ADS-Related Initiatives in the US

Andrew Hutton

Associate Director, Accelerators

Jefferson Lab, Newport News, Virginia, USA

Introduction

- **At this time, there are no government-funded ADS initiatives in the USA**
- However, there are many activities relevant to ADS, particularly high-power superconducting accelerators
  - CEBAF – 6 GeV, 1 MW electrons
  - SNS – 800 MeV, 1 MW protons
  - Project X – 3 GeV, 3 MW protons (design and prototyping)
  - ANL – Spent Nuclear Fuel Disposal Studies
- Several conferences on the use of Thorium as a nuclear fuel have been organized in the US

Earlier ADS Initiatives
2003 – 2006

Slides from Doug Wells (IAC)

U.S. Reactor-Accelerator Coupling Experiment:

(RACE, 2003 – 2006) was an ISU-led, DOE-funded research project (with U. Tex., TAMU, UNLV, U. Mich., INL, ANL, LANL, CEA, ECATS)

- Design, model, and conduct ADS experiments
- Predict and analyze subcritical multiplication and source-driven transients
- Map source importance & flux
- Study ADS startup and shutdown
- Study dynamic effects of power at different sub-criticality levels (feedback vs. source effects)
- Study start-up/shut-down scenarios
- In general, study all relevant aspects of current/power/importance/control rod relations

Driving neutron sources:

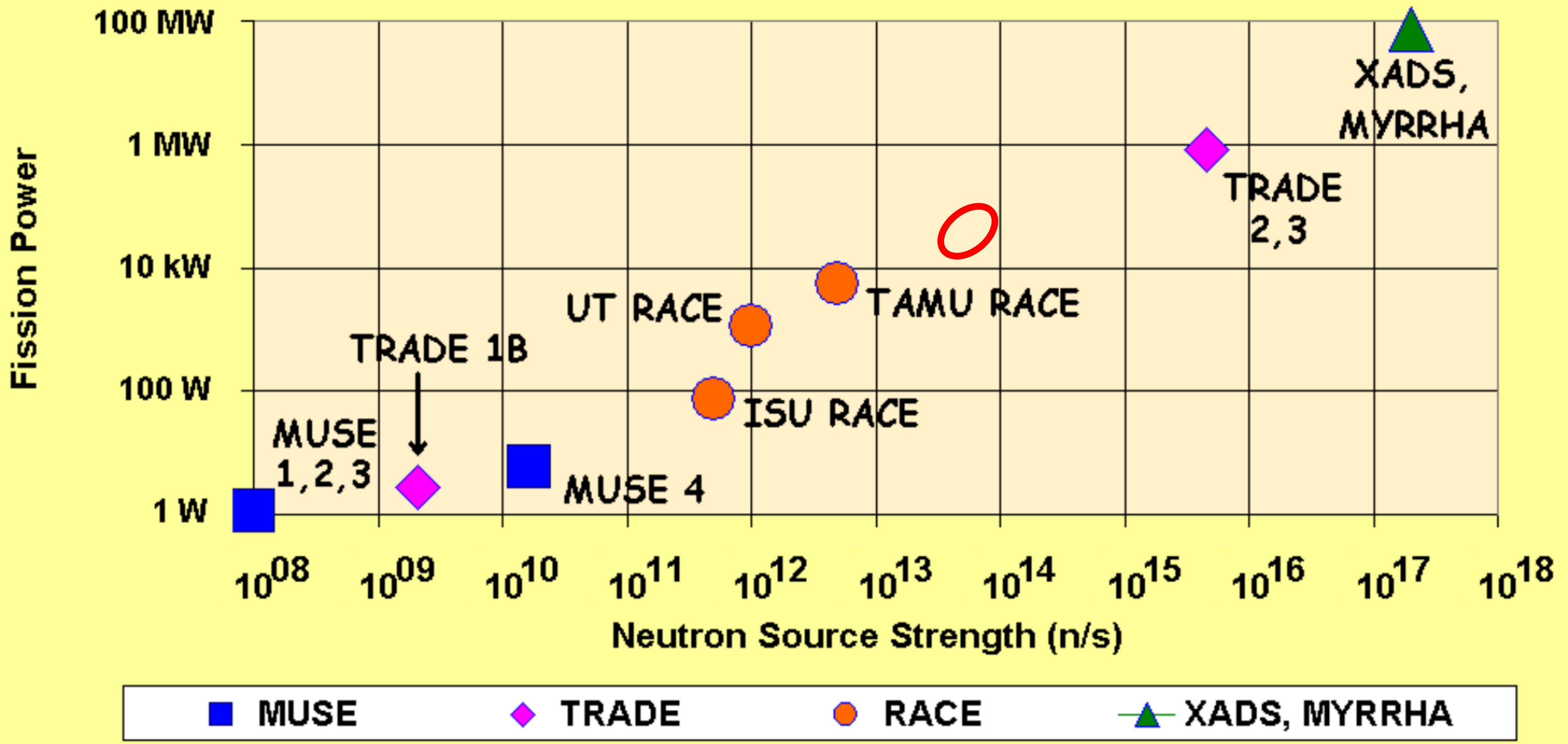
- MUSE DT-neutron source
  - » ~1.5x10^{10} n/s, 2.45 & 14.1 MeV
- RACE linear electron accelerator:
  - » ~10^{12} n/s/kW e-beam @ 25 MeV
  - » Intermediate energy: spallation-like spectrum plus small tail up to 20-25 MeV
- Potential future high-power RACE
  - » 50 kW power supply to linac & U target
  - » Potential neutron production up to ~10^{14} n/s

Idaho Accelerator Center

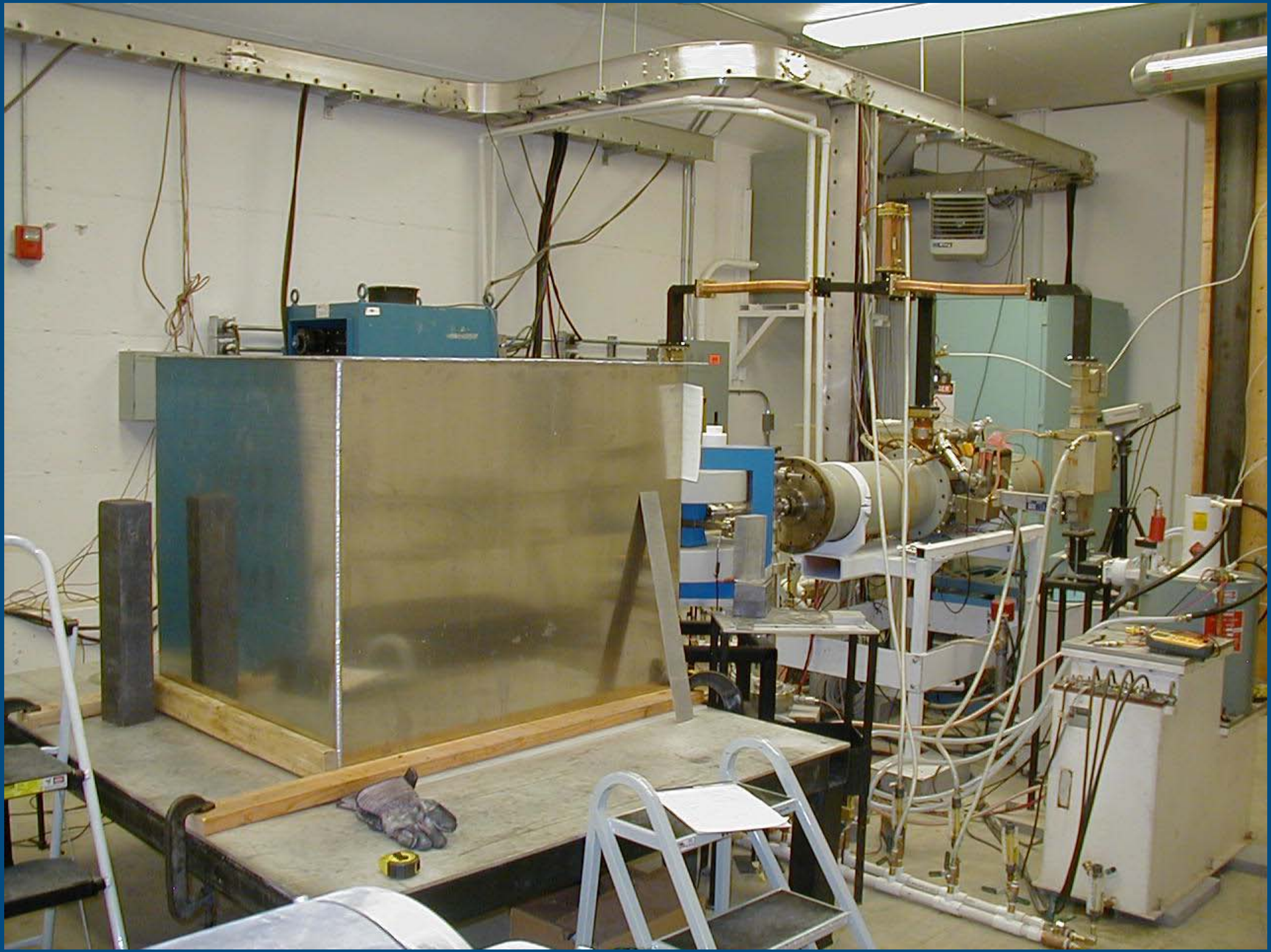
RACE ADS Experimental Program Characteristics

University	nominal power (kWth)	peak power (MWth)	target location	fuel type	fuel compo-sition	fuel enrich-ment	keff
ISU	0	0	center	plates	U-Al Alloy, Al clad	<20%	0.7-0.95
UT-Austin	1	1000	edge	rods	U-ZrH	<20%	~0.92 to 1.0
Tx A&M 1	10	1000	edge, graphite column	rods	U-ZrH "FLIP" fuel	70%	up to 1.0
Tx A&M 2	10	1000	center	rods	U-ZrH	<20%	up to 1.0

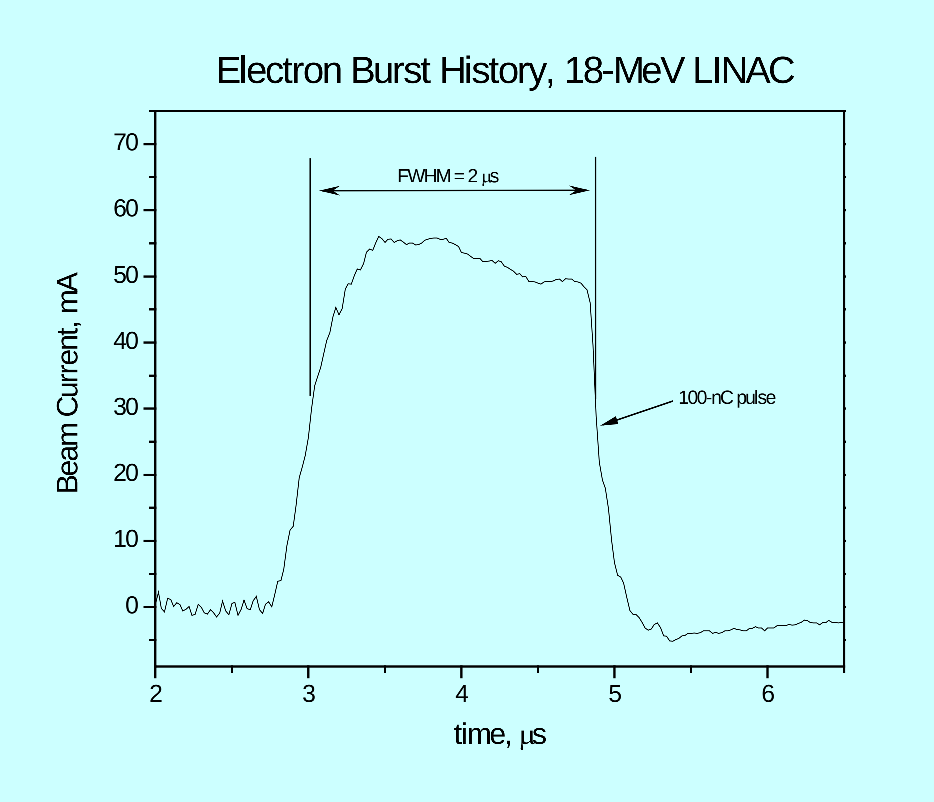
Source strength and reactor power comparisons:



ISU Accelerator and Zero-Power Sub-Critical Assembly:



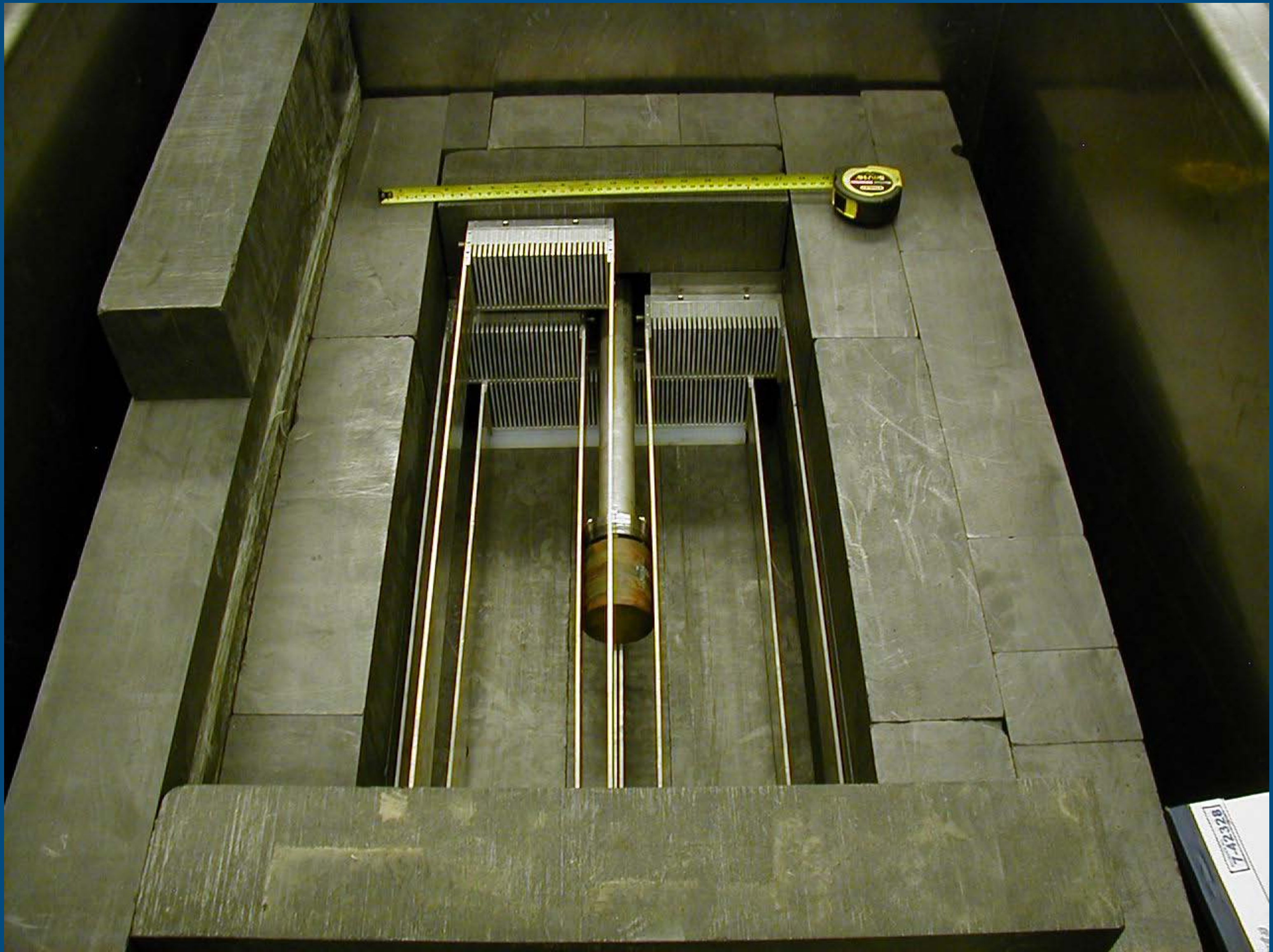
ISU Electron Linac



- **Characteristics:**
  - » **25 MeV**
  - » **80-100 mA peak**
  - » **2-5 µs pulsewidth**
  - » **0 to 100 Hz**
- **25 MeV * 80 mA * 5 µs * 100 Hz = 1 kW**

  → ~1 x 10^{12} n/s

ISU RACE fuel trays and target inside the graphite reflector



Linac for Texas RACE (Phase II-III)

- 20 MeV
- 80-100 mA peak
- 2-10 μs pulse width
- 0 to 180 Hz
- Tested in June, 2004

Linac for Texas RACE (Phase II-III)

Accelerator Installed, 2004, adjacent to reactor (inside concrete bunker):

Primary Results of the U.S. RACE Program

Experimental results of the RACE-ISU international collaboration on ADS, C. Jammes, D. Beller, E. Stankovskiy, K. Sabourov, F. Harmon, and K. Folkman, Proceedings of the Eighth International ANS Topical Meeting on Nuclear Applications and Utilization of Accelerators, pgs. 863-868, American Nuclear Society, (2007).

Modeling of the RACE-ISU subassembly to analyze neutronics experimental data, C. Jammes, E. Stankovskiy, and D. Beller, Proceedings of the Eighth International ANS Topical Meeting on Nuclear Applications and Utilization of Accelerators, pgs. 869-876, American Nuclear Society, (2007).

Analysis of Neutron Production in the High-Powered RACE Target, T. Beller, R. LeCounte, and D. Beller, Proceedings of the Eighth International ANS Topical Meeting on Nuclear Applications and Utilization of Accelerators, pgs. 910-914, American Nuclear Society, (2007).

Thermal Analysis of the High-Powered RACE Target, R. LeCounte, T. Beller, and D. Beller, Proceedings of the Eighth International ANS Topical Meeting on Nuclear Applications and Utilization of Accelerators pgs 915-918, American Nuclear Society, (2007).

Overview of the U.S. Reactor-Accelerator Coupling Experiments (Race) Project, D. Beller, Frank Harmon, Thomas E. Ward, and Frank Goldner, Proceedings of the Eighth International ANS Topical Meeting on Nuclear Applications and Utilization of Accelerators pgs 829-835, American Nuclear Society, (2007).

High-Powered Accelerator Target Design for the AFCI RACE Project, T. Beller, R. LeCounte, B. Howard, and D. Beller, Proceedings of the Eighth International ANS Topical Meeting on Nuclear Applications and Utilization of Accelerators, pgs 969-972, American Nuclear Society, (2007).

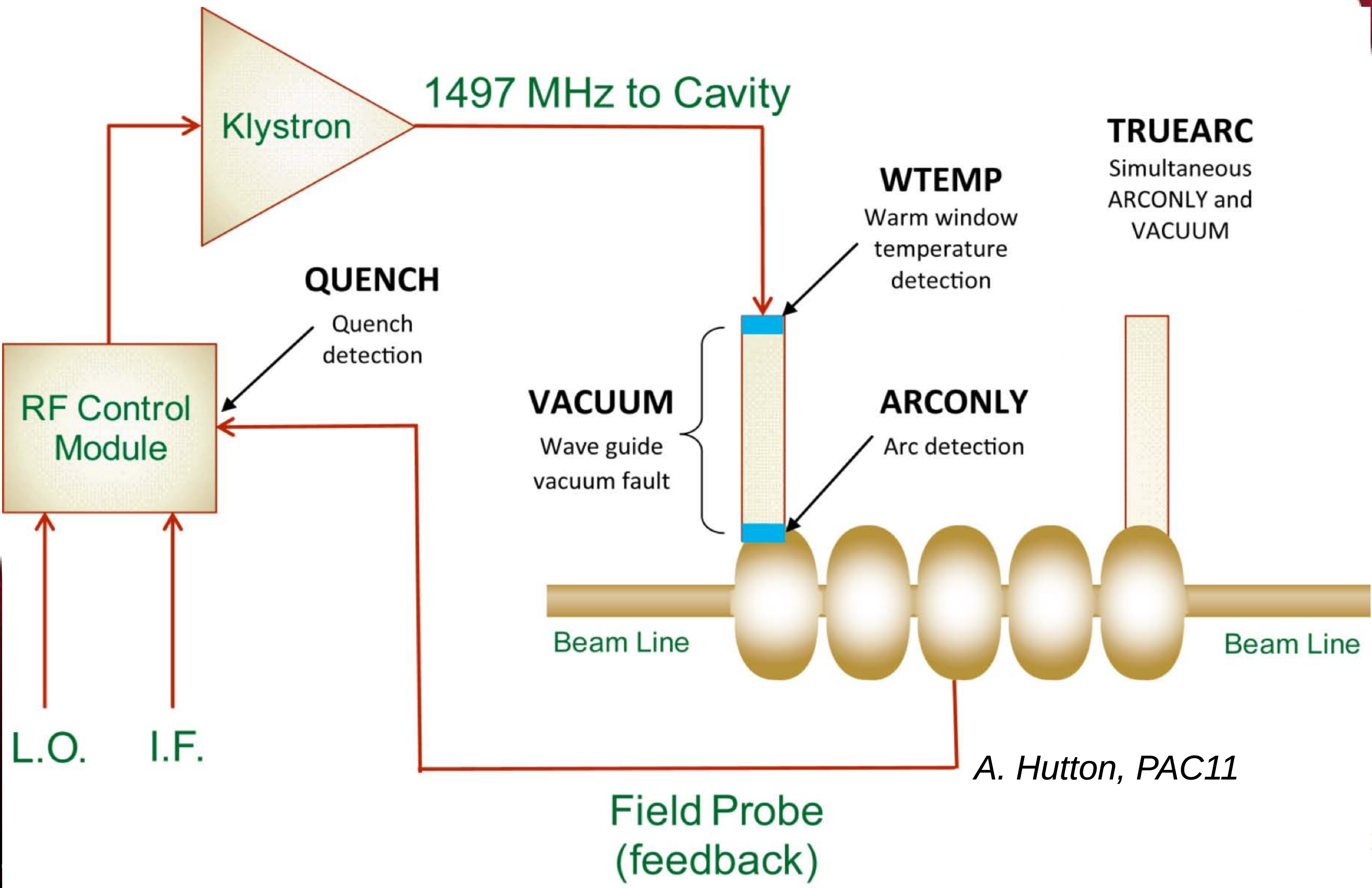
Idaho Accelerator Center

CEBAF

Experiments at CEBAF

- Primary focus has been reduction of RF trips
- Progress in developing tools to characterize RF trips
- Currently focusing on “top 50 cavities” of each type
- We now have software in place to identify weak hardware
  - Helps maintenance crews find problems
- Long-term goal
  - Rebuild a section of the linac as a high-reliability test bed

Trip Input Schematic

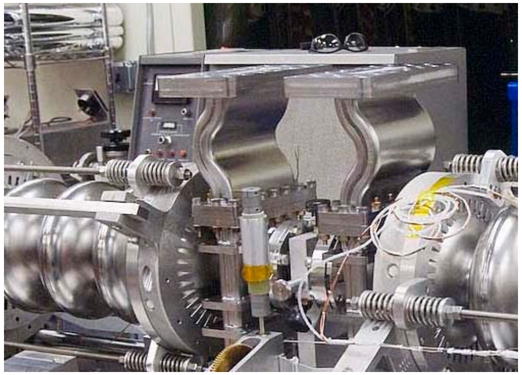


A. Hutton, PAC11

RF trip data presented at PAC11

Average trips per cryomodule per year
data from Aug09 – Sep10

	C-20	C-50
Total	516.3	579.0
TRUEARC	278.4 →	24.8
VACUUM	66.4 →	166.0
ARCONLY	81.75	20.0
QUENCH	100.71 →	359.9
WTEMP	16.2	17.1

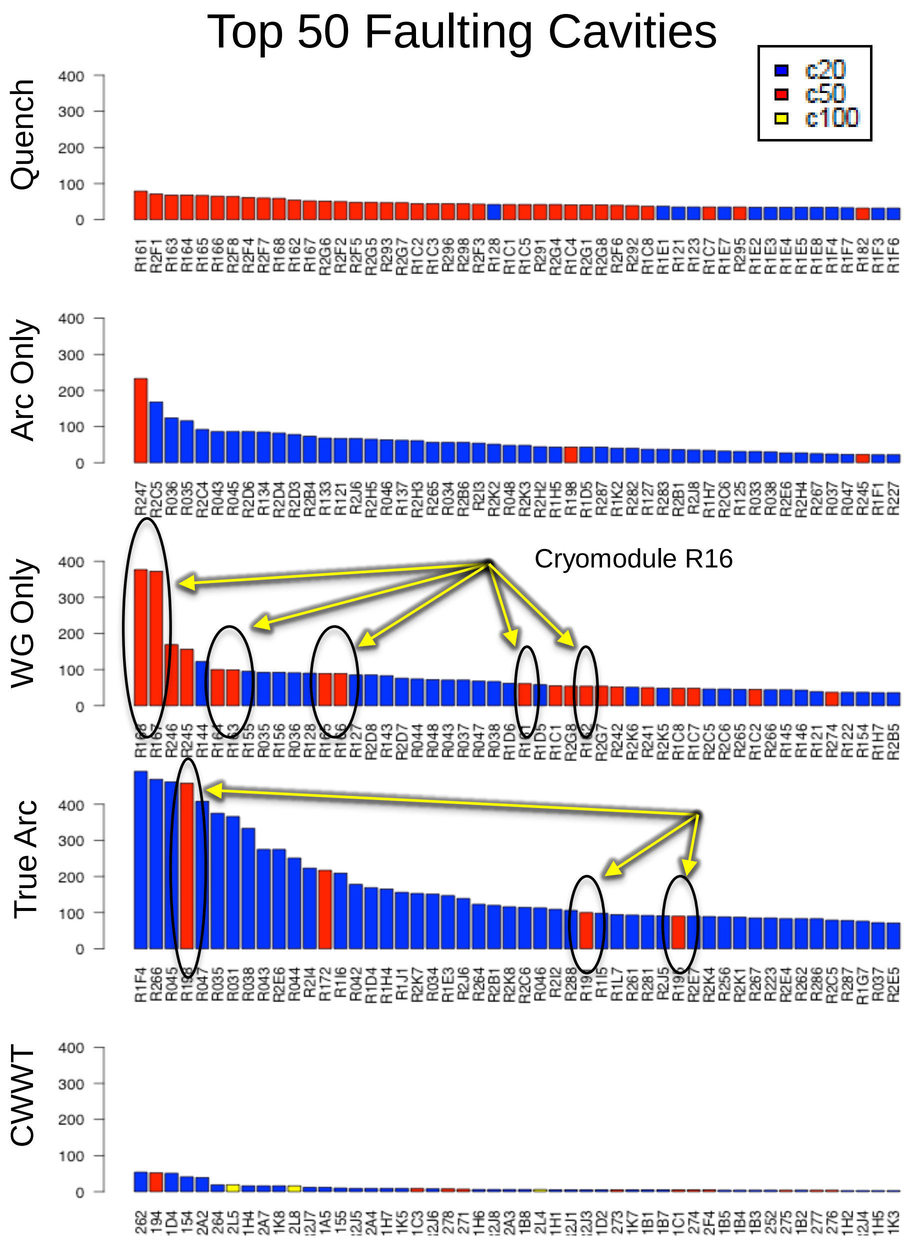


Addition of doglegs

20% of C20 trips
62% of C50 trips

A. Hutton, PAC11

Largest Fault Rates



- C50 cavities
  - Problems with Quenches
  - Few cavities / cryomodules with lots of faults
- C20 cavities
  - Main problems with arc-related faults
- C100 cavities
  - Among the highest CWWT fault counts
- Shows us what we need to work on!

SNS

Slides from John Galambos (ORNL)

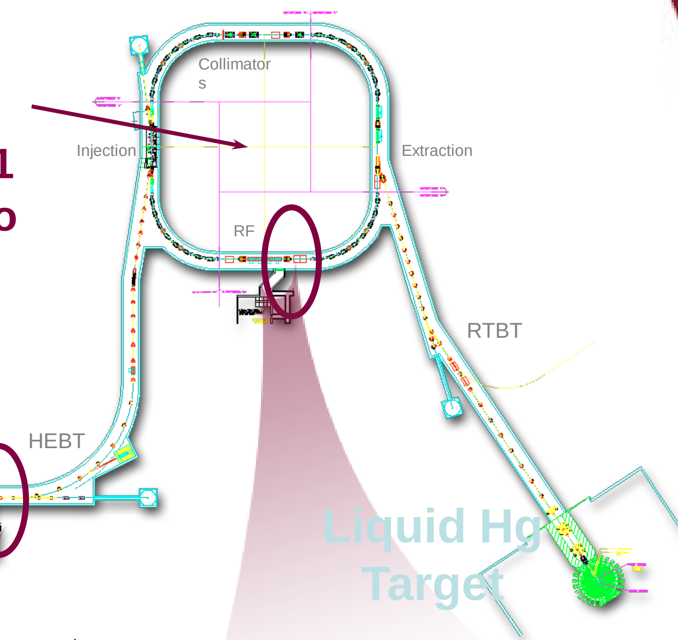
SNS is a neutron source driven by a pulsed proton accelerator

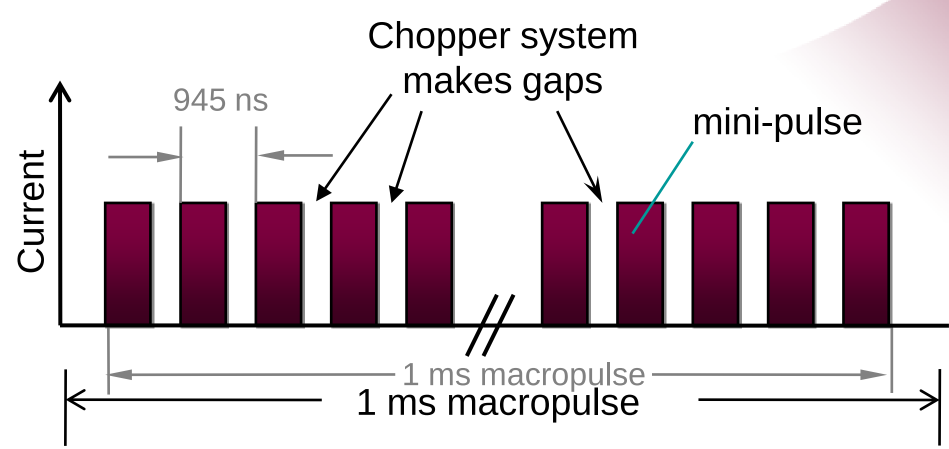
Front-End:

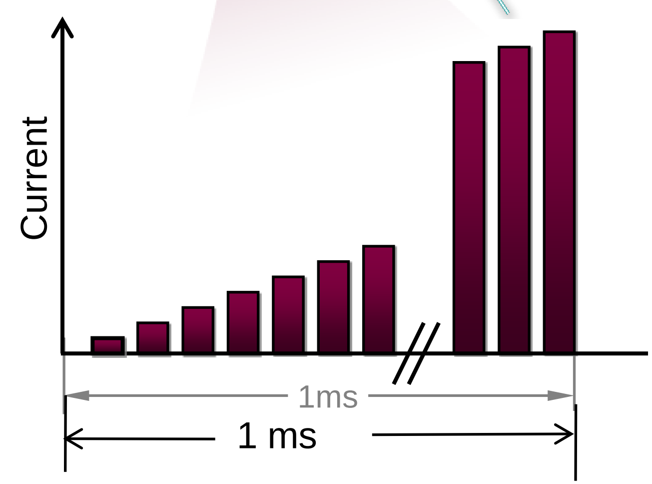
Produce a 1-msec long, chopped, H- beam

1 GeV LINAC

Accumulator Ring: Compress 1 msec long pulse to 700 nsec



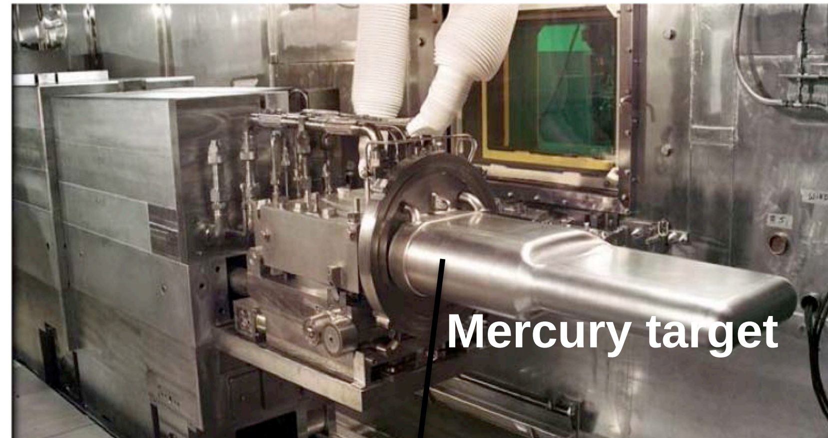




SNS Has ADS Relevant Components

SRF Cavities / Cryomodules

Collimators



LINAC

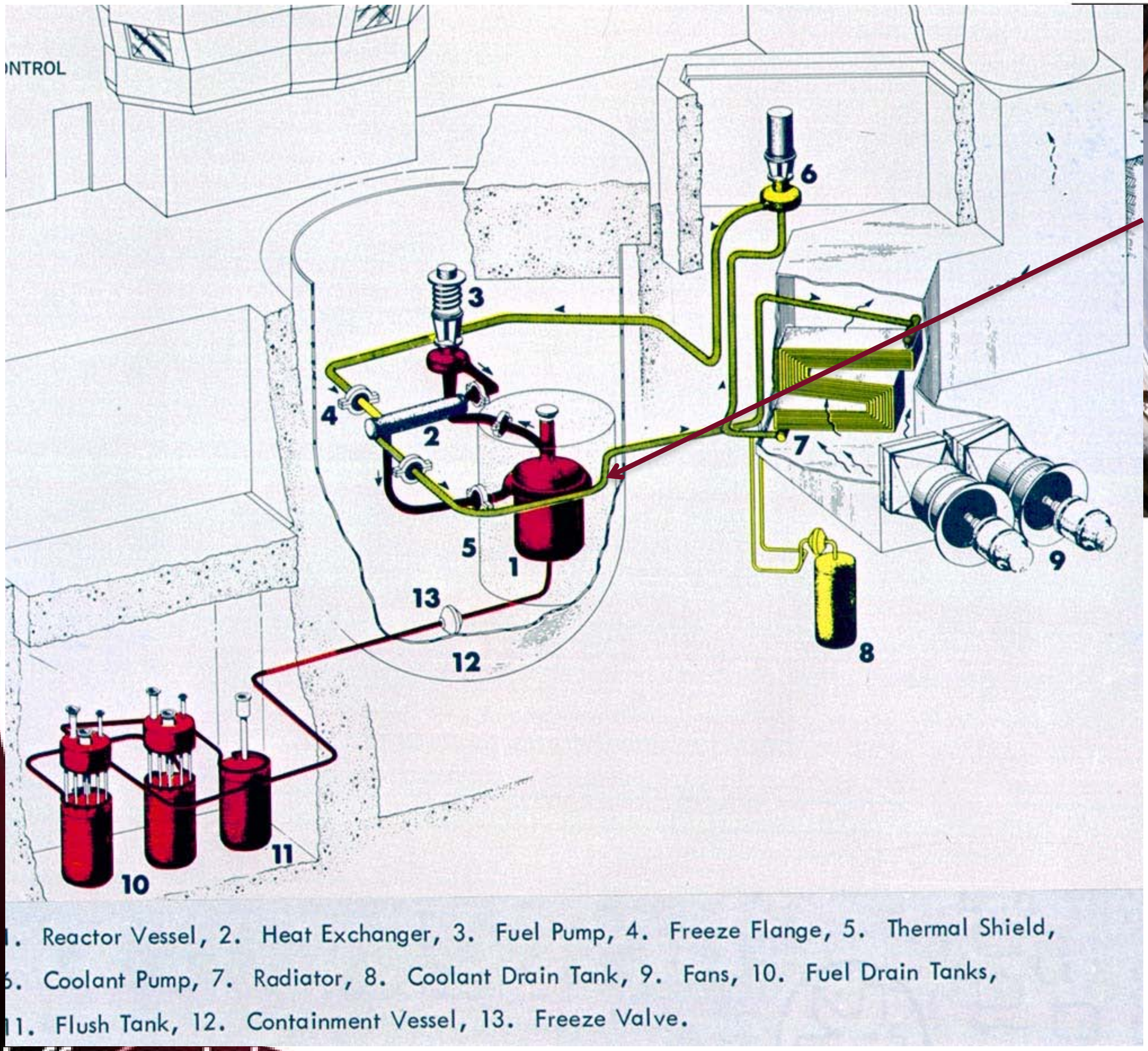
Target

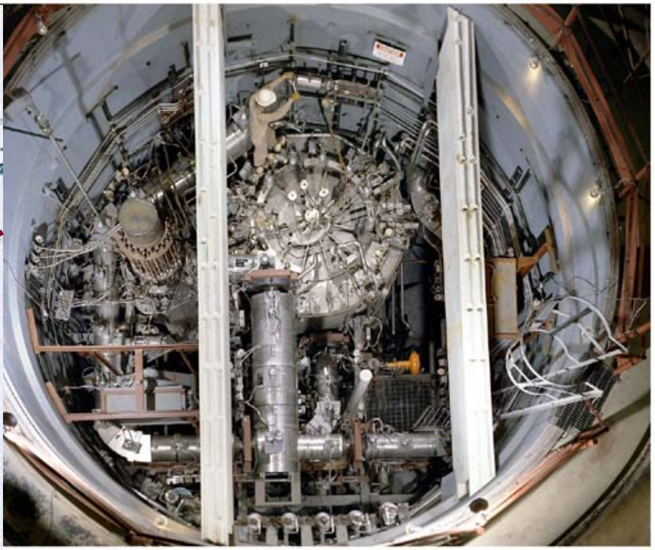
High power (MW) proton beam operation

SNS Beam Parameters

	Design	Operational Value	Best Ever
Power (MW)	1.4	1	1.08
Energy (MeV)	1000	925	1000
Repetition rate (Hz)	60	60	60
Pulse length (ms)	1	0.8	1
<macro-pulse current> (mA)	26	23	26
Beam duty factor (%)	6	4.8	4.8
Stored beam intensity (ppp)	1.5×10^{14}	1.1×10^{14}	1.5×10^{14}

Molten Salt Reactor, ORNL



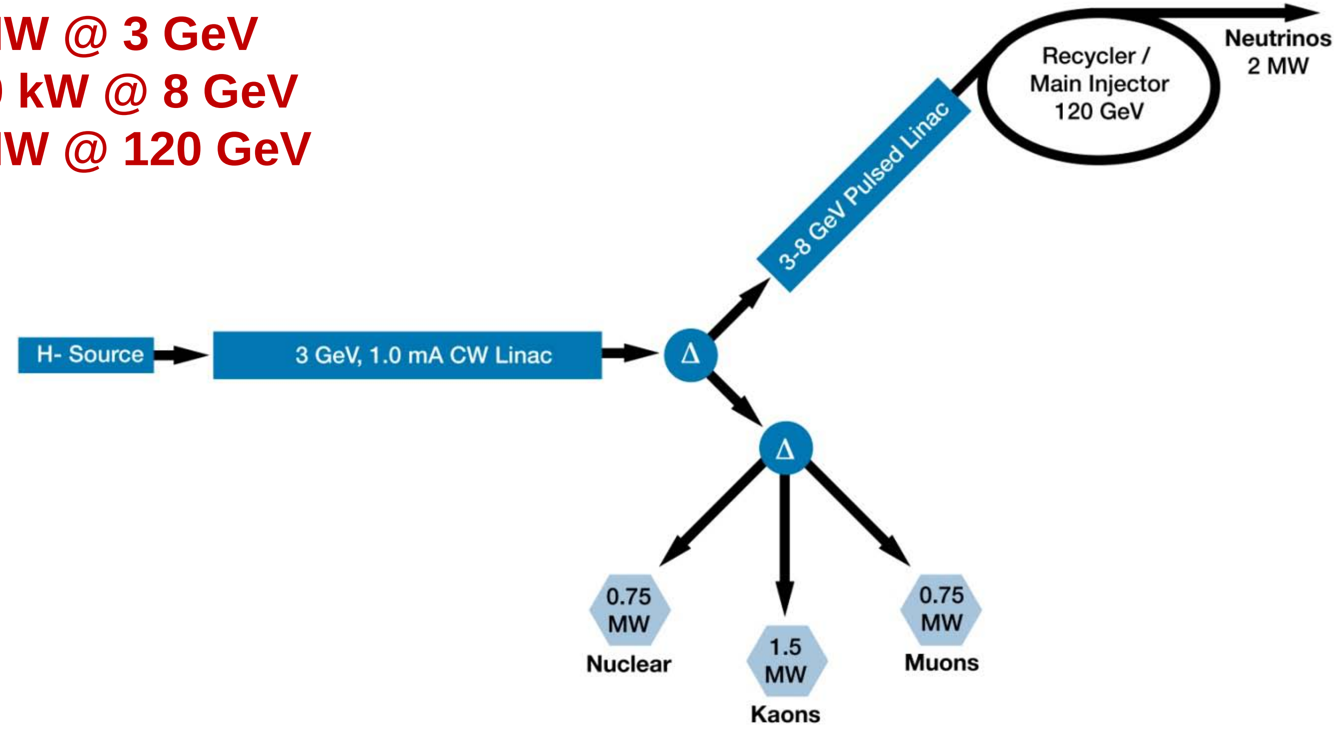


Project X

Slides from Steve Holmes (FNAL)

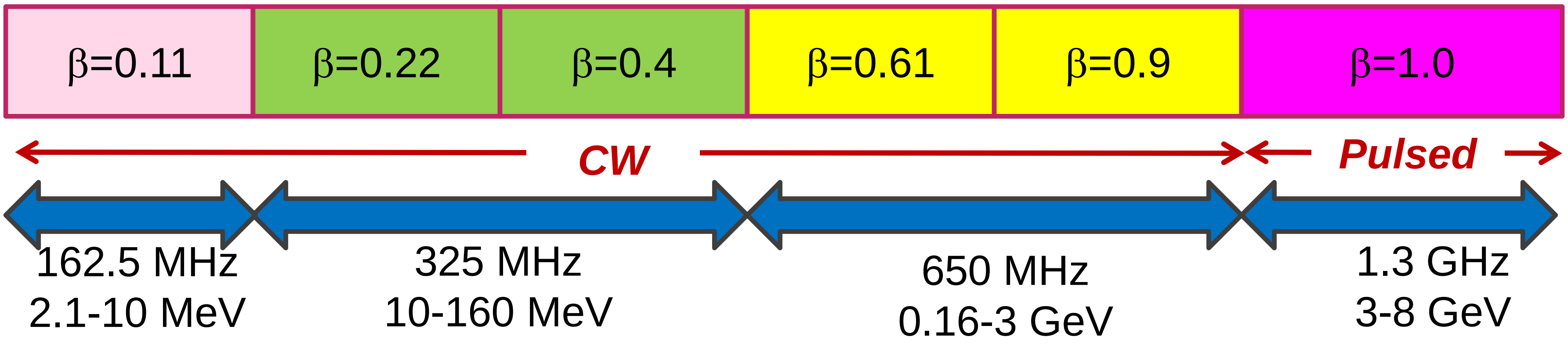
Reference Design

3 MW @ 3 GeV
200 kW @ 8 GeV
2 MW @ 120 GeV



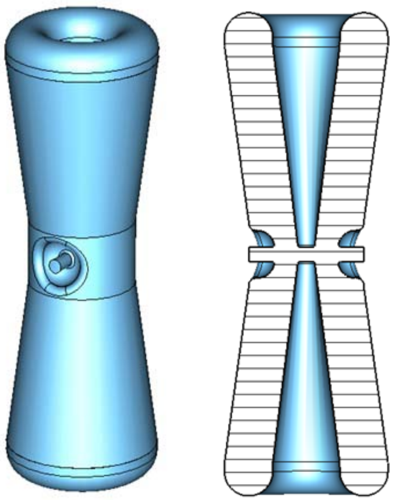
- Reference Design supports a wide-ranging program of elementary particle and nuclear physics research

SRF Linac
Technology Map



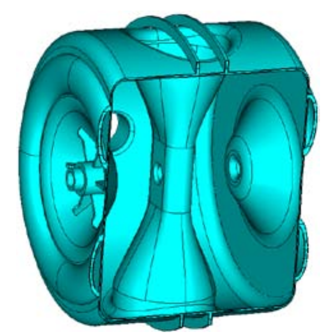
Section	Freq	Energy (MeV)	Cav/mag/CM	Type
HWR (β_G=0.1)	162.5	2.1-10	9/6/1	HWR, solenoid
SSR1 (β_G=0.22)	325	10-42	16/18/ 2	SSR, solenoid
SSR2 (β_G=0.47)	325	42-160	36/20/4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-460	42 /14/7	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

162.5 and 325 MHz Cavities

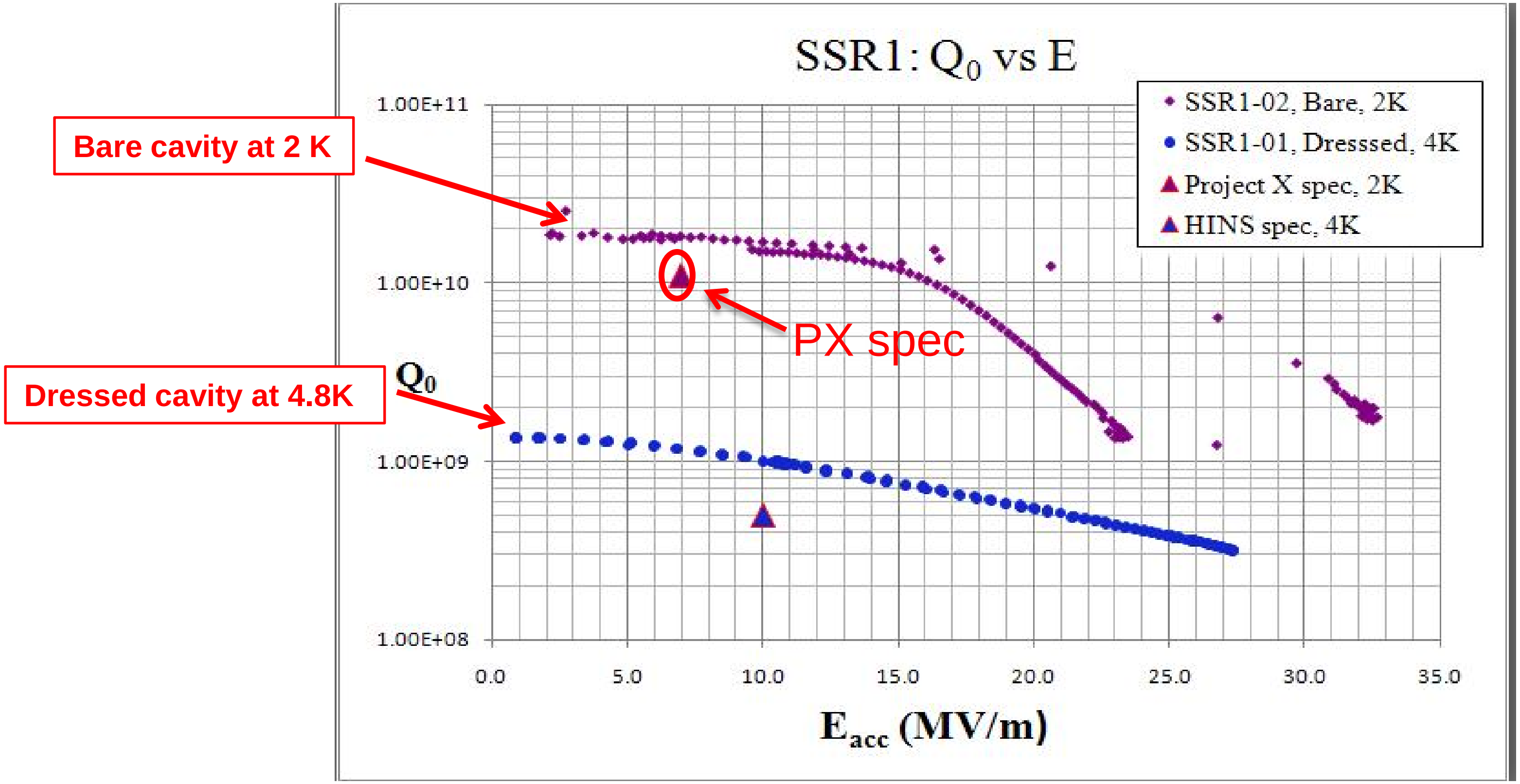


- **HWR (β = 0.11) Half Wave Resonator**
  - EM and Mechanical Design starting at ANL
  - Optimize to achieve tight packing in PX front end
- **SSR1 (β = 0.22) Single Spoke Resonator**
  - Two prototypes fabricated by industry, processed in collaboration with ANL, and tested at Fermilab
  - Two cavities in fabrication at IUAC-Delhi (Fall 2011)
  - Ten cavities in fabrication by US industry (4 have arrived)
  - One cavity dressed with He vessel, coupler tuner
  - Tests in progress (next slides)

- **SSR2(β = 0.47)**
  - EM design complete
  - Awaiting Mechanical Design
  - Prototype in FY12-FY13



SSR1 Performance

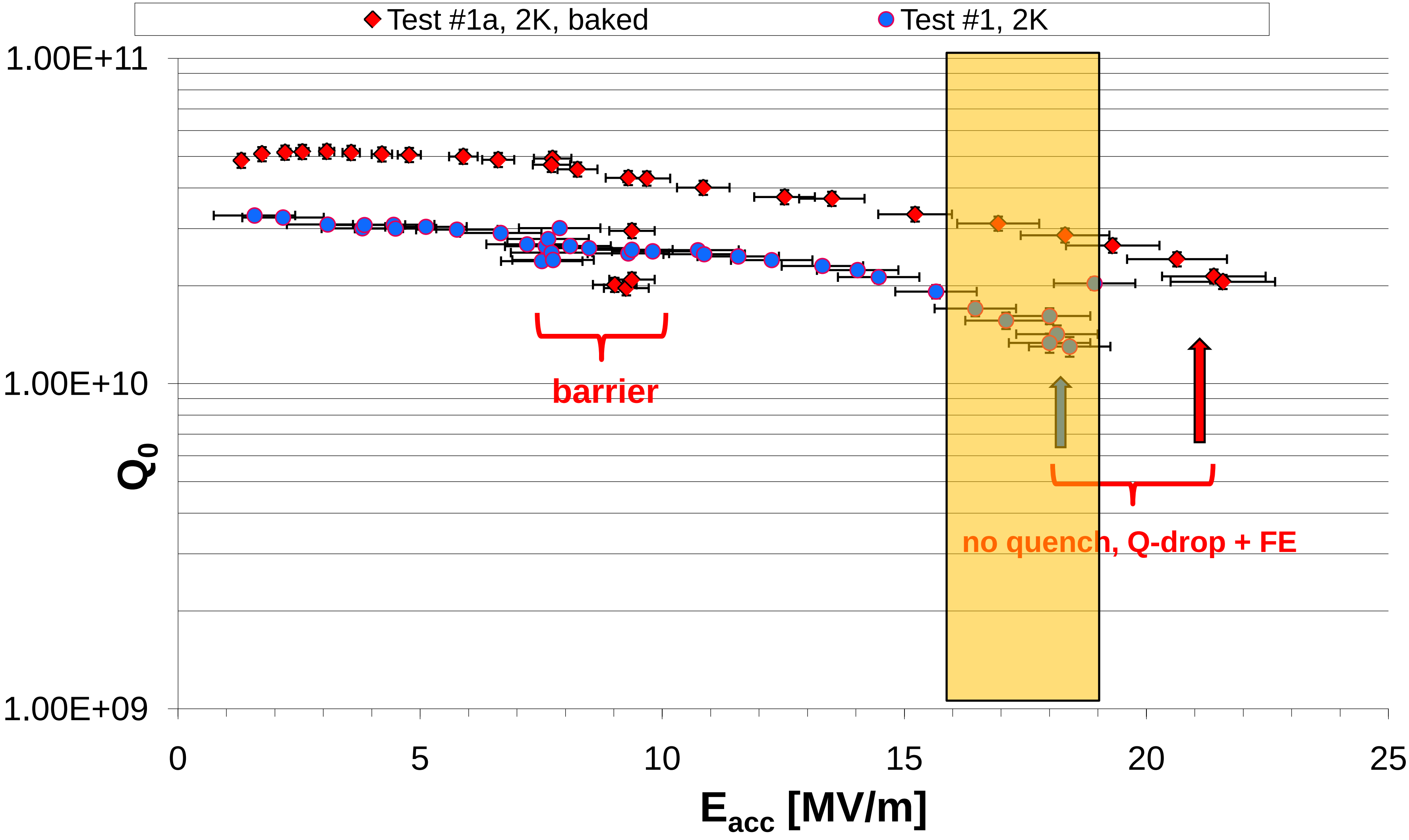


- Two SSR1 spoke resonators bare cavities test
  - Both exceeded PX requirement for Q_0 and gradient
  - Modifications in progress to allow CW tests of dressed spoke resonators at 2 K

Project X 650 MHz Cavity Prototypes

- Single-cell designs complete for β = 0.6 & 0.9 5-cell cavities
- Prototypes fabricated:
  - Single-cell β = 0.6: 2 prototypes at JLab, 6 ordered industry
  - Single-cell β = 0.9: 5 cavities ordered from industry 11
  - Prototypes at both βs are also being fabricated in India
  - Two 5-cell β = 0.9 cavities ordered from industry
- Infrastructure modifications: for 650 MHz in process
  - FNAL: Vertical Test Stand: Electronics, amplifier, tooling
  - FNAL: Cavity handling & HPR tooling, etc.
  - FNAL: Optical inspection system modifications
  - ANL: New electro-polishing tool
  - Industry: EP/BCP capability in US industry

Excellent Results from JLAB single cell tests



Argonne National Laboratory
Slides from Rod Gerig (ANL)

Near-Term Spent Nuclear Fuel Disposal Using Accelerator Drive System

- **Argonne has funded research to formulate a pre-conceptual design for facilities that can dispose of the SNF from US light water reactors**
  - **This study assesses the needs, proposes a solution, identifies all components, and outstanding R&D needs**
  - **The R&D team is one year into a three year study**

- **The talk will address progress to date including:**
  - **Basic facility parameters and configuration**
  - **Design choices and reasons for making them**
  - **Unique aspects of the Argonne approach**
  - **Work to be done in latter half of study**

The Current US SNF Inventory

- Through 2015, the expected US Spent Nuclear Fuel (SNF) inventory from the commercial nuclear power plants is ~ 70,000 metric tons
  - ~96% are uranium left from the fuel irradiation, which can be recycled and reused in current fission power reactors.
  - ~3% are short-lived fission products, (half life less than hundred years) .
  - ~1% are transuranic materials.
- Transuranic material composition of the 70,000 SNF after 25 years of cooling:
  - ~85% plutonium, total of 585 MT
    - Major contributor of the long-term radiotoxicity of the SNF in a geological repository
    - high-proliferation risks
    - Multi-methods of utilization, MOX fuel and Fast reactor.
  - 5.1% neptunium, 10.0% americium, 0.2% of curium
    - Major contributor of the long-term radiotoxicity of the SNF in a geological repository
    - Recycling can greatly reduce dose rate and heat loading in a geological repository
    - Very small delayed neutron fraction, which is difficult to use in critical reactors.
    - Subcritical system is the most appropriate method to utilize.

Design Study Guidelines

- Consider near term deployment as much as possible,
- Utilize current technologies with minimum extrapolation,
- Avoid multi-processing steps of the fuel materials,
- Operate the systems at the peak power and produce energy to cover the system cost as much as possible, and
- Minimize the required number of the accelerator driven systems,
- Demonstration facility should be readily scalable to full system.

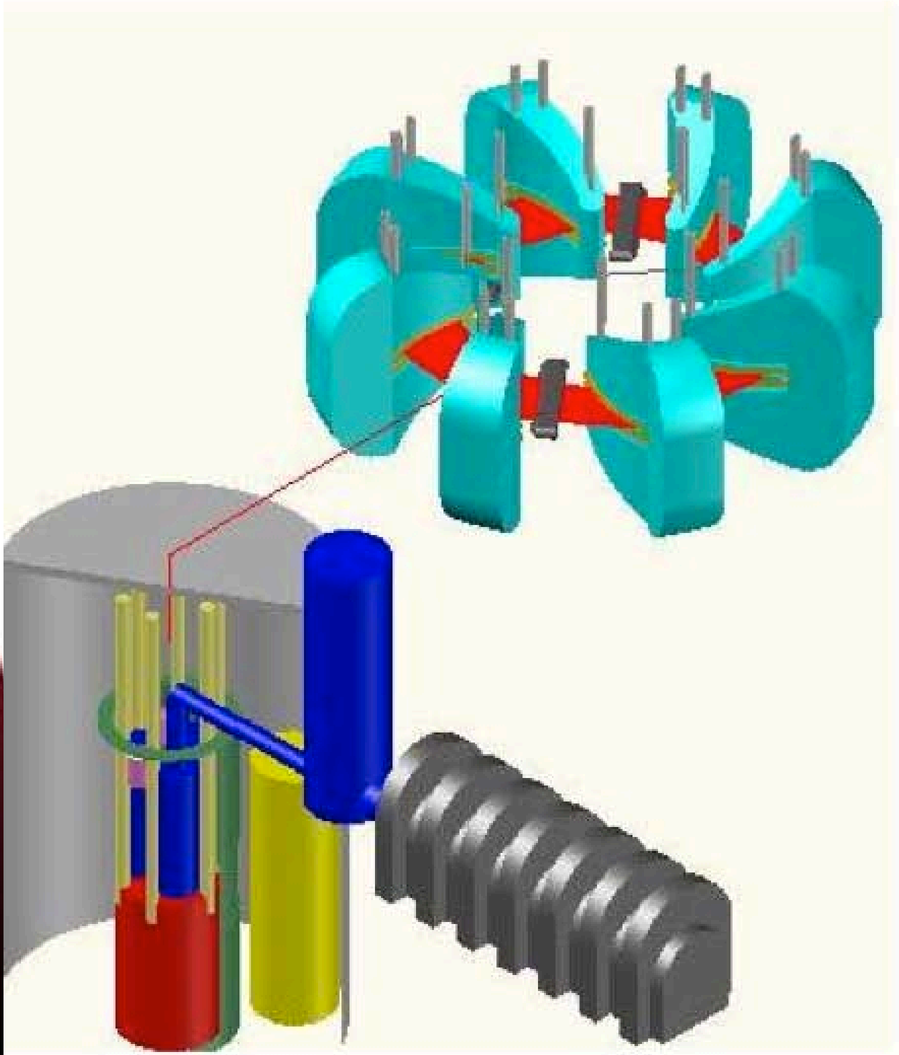
The study takes benefit of Argonne experience in:

- SRF for hadron accelerators
- Actinide chemistry, fuel recycling
- Subcritical core neutronics, and blanket design for removing power

The Argonne talk will summarize this work

Subcritical Fission Technology Center

Develop the ADSMS technology, and build a first single-beam unit for a **Subcritical Fission Technology Center** at Texas A&M:



- commission all of the systems of the accelerator and core,
- develop and assess methods to monitor functions within the core,
- perform measurements and studies needed for licensing operation for power generation
- Operator training

US Department of Energy

White Paper chaired by
Stuart Henderson FNAL (ex SNS)

Office of Science White Paper

Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production

H. Aït Abderrahim[h], J. Galambos[d], Y. Gohar[a], S. Henderson[c*], G. Lawrence[e], T. McManamy[d], A. C. Mueller[g], S. Nagaitsev[c], J. Nolen[a], E. Pitcher[e*], R. Rimmer[f], R. Sheffield[e], M. Todosow[b]

[a]*Argonne National Laboratory*
[b]*Brookhaven National Laboratory*
[c]*Fermi National Accelerator Laboratory*
[d]*Oak Ridge National Laboratory*
[e]*Los Alamos National Laboratory*
[f]*Thomas Jefferson National Accelerator Facility*
[g]*CNRS-IN2P3, France*
[h]*SCK•CEN, Mol, Belgium*
[*]*Co-chairs*

September 17, 2010

Office of Science White Paper

- Finding #15: For Industrial-Scale Transmutation requiring tens of MW of beam power many of the key technologies have been demonstrated, including front-end systems and accelerating systems, but

- demonstration of other components, improved beam quality and halo control, and demonstration of highly-reliable sub-systems is required

Technology readiness

Table 3: ADS technology readiness assessment. The color-coding is explained in the text.

		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance			
	Reliability			
Accelerating System	RF Structure Development and Performance			
	Linac Cost Optimization			
	Reliability			
RF Plant	Performance			
	Cost Optimization			
	Reliability			
Beam Delivery	Performance			
Target Systems	Performance			
	Reliability			
Instrumentation and Control	Performance			
Beam Dynamics	Emittance/halo growth/beamloss			
	Lattice design			
Reliability	Rapid SCL Fault Recovery			
	System Reliability Engineering Analysis			

Thorium Initiatives

Slides from Steve Peggs

Thorium Energy

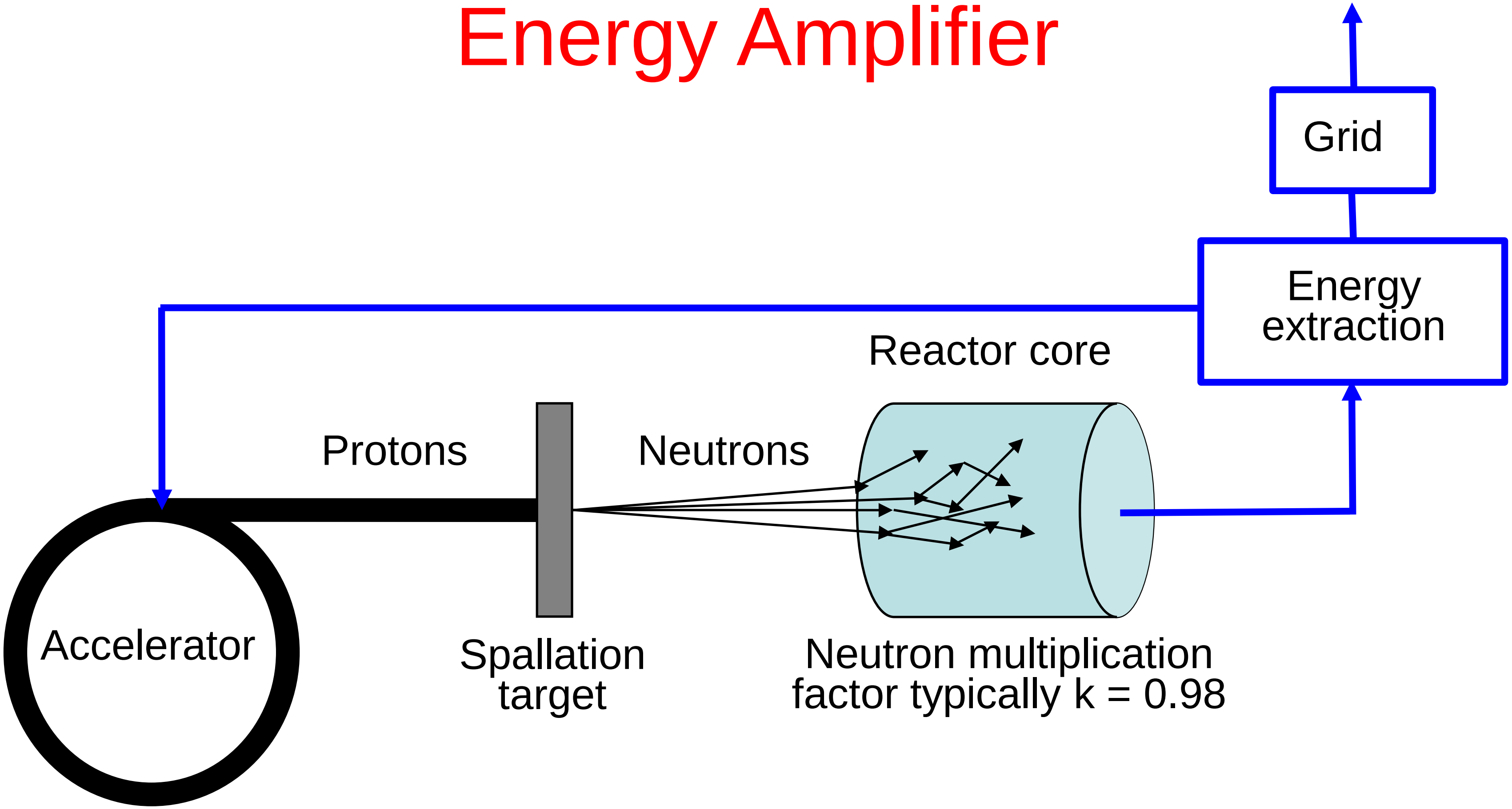
"Thorium Energy can potentially be implemented:
with solid or liquid fuel
with or without accelerators
each with different advantages and disadvantages"

Steve Peggs,
ESS & BNL

Thorium Energy Futures

- Thorium may be used in solid fuel form, or in molten salt systems
- In some approaches, the fuel can incorporate components from spent nuclear fuel (minor actinides, plutonium) to also serve a transmutation function
- Must consider the benefits and drawbacks of using an accelerator driven subcritical system versus a conventional reactor, for both solid fuel and molten salt cases, in particular addressing the power and reliability requirements of the accelerator
- None of the four options can yet be rated as better or worse than the other three, given todays knowledge.

Energy Amplifier



Protons hitting a target generate external neutrons into a subcritical thorium reactor core that “burns”, creating heat & electricity

Power generation ceases immediately when the beam stops

Inherent safety (?) at the cost of high reliability (?)

Sustainability

World Thorium Resources

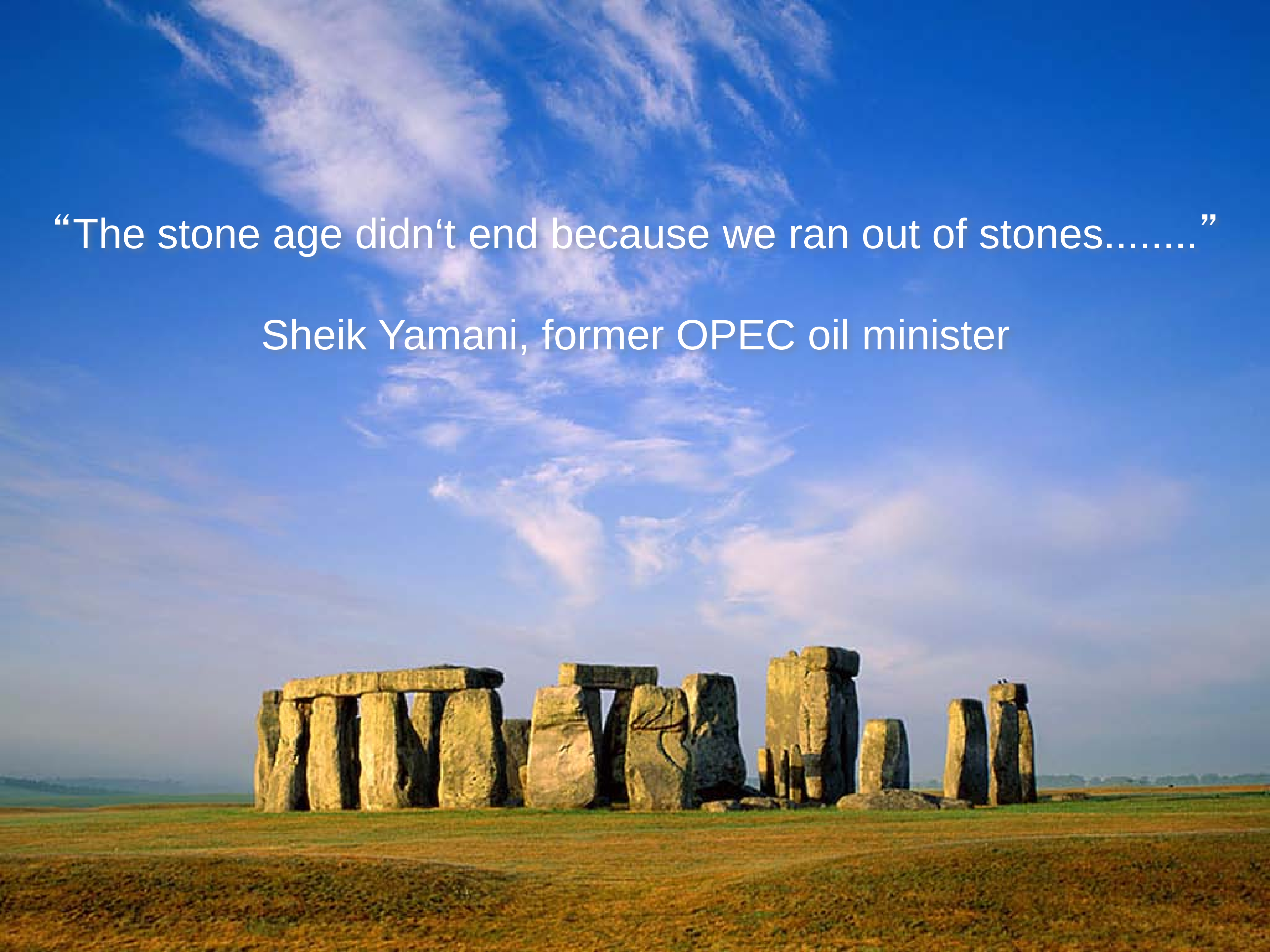
Country	Reserve Base (tons)
Australia	340,000
India	300,000
USA	300,000
Norway	180,000
Canada	100,000
South Africa	39,000
Brazil	18,000
Other countries	100,000
World total	1,400,000

Source: U.S. Geological Survey, Mineral Commodity Summaries, January 2008

Known Thorium reserves are more than sufficient for millennia of significant power production.

India, Australia, Canada, U.S., Norway have lots of Thorium.

More will be found – Thorium has been of little interest, so far


“The stone age didn‘t end because we ran out of stones.......”
Sheik Yamani, former OPEC oil minister

Thorium Energy Conferences

The non-profit Swedish foundation ITheO organized the second annual conference on Thorium in the USA

ThEC11 at CCNY in New York (with local support from BNL)

ThEC11 (Oct 2011) was attended by 78 people from 11 countries:

10 from industry

19 from 10 laboratories (accelerator & nuclear engineering)

26 from 14 universities

23 other: government, private, media, environmental, financial, ...

U.S.:

Ex-congressmen: (Democrat, Republican) = (1,1)

Companies: (AES, Flibe, Muons Inc, Nevada Thorium = (2,2,1,2)

Labs: (ANL, BNL, FNAL, LANL, LBL, Navy, ORNL) = (1,10,1,1,1,1,1)

Unis: (CCNY, CGI/UW, Columbia., Dartmouth, LHU, Maryland, Oregon,

Penn, Rutgers, Skyline, Stevens, TAMU) = (7,1,1,1,1,1,1,1,1,1,1)

Contributors

Bill Foster, Ex-Congressman "What Life is Like as a Scientist in Congress"

Bob Cywinsky, Uni Huddersfield "The way forward: Science, Technology, or Politics?"

Gary Krellenstein, Ex-JPMorgan "Thorium Economics"

Hywel Owen, Uni Manchester "ADS Demonstrator Issues"

Jess Gehin, ORNL "Liquid Fuel: Molten Salt Reactors"

John Duncan, UK Foreign Office "Towards a World Without Nuclear Weapons"

Kirk Sorensen, Flibe Energy "Introducing Flibe Energy"

Laurence O'Hagan, TWF "The Weinberg Foundation: Continuing His Vision"

Luciano Calabretta, INFN "Developing a High Power Cyclotrons to Drive Subcritical Reactor"

Michael Todosow, BNL "AHWR Non-proliferation Attributes"

Ondrej Beneš, EC Karlsruhe "Physico-chemical Properties of Thorium Fuels"

Oystein Asphjell, Thor Energy "Thorium use in LWRs; the Low-hanging Fruit of Th-utilization"

Parker Griffith, Ex-U.S. Representative "Science Doesn't Speak for Itself"

Paul Friley, BNL "Thorium Energy Economics"

Pavel Soucek, EC Karlsruhe "Electrochemistry of Molten Salt"

Peter McIntyre, Texas A&M "ADS Fission in a Molten Salt Core"

Robert Arnold, UK DECC "New Nuclear Technologies in the UK Energy Strategy"

Robert Bari, BNL "Nonproliferation Models"

Robert Hargraves, Dartmouth "Nuclear Ammonia: Thorium's Killer App"

Rol Johnson, Muons Inc "Accelerators for Subcritical Molten Salt Reactors"

Stuart Henderson, FNAL "Report from the DOE ADS Working Group"

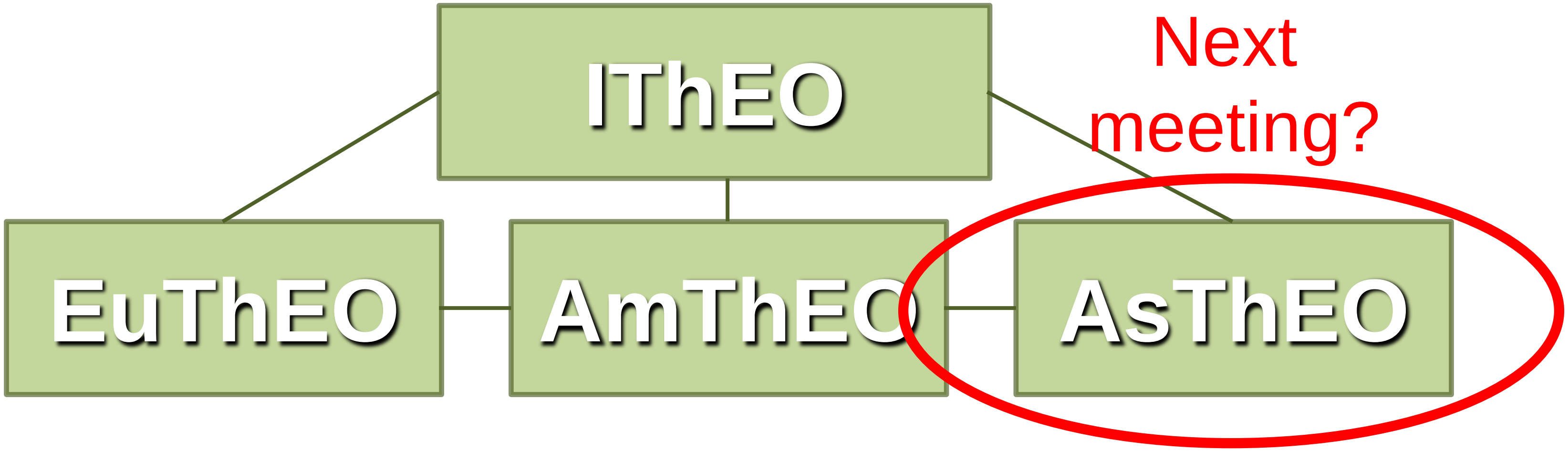
Takashi Kamei, Kyoto Uni "The Thorium Energy Bank"

Tony Favale, AES "The U.S. Socio-economic Case for Spent Fuel Treatment"

Yacine Kadi, CERN "Neutronic Analysis and Transmutation Performance of Th-based Molten Salt Fuels"

ThEC11
New York City

IThEO goes regional?



“IThEO is an affiliation of academic institutions, research laboratories, industrial companies, and individual scientists, engineers, technologists and policymakers who share a common interest in developing thorium technology for clean, safe and sustainable nuclear energy and waste management”

“The overriding purpose of ITHEO is to provide a platform for discussion and a focus for action in the development and deployment of thorium energy”

Thorium Energy Alliance (TEA)
Information from John Kutsch

Thorium Energy Alliance Activities

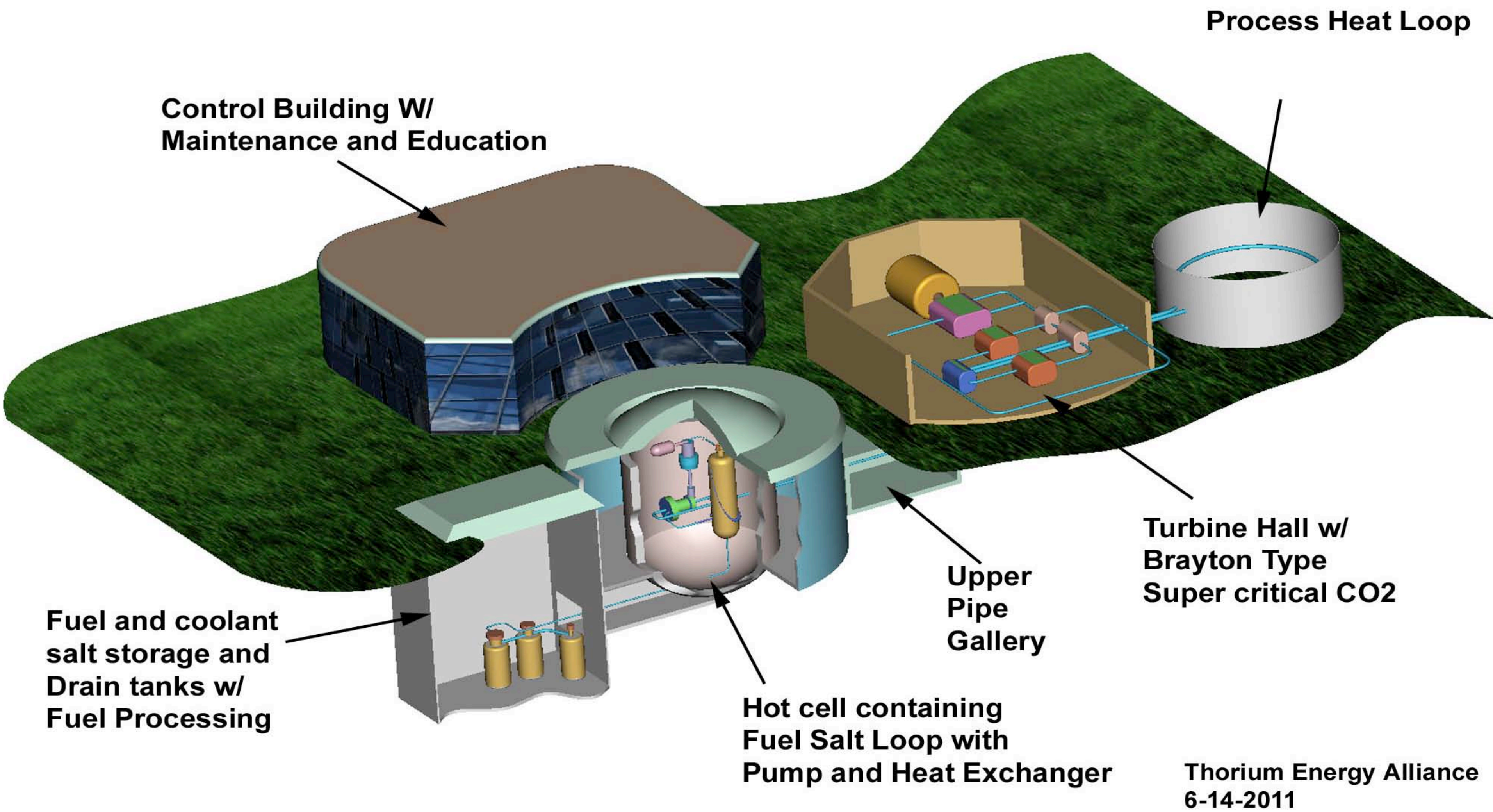
- The Thorium Energy Alliance (TEA) lobbies in the USA for use of Thorium as a nuclear fuel
- TEA has been the lead advocate of 3 bills before congress that open up Rare Earth production by reclassifying Thorium
    - Provides a pathway to using Thorium in industry and for nuclear energy
- Organize conferences on thorium energy in the USA

3rd TEA Conference on the Future of Energy

- 4th meeting will be held on May 28th 2012 in Chicago

Proposed Molten Salt Research Reactor

Proposed research reactor that TEA is trying to get a consortium of Universities to build



ADS Initiatives at JLab

JLab Interest in ADS

- Jefferson Lab's interest in ADS is a natural extension of our scientific mission and expertise developed for the research needs of the Nuclear Physics program
- Jefferson Lab pioneered the large-scale use of superconducting radiofrequency (SRF) accelerating technology, and has a long record of success in accelerator-related, inter-institutional collaborations
- Jefferson Lab designed and built the superconducting linear accelerator for the Spallation Neutron Source (SNS) at ORNL
  - The SNS experience is relevant because the key to ADS subcritical reactors will be the reliable, high-power acceleration of protons for the spallation process to produce neutrons, the key to nuclear fission

Virginia Consortium

- A consortium of Virginia Universities, Industrial partners, and JLab has been established to develop US leadership in ADS R&D while preparing to host an ADS facility in Virginia
  - Goal - pursue funding for an electron accelerator coupled to a small, non-critical reactor core to study cross-sections and reaction rates
  - Consortium led by **Prof. Sama Bilbao y Leon**, Director of Nuclear Engineering Programs at Virginia Commonwealth University
  - Submitted a pre-proposal to National Science Foundation(NSF) for funding
    - "Science & Technology Center for the Application of High-Power Accelerators for the Advancement of Innovative Multidisciplinary Science"

US Participation in MYRRHA

- US participation in MYRRHA would provide a way for the DOE to explore ADS, with the advantage that Belgium is taking responsibility for nuclear regulatory approval
- Andrew's (ambitious) goal:
  - The US would develop enabling technologies for the MYRRHA SRF linac, with JLab having a key lead role in the USA
    - Other DOE labs and other institutions would be integrated into the US effort
- Andrew's (even more ambitious) goal:
  - JLab contribution would be funded by DOE as an "in-kind" contribution to MYRRHA

Summary

- **At this time, there are no government-funded ADS initiatives in the USA**
- **At this time, there are no government-funded Thorium initiatives in the USA**
- There are many US scientists and engineers who are actively working on ADS-related topics
  - Convinced that this is the right thing to do
  - Seeking funding to develop a demonstration program
  - Trying to get support from the US nuclear community