’d

- **Neutron capture rate measurements in ^{99}Tc, ^{127}I, and ^{129}I**
- **High statistics measurement of the ^{99}Tc apparent neutron capture cross-section**

Abánades, 4th RCM, Feb 2010

TARC, Conclusions from Flux Benchmark Exercise

- **Lead moderation reasonably well reproduced by the participants.**
- **Larger uncertainties in high Energy (>1MeV) results, with JAERI-JENDL data underestimating fast flux measurements**
- **JAERI-LA150 yields better C/E agreement over the whole energy range**
- **Discrepancies due to source description and coupling**
- **LibADS (IAEA user library based on ENFB-VII) yields lower epithermal neutron flux values, possibly due to different elastic scattering angle distribution**
- **Larger discrepancies observed for the integral fluence results with increasing distance from the centre**

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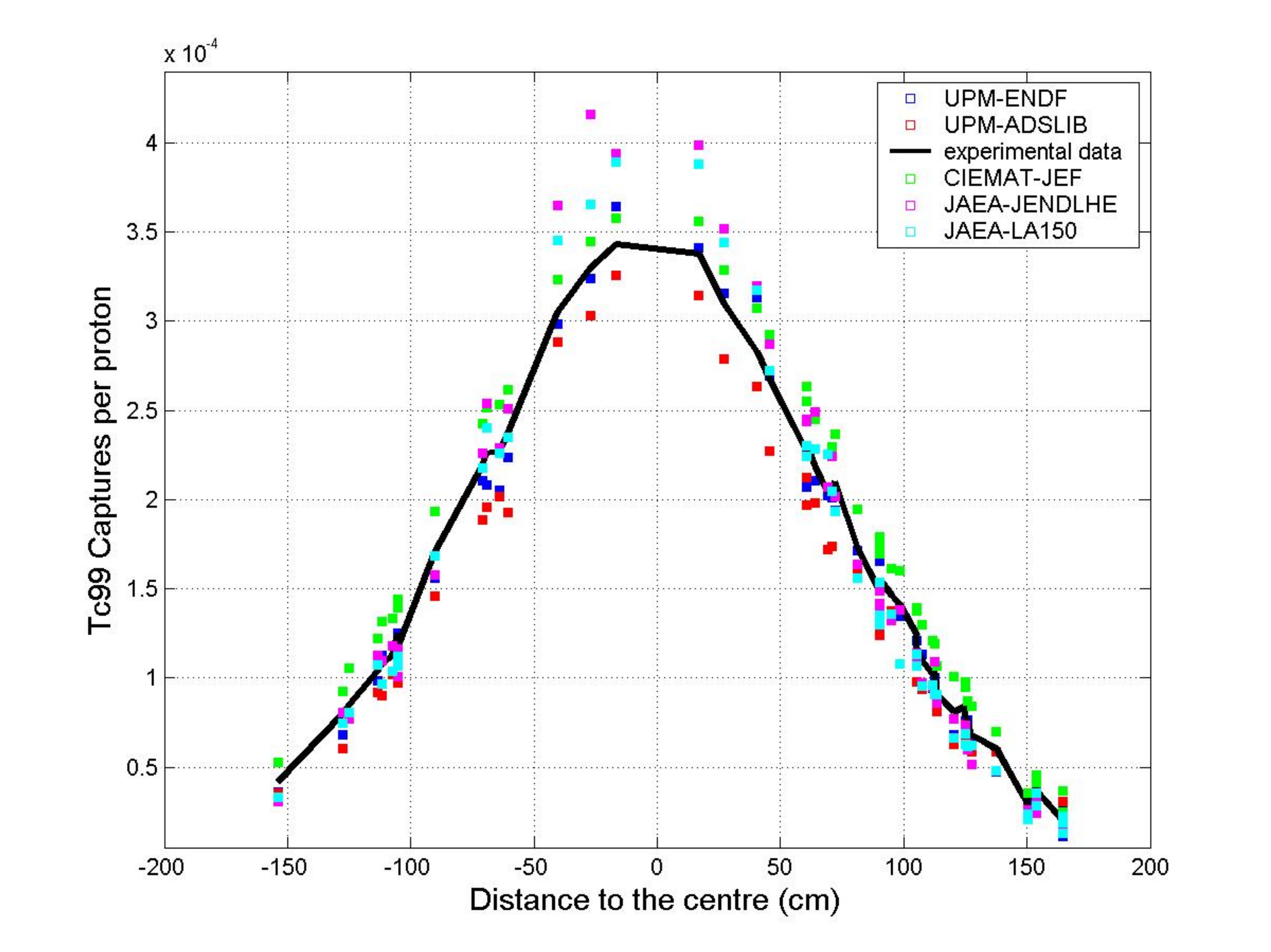
TARC, ^{99}Tc Neutron Capture Rates Results



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TARC, Conclusions ^{99}Tc Neutron Capture Rates

- Experimental and calculated results agree within 20%
- Overestimation by JEF over the whole distance
- Mostly underestimation by the other results at far distances
- Clear underestimation by ADSLib in the whole range, in agreement with the lower energy flux in ADSLib calculation in the epithermal energy
- Cross section differences are negligible
- The most important sources for discrepancies are linked to the detailed Tc sample modelling (self-shielding effect), and to the treatment of the neutron moderation in the huge lead bloc

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ADS Kinetics Analytical Benchmarks

- Diffusion calculations
  - Pulsed-source transients
    - ✓ Homogeneous reactor, 3-group diffusion approximation
    - ✓ Heterogeneous reactor, 1-group diffusion approximation
  - Rod-ejection accident
    - ✓ Homogeneous reactor with a localized control rod, 3-group diffusion approximation
    - ✓ Heterogeneous reactor, 1-group diffusion approximation
  - Material perturbation accident
    - ✓ Two-zone system, 1-group diffusion approximation
- Transport calculations
  - Pulsed-source transients
    - ✓ Homogeneous system, 1-group transport

Dulla/Ravetto, 4th RCM, Feb 2010

ITEP Spallation Targets (Thin Target Irradiations)

Proton energy (GeV)	Targets																					
	^{nat}Cr	^{56}Fe *	^{nat}Ni	^{59}Co	^{63}Cu	^{65}Cu	^{93}Nb	^{99}Tc	^{181}Ta	^{182}W	^{183}W	^{184}W	^{186}W	^{nat}W	^{nat}Hg	^{206}Pb	^{207}Pb	^{208}Pb	^{nat}Pb	^{209}Bi	^{232}Th	^{nat}U
0.04	14	18	20				19		9					19		13	9	8	18	13		
0.07	17	21	22				28		17					31		28	29	28	28	35		
0.1	19	24	27				37	18	31					45	44	46	42	36	43	50	87	108
0.13				25	11	6										22	22	20		26		
0.15	22	25	28				46		40					53		65	65	63	63	71		
0.2				29	29	29		39		32	35	36	36		65						128	123
0.25	28	33	37				58		53					69		94	94	94	95	106		
0.4	31	37	36				64		82					83		112	112	113	116	128		
0.6	33	38	40				75		101					104		139	140	141	141	147		
0.8*	33	38	43				85	72	105	70	76	77	60	110	103	156	152	154	154	162	130	195
1.0		38						64										114				
1.2	33	39	43	41	47	54	96	67	143					155		170	170	170	171	183	214	226
1.5		38			35	36										92	93	94	93	99		
1.6	33	38	46	41	42	47	106	78	152	109	111	114	119	164		180	180	182	181	192	212	231
2.6	33	38	46	41	42	48	107	85	166					181	141	171	171	172	178	198		

Titarenko/Batyaev, 4^{th} RCM, Feb 2010

ISTC#839-0 (1997-1998)
ISTC#839 (1999-2001)
ISTC#2002 (2002-2005)
ISTC#3266 (2006-2009)

ITEP Spallation Targets (Thin Target Irradiations), Conclusions

- 14518 residual nuclides measured from 1997 – 2009
- Theoretical simulations by Monte-Carlo codes (INCL4, CEM03.02, Bertini, Isabel)
  - Pb, Bi: <F> ~1.5-2 for most codes at Ep>0.1GeV
  - Ta, W: <F> ≥ 2 for all codes
  - Fe, Cr, Ni: <F> > 2
    (only CEM03.02 yields <F> below 2 at Ep=0.5-1.0 GeV)
  - Low energies are not well described by all the codes
- If the goal is <F> below 2, further development of the codes' theoretical models is required
- Further experimental activity should address low and middle mass targets (e.g. Mo, Ti, Zr, Sn, In, C, Al)

Mean squared deviation factor:

$< F >= 10^{\sqrt{A}}$ where $A = \left\langle \left(\lg \sigma_{calc,i} / \sigma_{\exp,i} \right)^2 \right\rangle$

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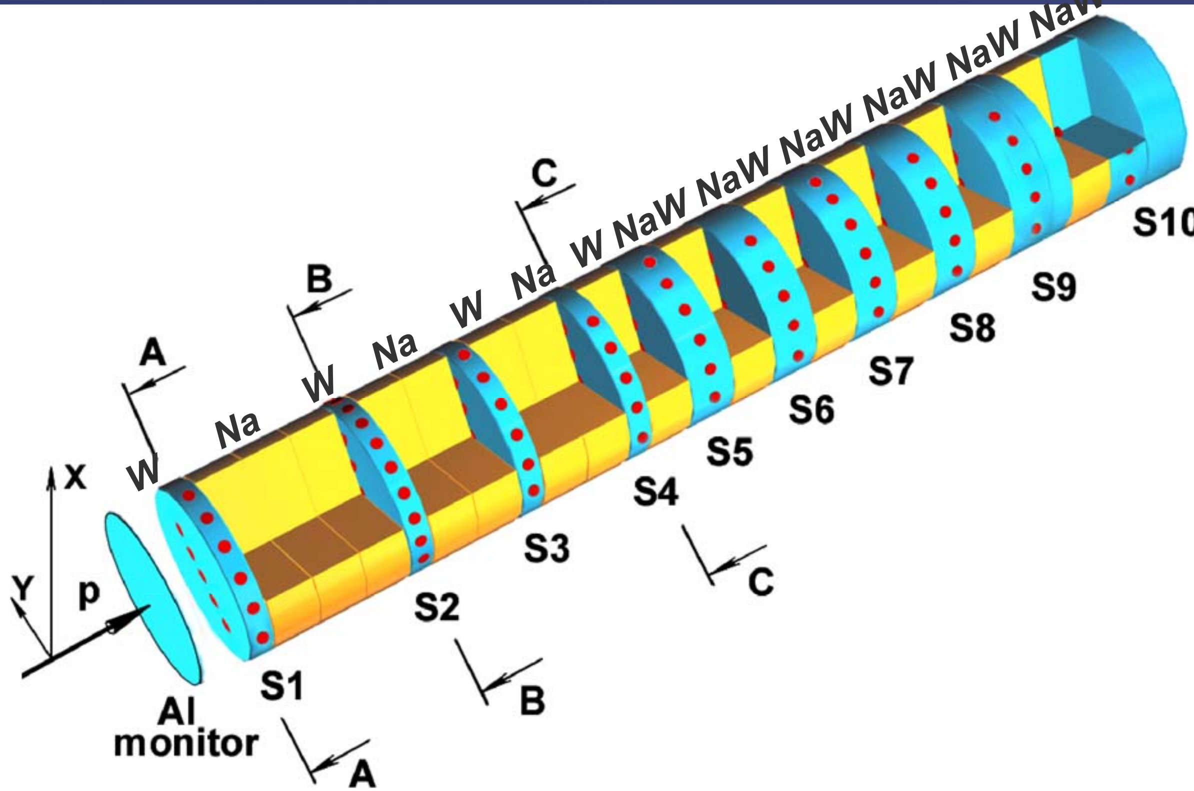
ITEP Spallation Targets, W-Na Thick Target Irradiations



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Sample arrangements:

Points S1, S3-10:

^{181}Ta, ^{115}In, ^{209}Bi, ^{27}Al, ^{197}Au

Point S2:

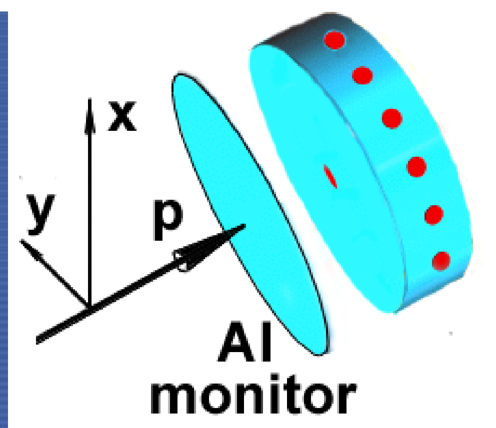
^{12}C, ^{19}F, ^{27}Al, ^{63}Cu, ^{65}Cu, ^{59}Co, ^{64}Zn, ^{93}Nb, ^{115}In, ^{169}Tm, ^{181}Ta, ^{197}Au, ^{209}Bi.

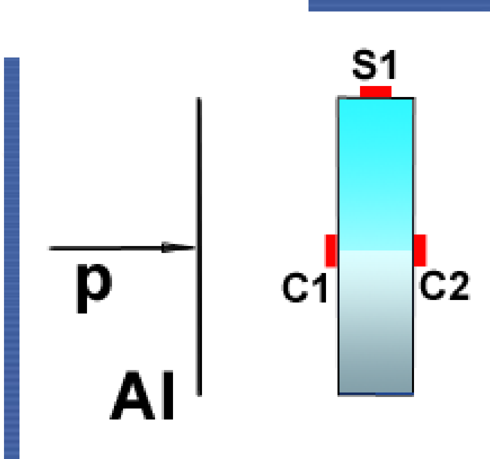
Points C1-C10 (axis):

^{27}Al, ^{59}Co

E_p=0.8GeV
T_{irr}=10h
*N_p=6*10^{14}*

E_p=0.8GeV
T_{irr}=2h
*N_p=0.7*10^{14}*





Sample arrangements

Point S1:

^{12}C, ^{19}F, ^{27}Al, ^{63}Cu, ^{65}Cu, ^{59}Co, ^{64}Zn, ^{93}Nb, ^{115}In, ^{197}Au, ^{209}Bi.

Points C1, C2 (axis):

^{27}Al, ^{59}Co , ^{115}In

ITEP Spallation Pb Target Irradiation (0.8 MeV Protons)

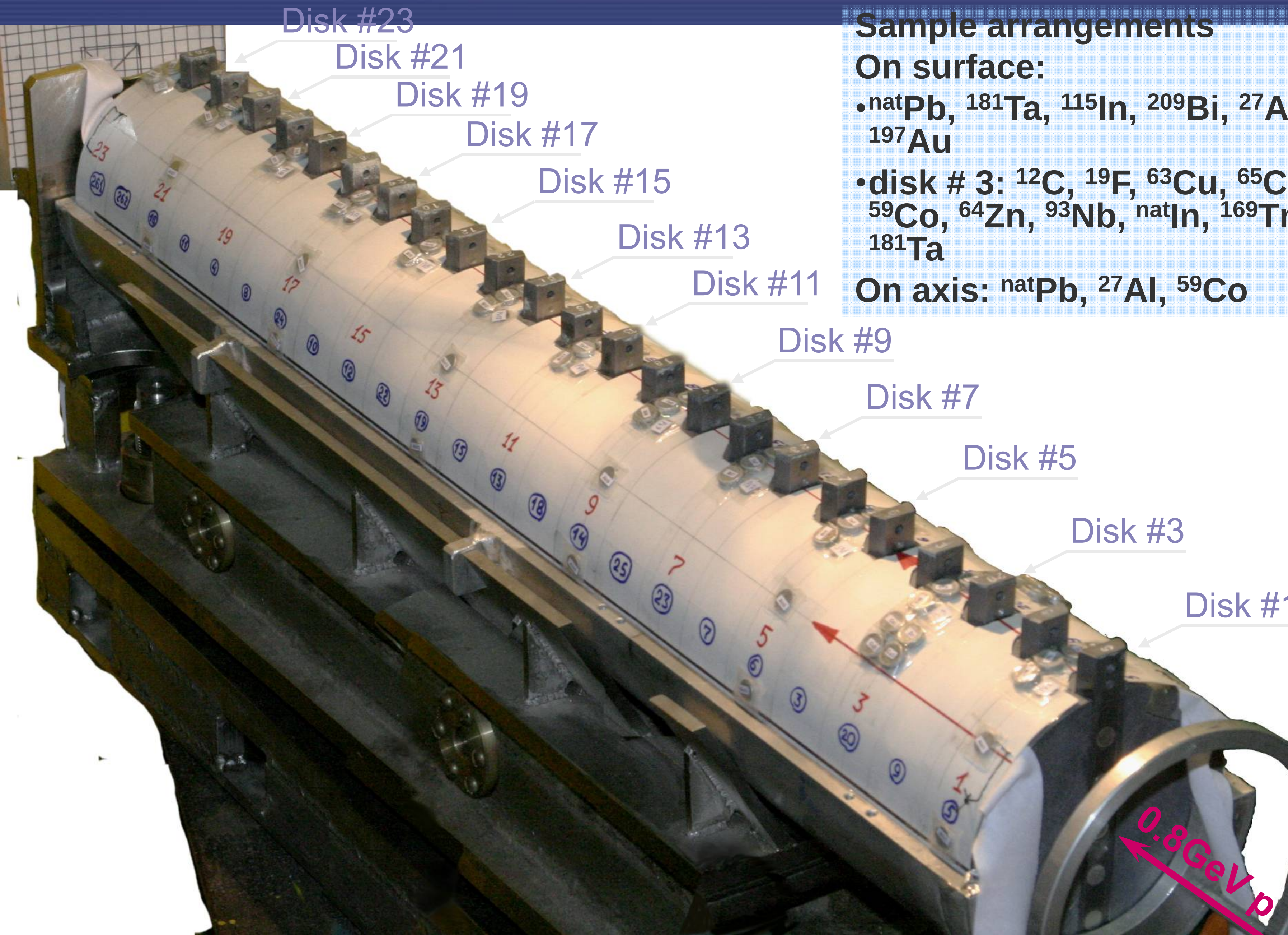
Titarenko/Batyaev, 4^{th} RCM, Feb 2010

Sample arrangements

On surface:

- ^{nat}Pb, ^{181}Ta, ^{115}In, ^{209}Bi, ^{27}Al, ^{197}Au
- disk # 3: ^{12}C, ^{19}F, ^{63}Cu, ^{65}Cu, ^{59}Co, ^{64}Zn, ^{93}Nb, ^{nat}In, ^{169}Tm, ^{181}Ta

On axis: ^{nat}Pb, ^{27}Al, ^{59}Co



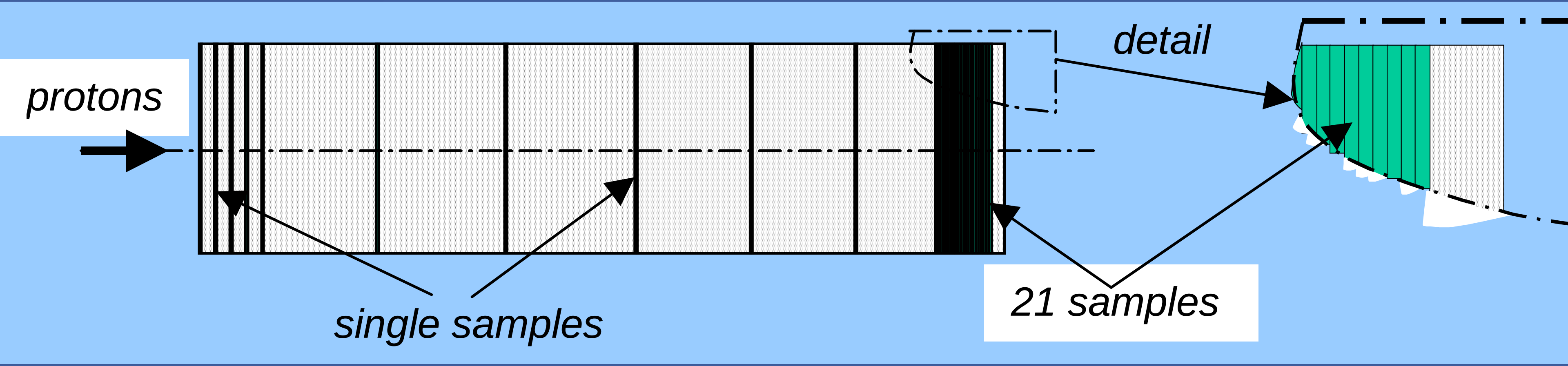
ITEP Spallation Targets, Conclusions

- 979 reaction rates measured on W-Na target
- 2467 reaction rates in 244 activation samples measured on and inside Pb target
- Target irradiations simulated via LAHET (ISABEL)+HMCP
- 167 excitation functions for activation reactions estimated allowing to
  - Well reproduce the measured reaction rates
  - Determine the neutron yield and the distributions of neutron and proton flux inside and on the target
  - Substantiate Pb target activation up to 3000 yrs cooling time
- C/E agreement much more satisfactory for thick target than for thin targets

Titarenko/Batyaev, 4th RCM, Feb 2010

JINR Dubna Pb Spallation Target

- JINR Dubna 660 MeV proton accelerator
  - Ep = 660 ± 4 MeV
  - Ipmax = $3 \cdot 10^{10}$ p/s,
  - Irradiation time: 8 – 9 hrs
  - Minimum decay time: 2 hrs
- The spallation target consisted of 80 mm diameter cylindrical Pb disks (1, 10, and 50 mm thickness)



Janczyszyn, 4th RCM, Feb 2010

JINR Dubna Pb Spallation Target, cont'd

- **Target activation (radionuclide production)**
  - n, p, α, π^- distribution and spectra
  - Whole target activation and activity distribution along the target
    - ✓ Instantaneous
    - ✓ Accounting for decay during and after the activation
- **Heat generation**
  - Whole target heating rate
    - ✓ Share of various particles (n, p, α, π^-, γ)
    - ✓ With p beam on and off (after)
  - Distribution of power release (axial and radial)

Janczyszyn, 4th RCM, Feb 2010

JINR Dubna Pb Spallation Target, cont'd

Codes and models for the analyses

- MCNPX2.5.0 with various codes for radionuclide decay calculations (EVOLCODE2, Evizo)
- MCNPX2.2.3
- MCNPX2.6e and f
- CEM, INCL4-ABLA, Bertini-Dresner, Isabel

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JINR Dubna Pb Spallation Target, Conclusions

- The physical models used to calculate whole target radionuclide production rates yield unsatisfactory results for the majority of nuclides
  - Depending upon the radionuclide, only between 12% and 45% of the calculated production rates are within a 20% C/E range
  - The shape of the nuclide (activity) distribution is well simulated, but the absolute values show the same trend as for the whole target activation
- Satisfactory results for the target heating
  - Whole target heating results are consistent among the various participants, with only small differences between the physical models
  - Same conclusion for after-heat results and for the axial and radial heat distribution results

Janczyszyn, 4th RCM, Feb 2010

For more information, please visit www.iaea.org/inisnkm/nkm/aws/fnss/index.html

Thank You !

JINR Dubna Pb Spallation Target, Conclusions, cont'd

- **Nuclide dependent C/E results for whole target radionuclide production rates accounting for decay during and after the activation**
  - C/E within 20% (considered acceptable) for
    - ✓ ^{185}Os (12 benchmark contributions)
    - ✓ ^{194}Au / ^{194}Hg (9 benchmark contributions)
    - ✓ For ^{175}Hf, ^{183}Re and ^{207}Bi (4 – 6 benchmark contributions)
  - Most calculations overestimate the production rates of nuclides from ^{60}Co to ^{121}Te
  - Most calculations underestimate the production rates of nuclides heavier than ^{121}Te

Janczyszyn, 4th RCM, Feb 2010

JINR Dubna Pb Spallation Target, Conclusions, cont'd

- **C/E results for activity distribution along the target accounting for decay during and after the activation**
  - Only the CEM model reproduces well the 46Sc distribution
  - All models underestimate the 95Nb production rate, with CEM and Bertini-Dresner being the worse
  - All models are overestimating the 183Re production rate

Janczyszyn, 4th RCM, Feb 2010