Thorium Energy and Accelerator-Driven Reactors

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Fermilab

U.S. DEPARTMENT OF ENERGY

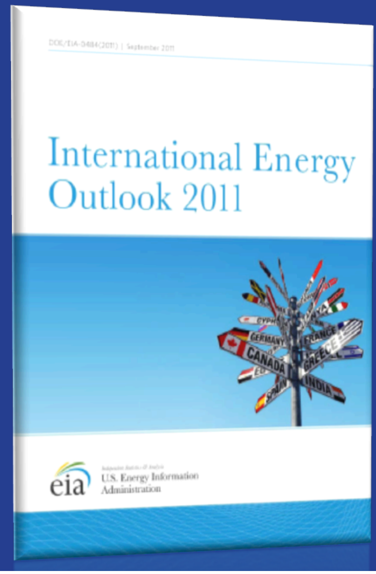
Fermilab

The Challenge

Energy Demand

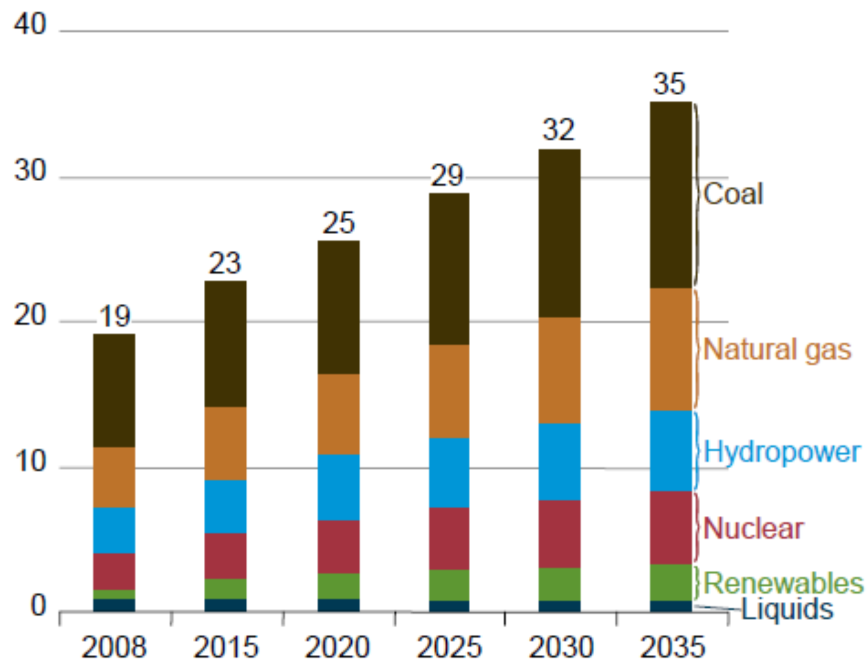
Projections from 2008 to 2035:

- World marketed energy consumption is projected to increase by 53%
- World CO_2 emissions increase by 43%
- World net electricity consumption increases by 84%
- World coal consumption increases by 50%
- World Nuclear power generation increases by ~90%, but remains flat at ~14% of total electricity generation



Energy Information Administration, US Dept of Energy

Figure 17. World net electricity generation by fuel type, 2008-2035 (trillion kilowatthours)

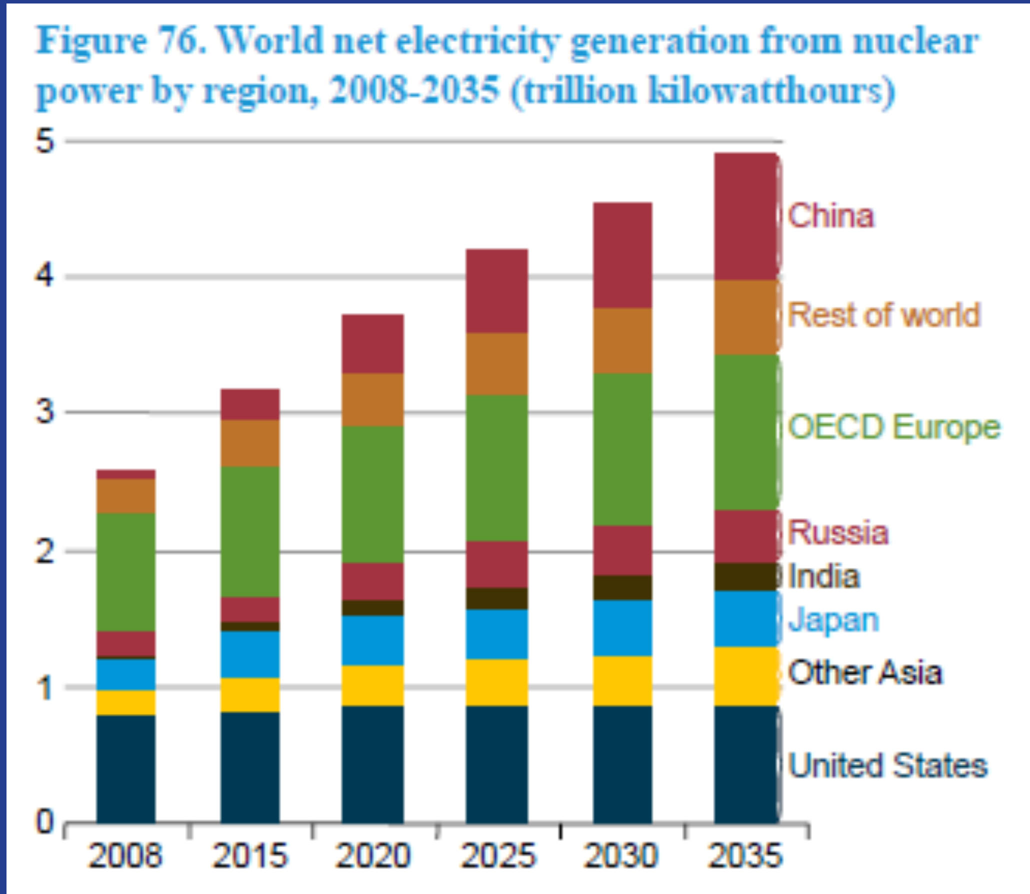


Can Nuclear Power Play a Larger Role?

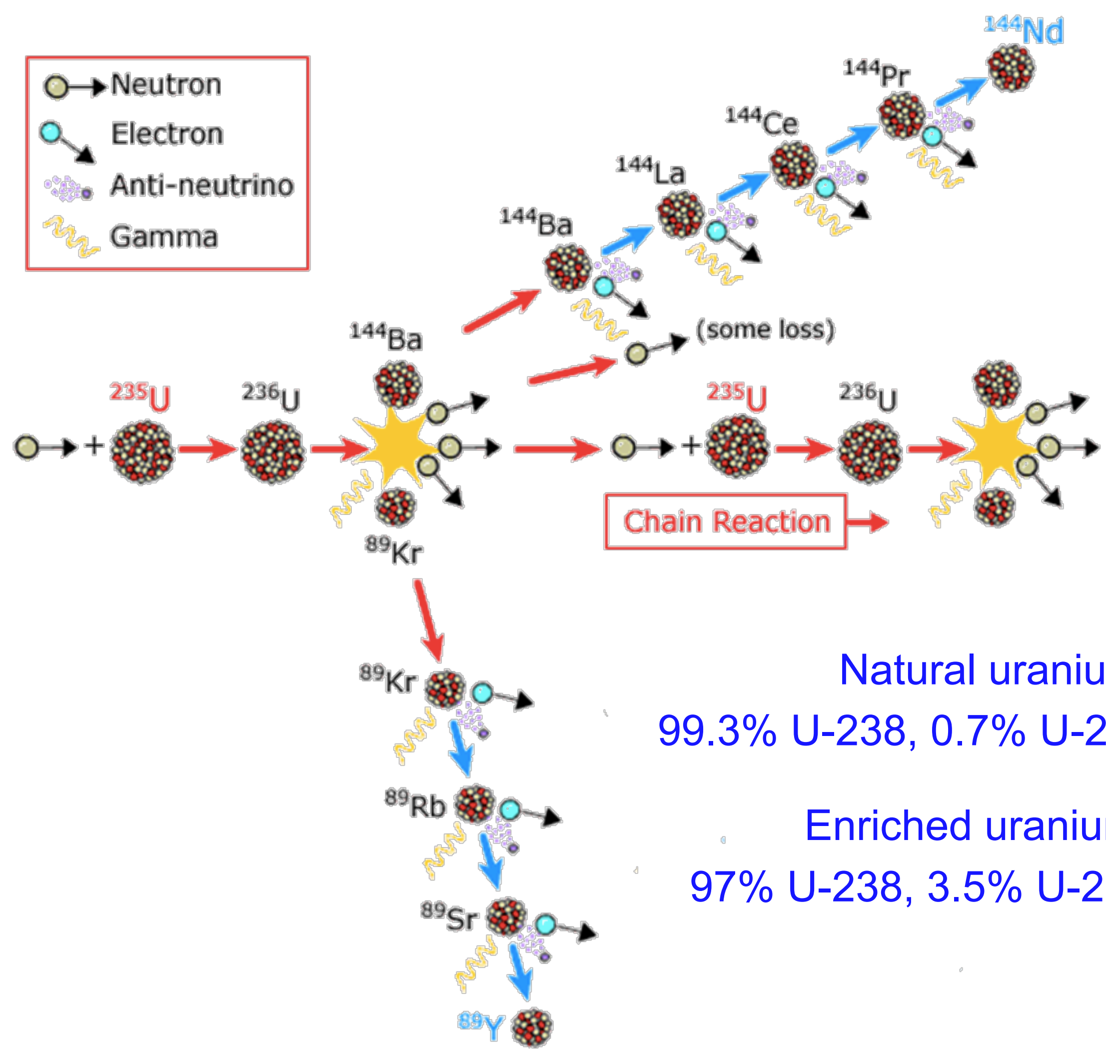
Nuclear Power has the potential to meet the substantial carbon-free power needs of the future, but nuclear's future is not bright

- Public acceptance
- Real accidents
- Radioactive waste
- Proliferation concerns
- Not competitive in terms of cost

There is a growing interest in Thorium as a nuclear fuel, and in incorporating accelerators into the fuel cycle



Nuclear Power Today is Based on the Uranium Fuel Cycle



Natural uranium:
99.3% U-238, 0.7% U-235

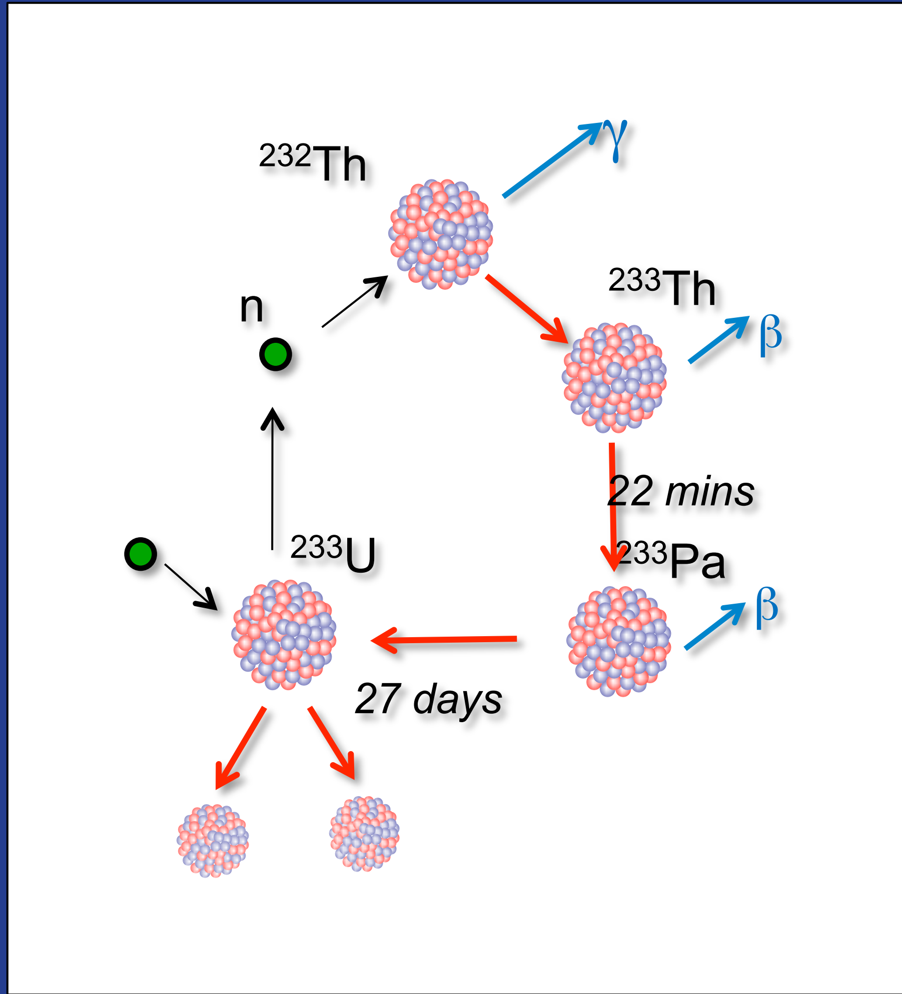
Enriched uranium:
97% U-238, 3.5% U-235

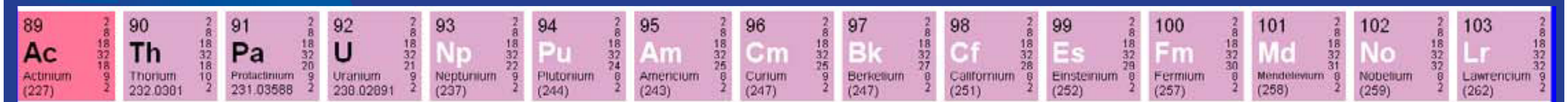
Re-Think.ing Thorium

What Does Thorium Have to Offer?

Thorium/Uranium Fuel Cycle

- U-235 is the only naturally occurring fissile material
- U-233 is also fissile but does not exist in nature
- U-233 can be produced from Th-232 via neutron capture
- Reactors that generate fissile U-233 from Th-232 are Breeder Reactors

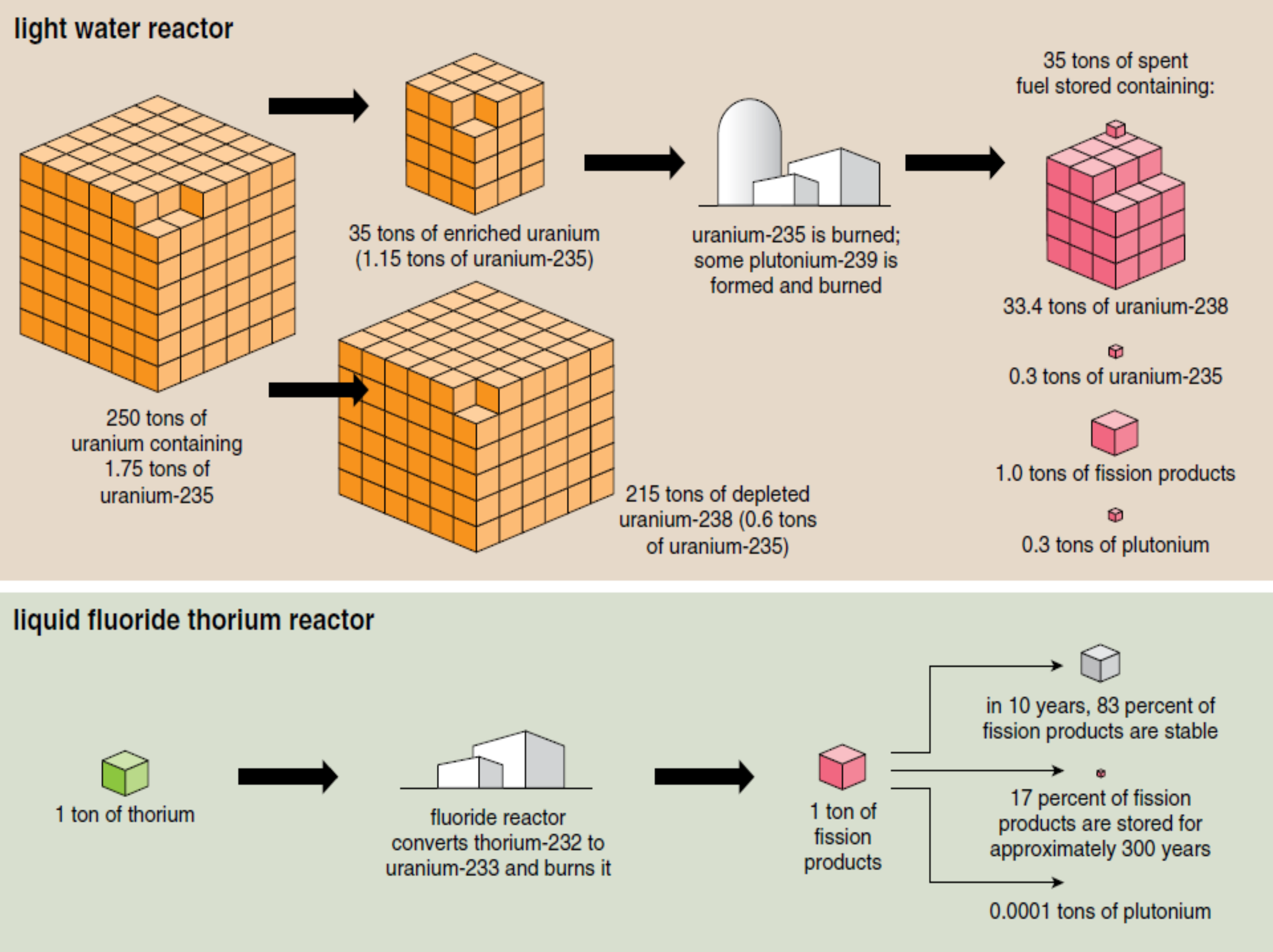




Advantages of Thorium

- As a resource, Thorium is
  - ~4 times more abundant than U-238,
  - 400 times more abundant than U-235
  - As abundant as lead
- There is enough Thorium to power the needs of the planet for hundreds of thousands of years
- Thorium currently costs only US$30/kg, while the price of Uranium has risen above $100/kg, not including costs for enrichment and fuel fabrication.
- The Th/U fuel cycle produces vastly smaller quantities of problematic wastes (minor actinides)
- The Th/U fuel cycle is considered proliferation-resistant
  - coproduction of a highly radioactive isotope, U-232, provides a high radiation barrier to discourage theft and proliferation of spent fuel.

Advantages of Thorium: Raw Material and Resource Utilization for 1GW-year



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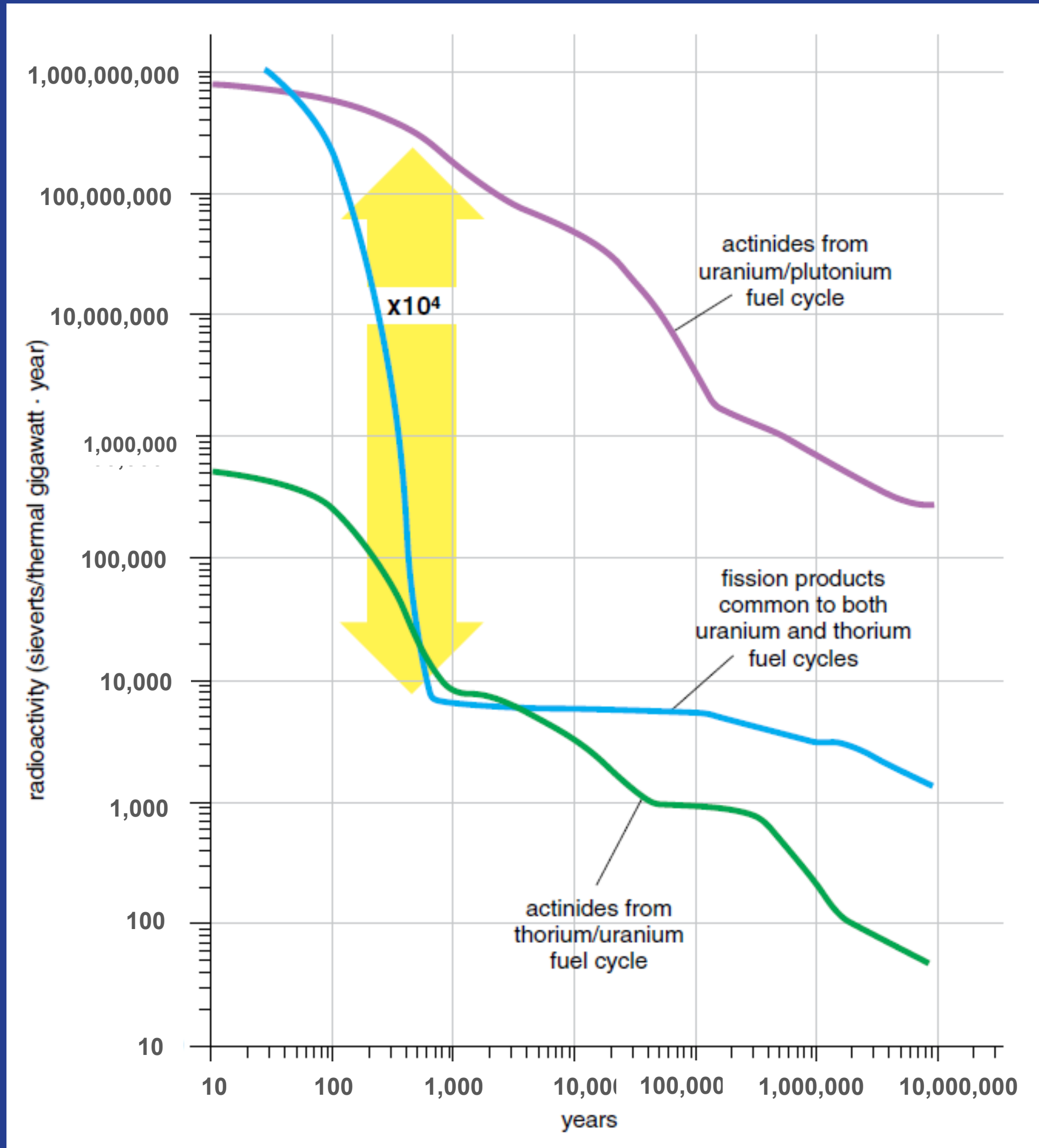
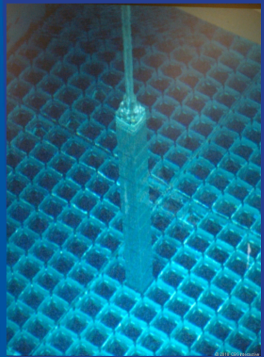
Advantages of Thorium: Waste Storage

- Thorium fuel cycle produces vastly smaller quantities of minor actinides
- Mass number of thorium is 6 units less than U-238, requiring many more neutron captures to produce transuranics

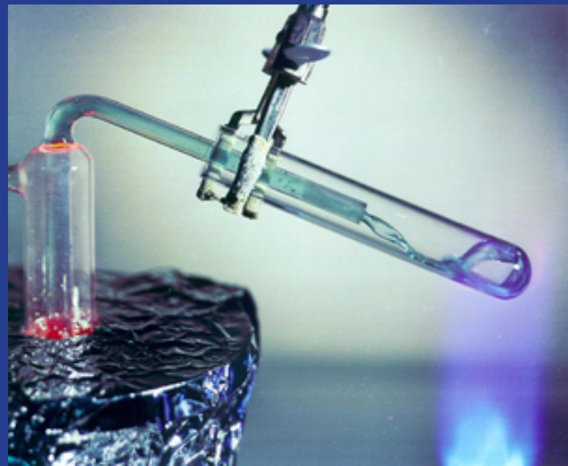


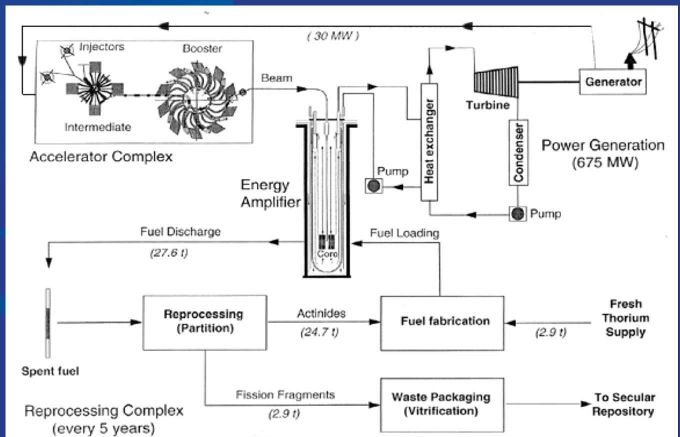
Deploying Thorium Energy: Three Approaches



Thorium fuel in solid form in conventional reactors

Thorium as fuel in molten-salt reactors





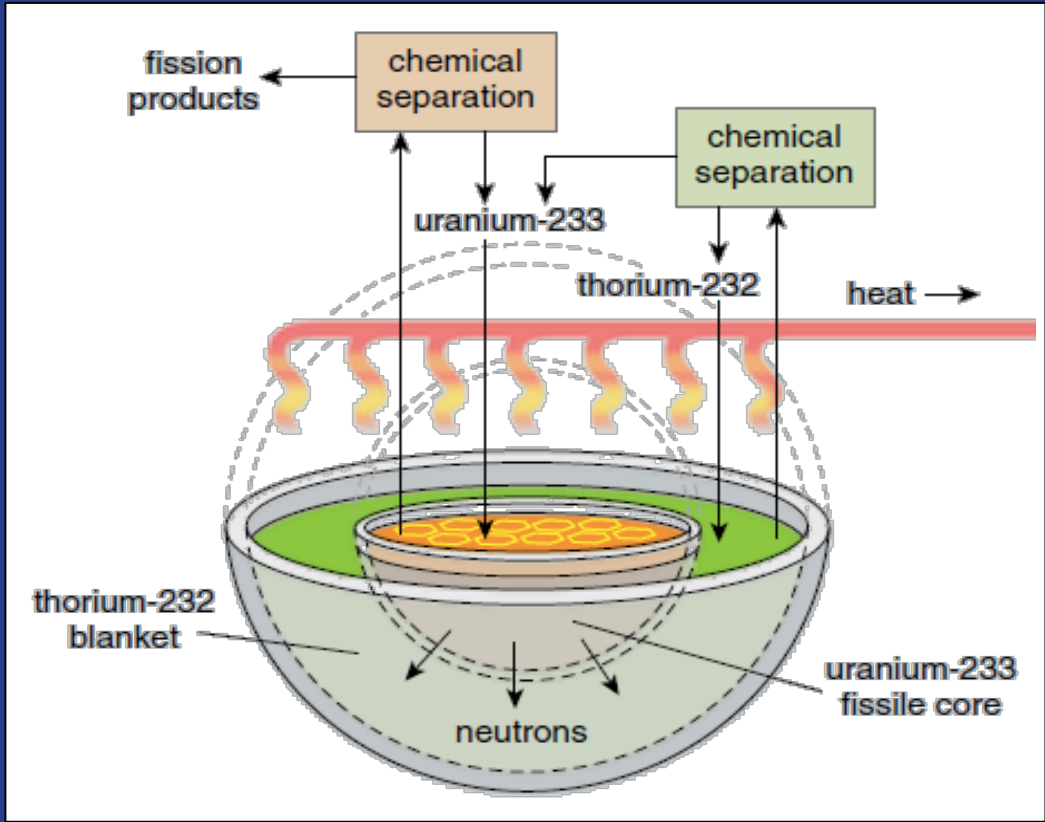
Accelerator-driven Subcritical Reactors using Thorium fuel

C. Rubbia, Energy Amplifier

LFTRs: Liquid Fluoride Thorium Reactors

Two fluid concept:

- Separate molten salt fertile material blanket surrounding molten salt fissile core
- The molten salt material is $LiF\text{-}BeF_2$ (“Flibe”)



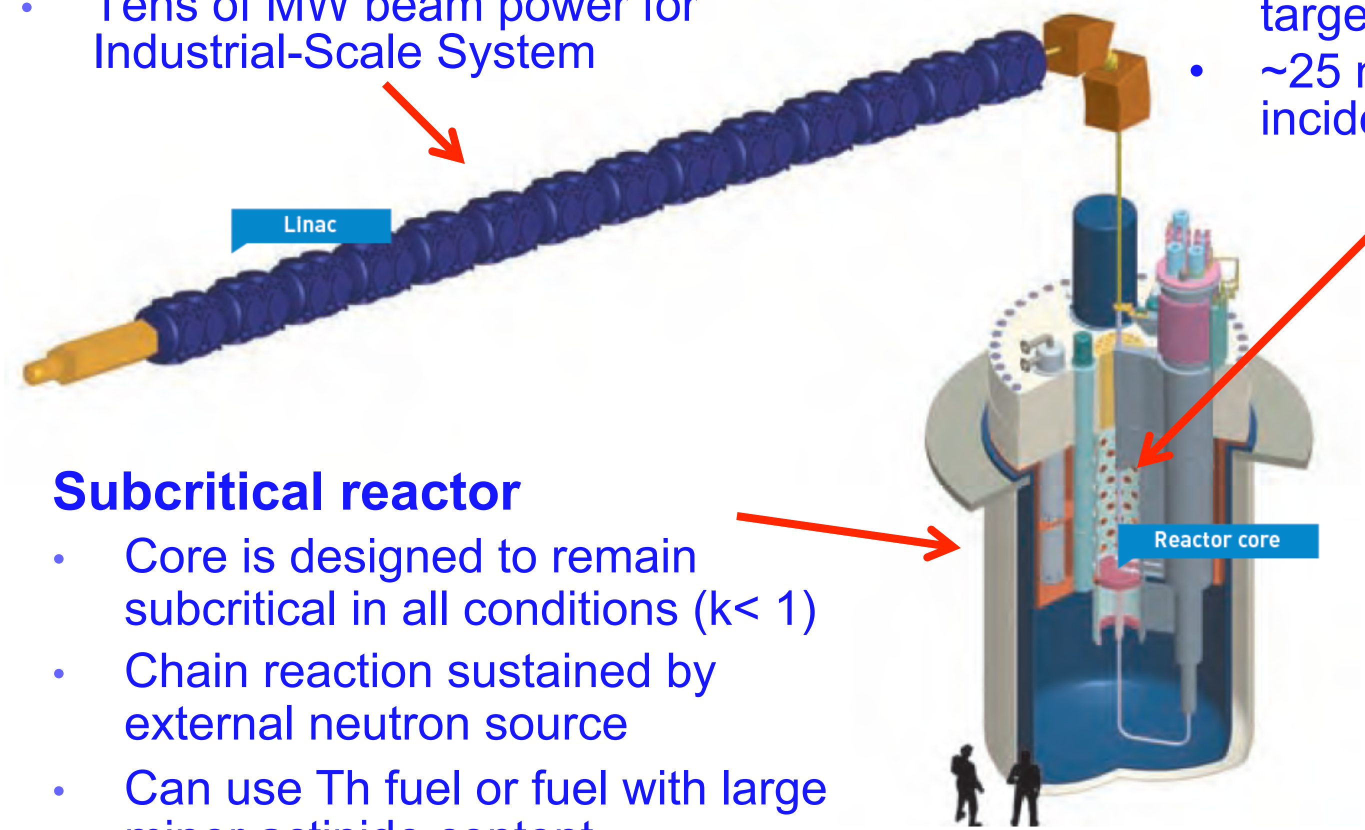
MSRs have a number of attractive features:

- Molten salts at atmospheric pressure,
- Safety: no melt down possible and intrinisic safety features
- High temperature enables higher thermal/electric conversion efficiency

Accelerator Driven Subcritical Reactors

High-power, highly reliable proton accelerator
- ~1 GeV beam energy
- ~1 MW of beam power for demonstration
- Tens of MW beam power for Industrial-Scale System

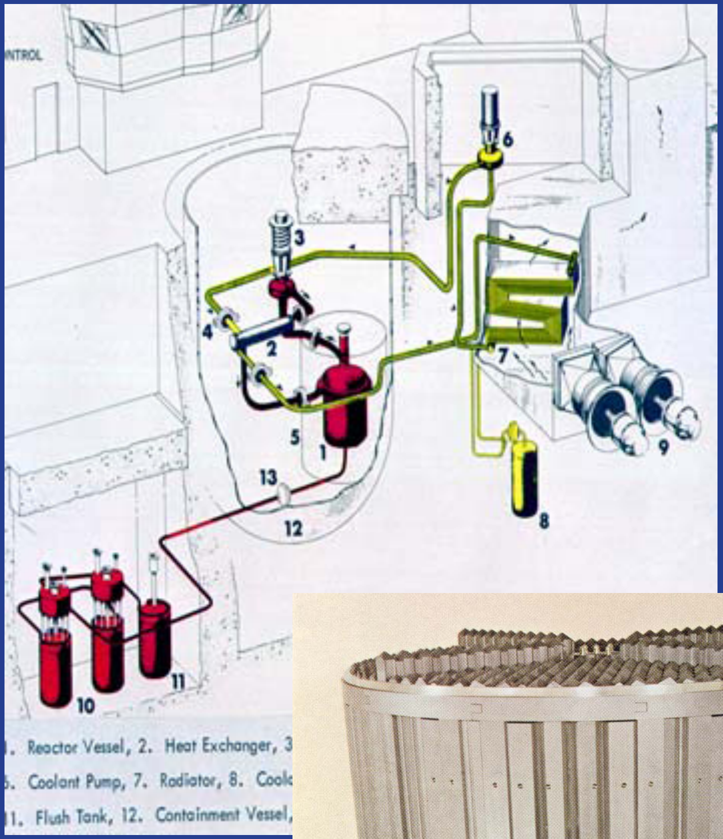
Spallation neutron target system
- Provides external source of neutrons through spallation reaction on heavy metal target
- ~25 neutrons produced per incident proton



Subcritical reactor
- Core is designed to remain subcritical in all conditions (k< 1)
- Chain reaction sustained by external neutron source
- Can use Th fuel or fuel with large minor actinide content

Thorium: Some History

- Thorium was recognized early on as a potentially useful fertile material
- Oak Ridge National Laboratory pursued Molten Salt Reactors (MSRs) in the 1950s and 1960s
- An 8 MWth thorium single fluid MSR was demonstrated at ORNL. It operated from 1965-1969. Fuel: LiF-BeF$_2$ with UF$_4$, ThF$_4$
- Shippingport (USA) Light Water Breeder Reactor operated 1977-1982 with solid Th oxide fuel generating 100 MWe.



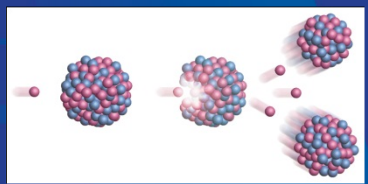
Applications of Accelerator Driven Systems (ADS)

Applications of Accelerator Driven Systems

- Accelerator Driven Systems may be employed to address several missions, including:

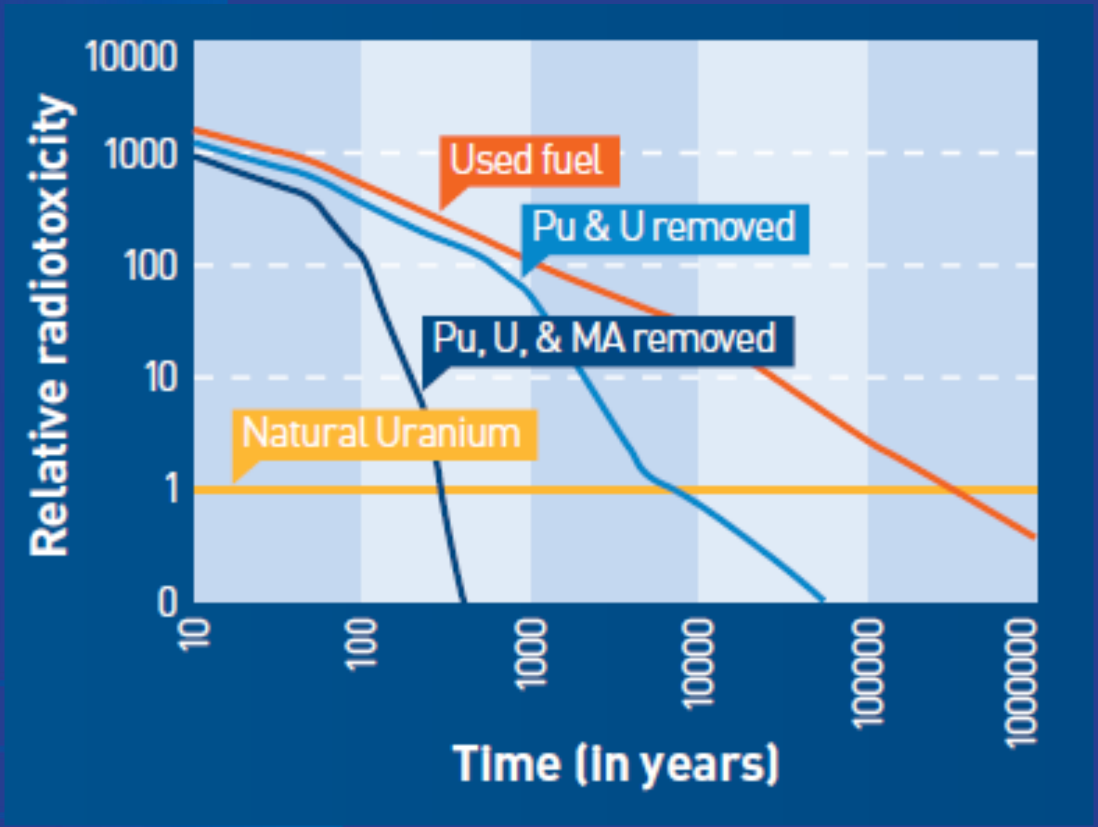
Transmuting selected isotopes present in nuclear waste (e.g., actinides, fission products) to reduce the burden these isotopes place on geologic repositories.

Generating electricity and/or process heat.



Producing fissile materials for subsequent use in critical or sub-critical systems by irradiating fertile elements.

Transmutation of Nuclear Waste



Why Bother with Accelerators?

What do Accelerators Bring to the Table?

- Comparisons of critical reactors and ADS have been carried out (see, e.g. OECD/NEA Report)
- Principal advantages of ADS are
  - ✓ greater flexibility with respect to fuel composition, and
  - ✓ potentially enhanced safety
- Secondary advantages
  - ✓ Beam current “swing” can compensate for reactivity changes

Nuclear Development

Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles

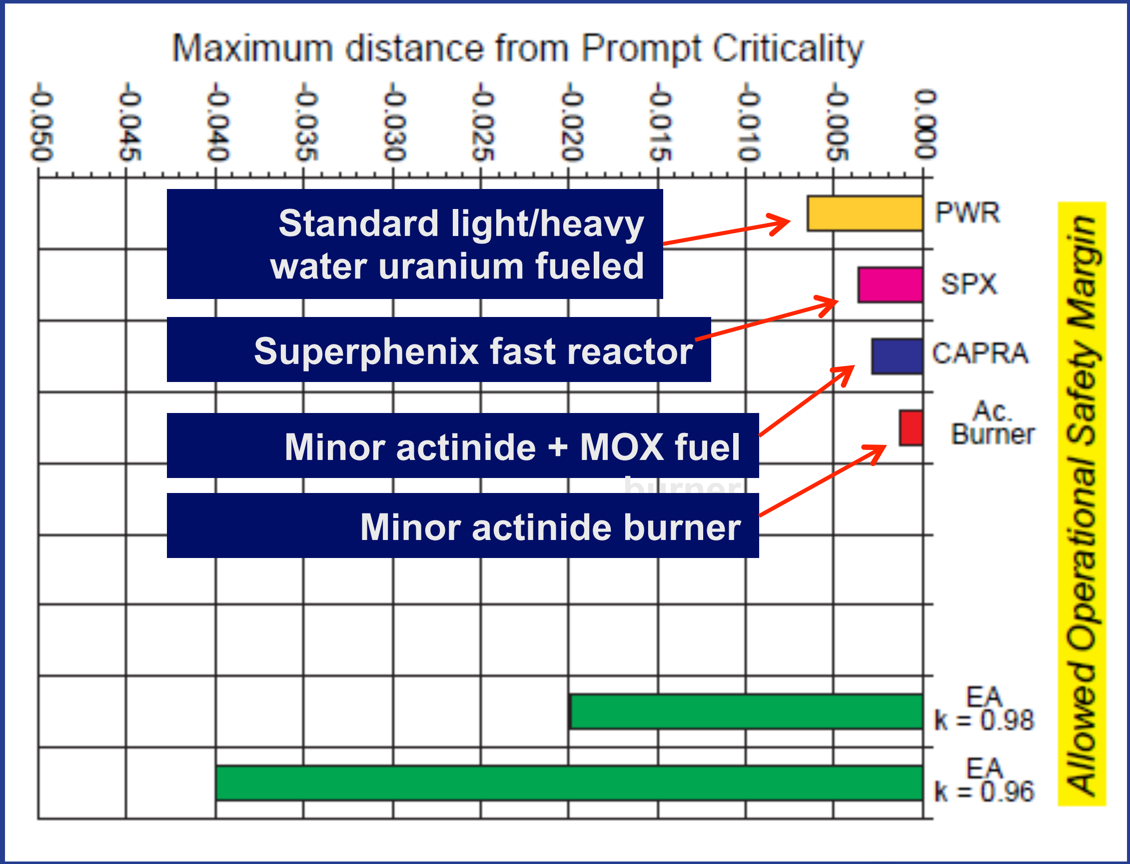
A Comparative Study

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Advantages of ADS

Fuel Flexibility:

- ADS are ideally suited to burning fuels which are problematic from the standpoint of critical reactor operation, namely, fuels that would degrade neutronics of the critical core to unacceptable levels due to small delayed neutron fractions and short neutron lifetimes
- Additionally, ADS allows the use of non-fissile fuels (e.g. Th) without the incorporation of U or Pu into fresh fuel.



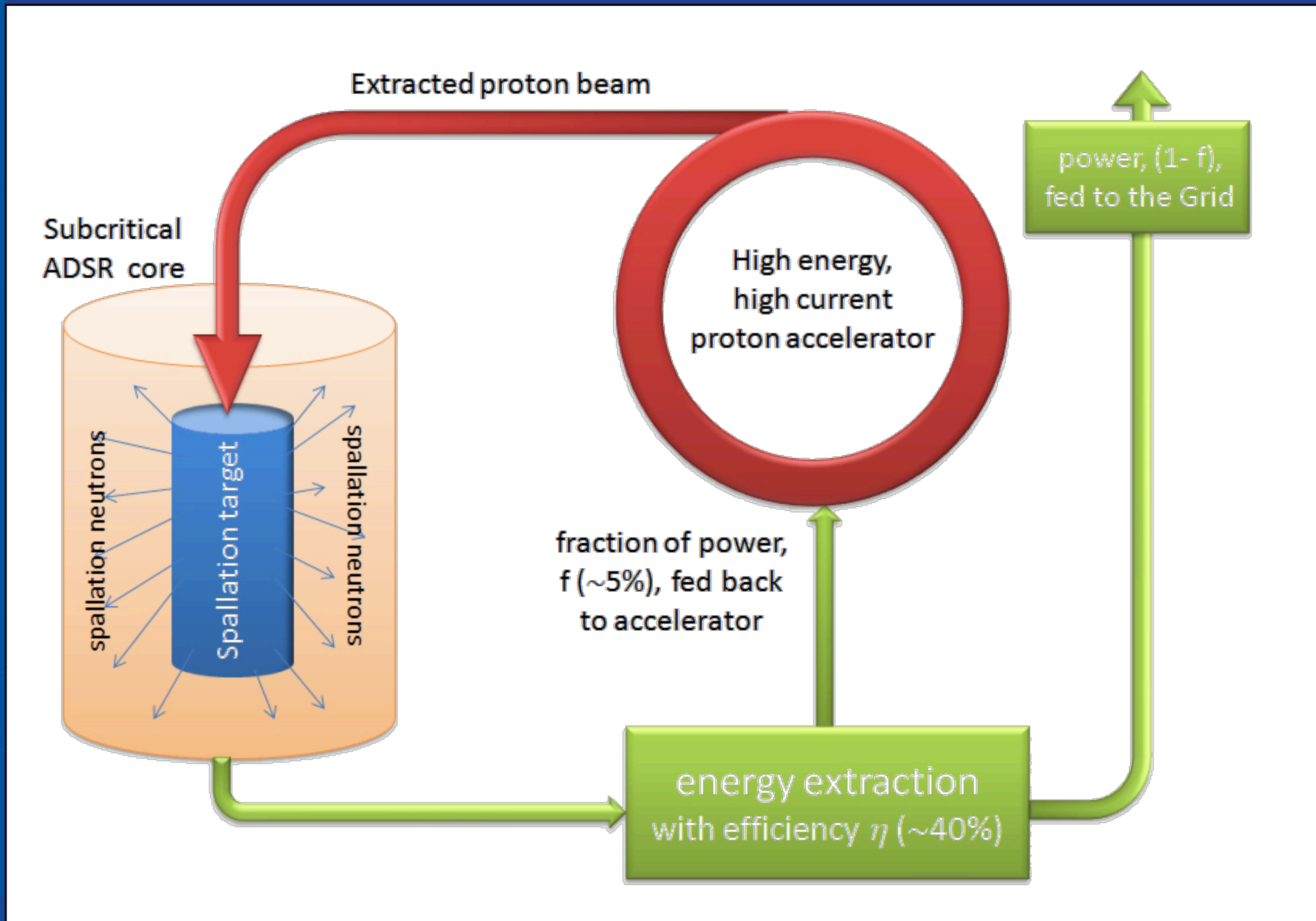
Potentially enhanced safety:

- External neutron source is eliminated when the beam is terminated

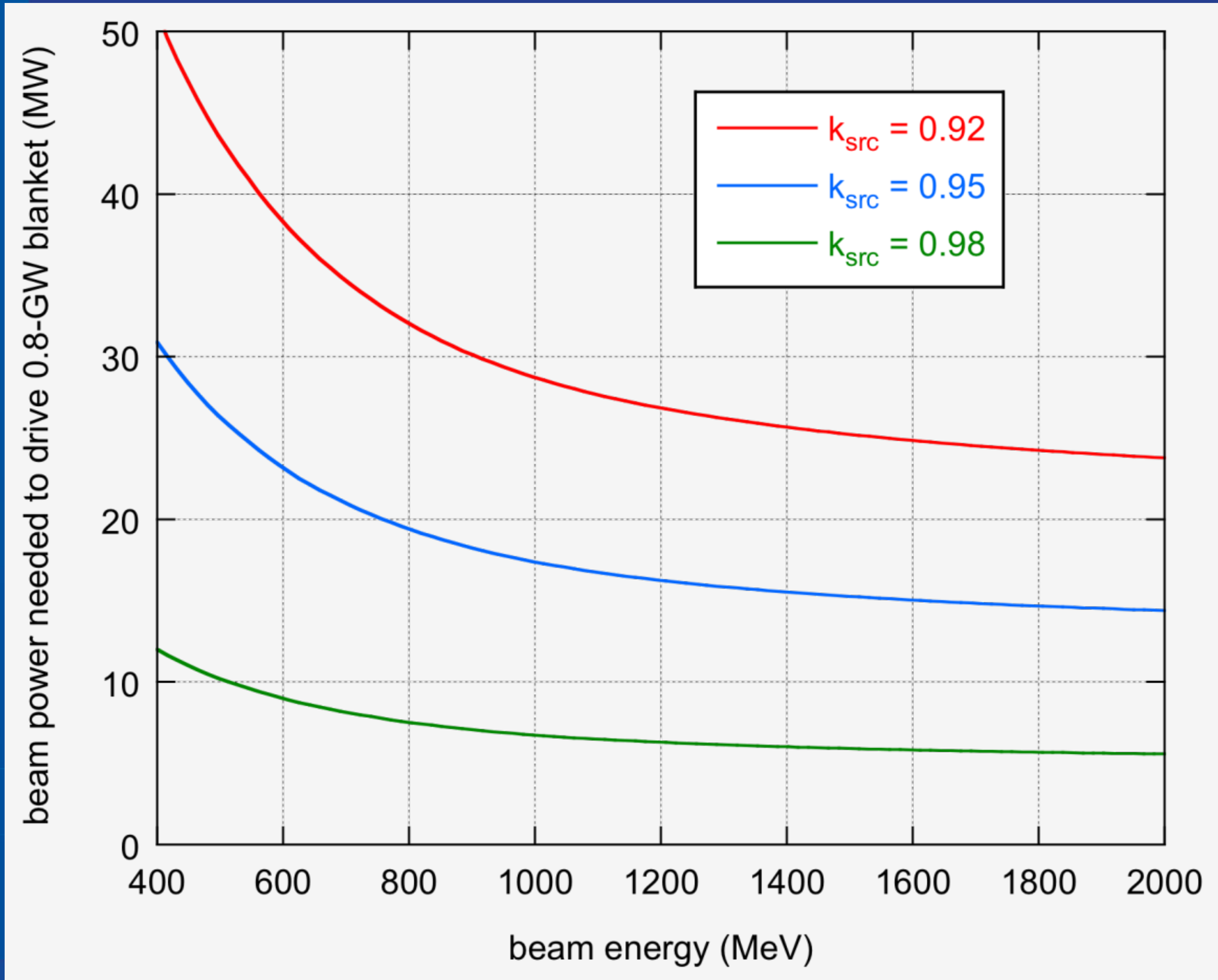
Accelerator Requirements and Capabilities

ADS as an Energy Amplifier

$$P_{thermal} = G_0 \frac{k}{1-k} P_{beam}$$



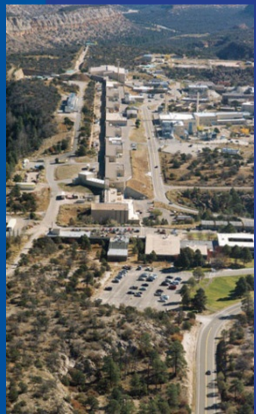
Beam Power Requirements

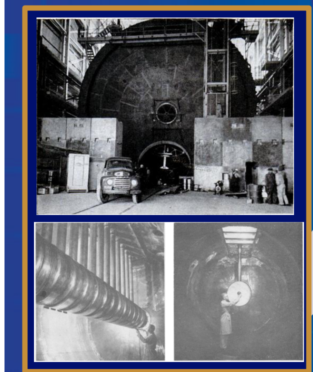


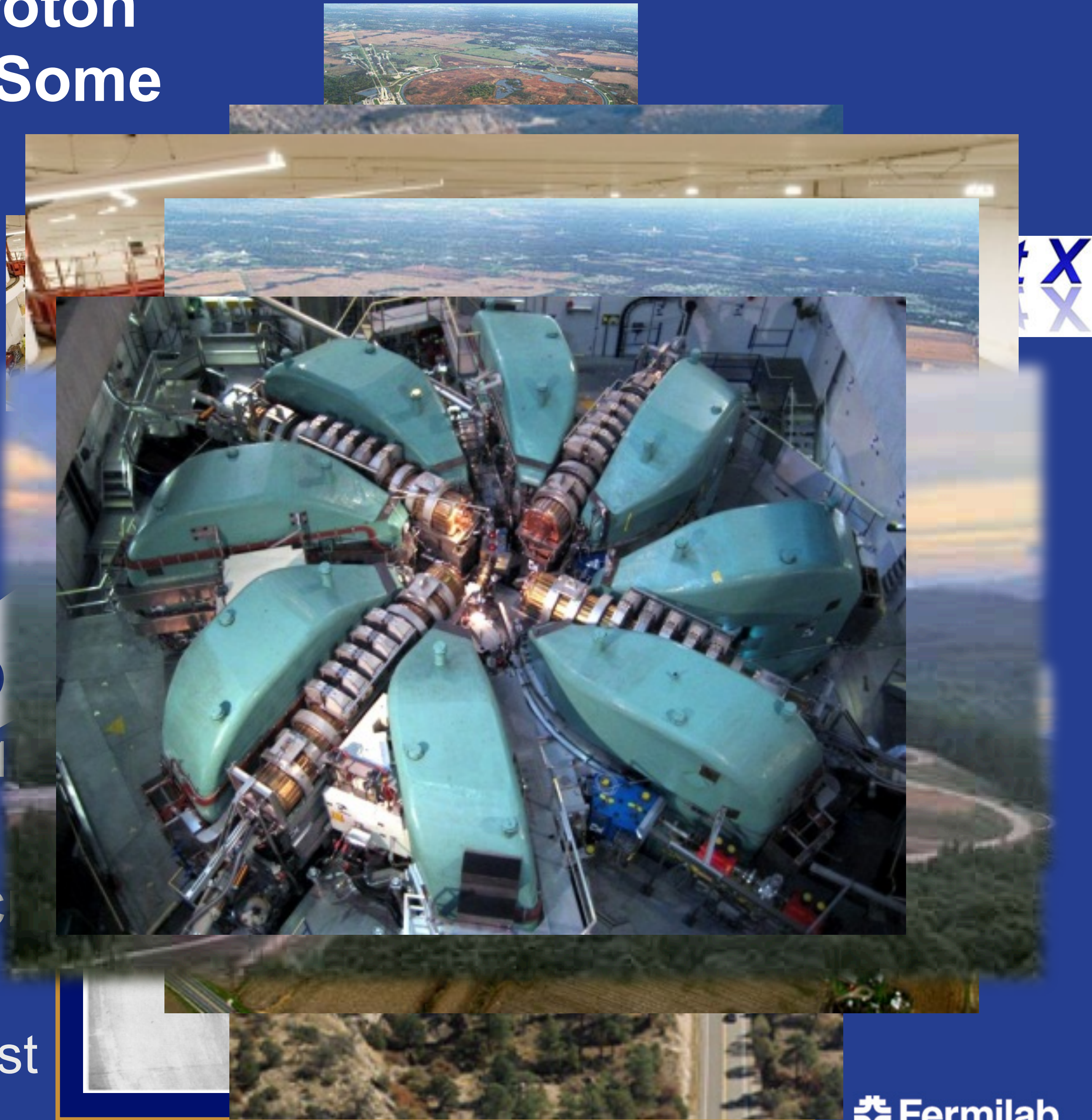
ADS Accelerator Requirements and Challenges

- Proton beam energy in the ~GeV range
  - Efficient production of spallation neutrons
  - Energy well-matched to subcritical core design
  - Minimize capital cost
- Continuous-wave beam in the > 10 MW regime
  - High power required for industrial systems to justify capital expense
- Low beamloss fractions to allow hands-on maintenance of accelerator components (< 1 W/m)
  - 1 W/m proton loss activates SS to ~100 mRem/hr
- Accommodate high deposited power density (~1 MW/liter) in the target.
- Beam Trip Frequency: thermal stress and fatigue in reactor structural elements and fuel assembly sets stringent requirements on accelerator reliability
- Availability typical of modern nuclear power plants

High Power Proton Accelerators: Some History







1972:
LANSC

1950s:
Materials Test
Accelerator

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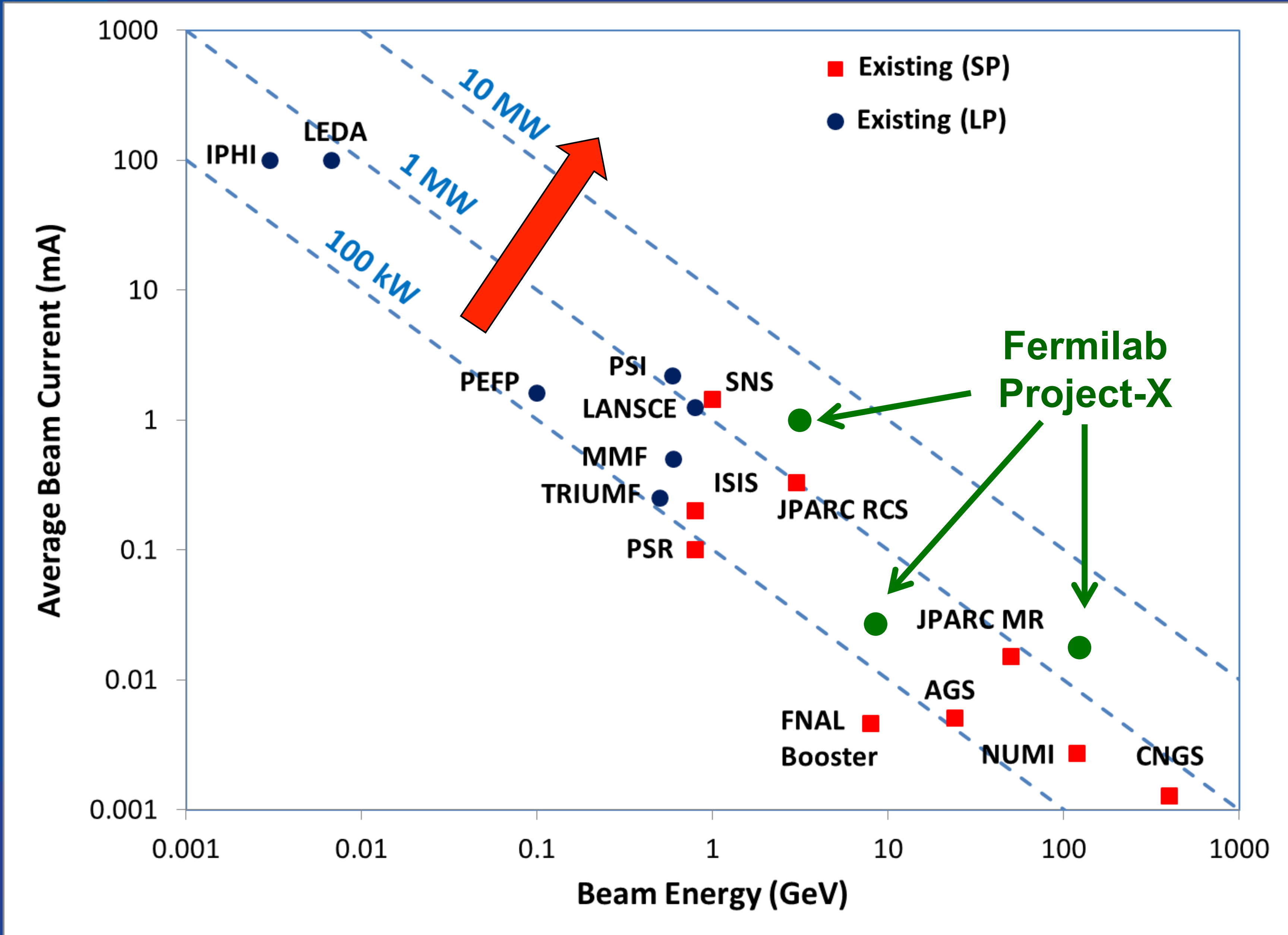
The Beam Power Landscape: Existing



DOE ADS Working Group

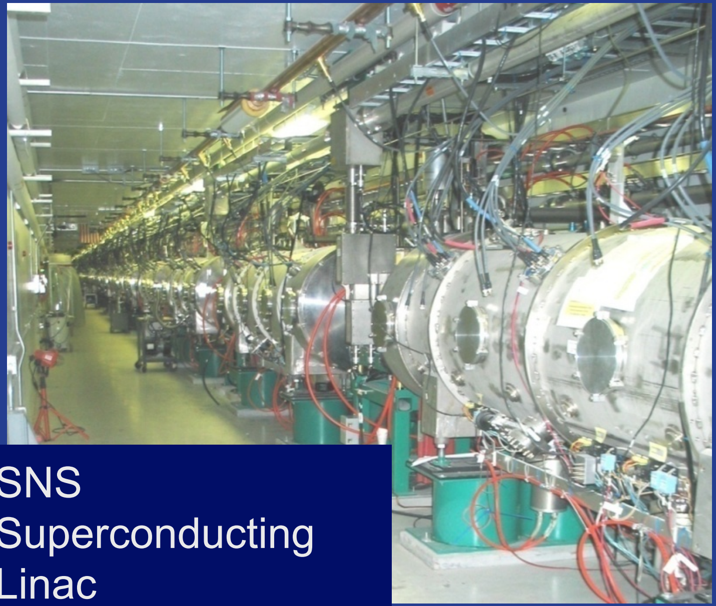
Recent interest in Accelerator Driven Systems in the US motivated a reassessment of accelerator technology

"Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production"

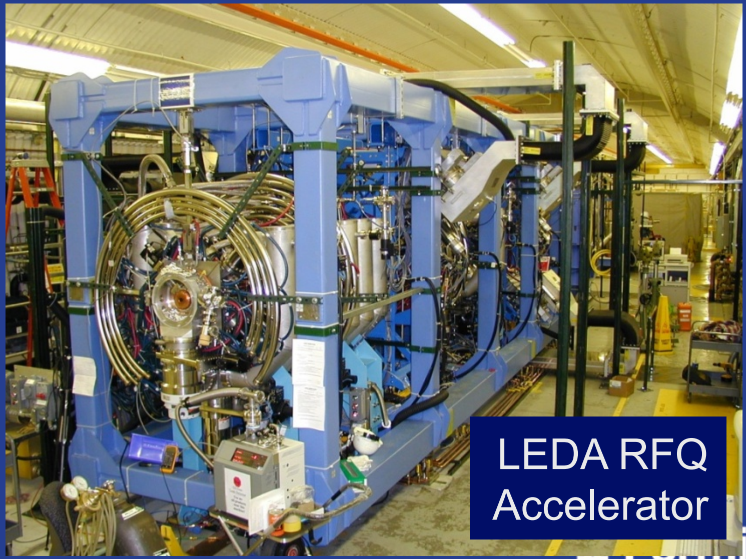
http://science.energy.gov/~/media /hep/pdf/files/pdfs/ADS_White_Paper_final.pdf

ADS-Relevant Technology Development in the Last 10-15 Years

- Modern, ***MW-class high power proton accelerators*** based on superconducting technology ***exist and operate with acceptable beam loss rates*** (Spallation Neutron Source)
- High-power Injector technology has been built and ***demonstrated ADS-level performance (100 MW equivalent) with beam*** (Low-Energy Demonstration Accelerator at Los Alamos)



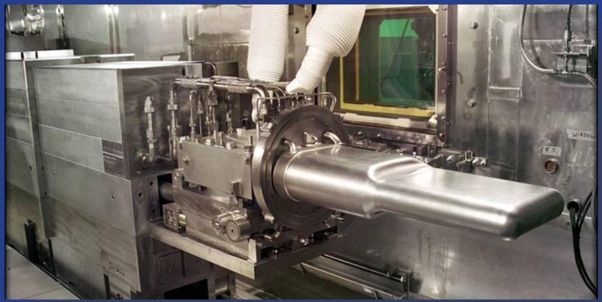
SNS Superconducting Linac



LEDA RFQ Accelerator

ADS-Relevant Technology Development in the Last 10-15 Years

- **Superconducting radiofrequency structures** have been built to cover a broad range of particle velocities (from v/c=0.04 to 1). Use of SRF offers potential for achieving high reliability



- **Liquid-metal target systems have operated** with MW proton beams (Pb-Bi loop - MegaPIE @ PSI, liquid Hg @ SNS)
- **Key technologies relevant to ADS applications that existed only on paper ~15 years ago have since been developed and demonstrated**

Recent Reliability Developments

- More than any other requirement, the maximum allowable beam trip frequency has been the most problematic, and in many ways has been perceived as a "show-stopper"
- Conventional wisdom held that beam trips had to be limited to a few per year to avoid thermal stress and fatigue on the reactor structures, the target and fuel elements
- Recent transient response analyses based on reactor components are in good agreement, and result in **much less-stringent beam trip requirements**
- Updated Beam-Trip Rate requirements, while still very challenging, appear manageable with i) modern linac architecture, ii) appropriate redundancy and iii) utilization of reliability engineering principles

Summary Assessment

Technology is sufficiently well developed to meet the requirements of an ADS demonstration facility

- some development is required for demonstrating and increasing overall system reliability.

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

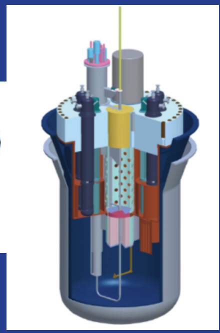
- demonstration of other components,
- improved beam quality and halo control, and
- demonstration of highly-reliable sub-systems is required.

The technology available to accelerator designers and builders of today is substantially different from, and superior to, that which was utilized in early ADS studies

What’s Next?

Enthusiasm is Mounting

- There is growing world-wide grass-roots interest in Thorium Energy and ADS, and growing private-sector interest
- **Europe**: Belgium has committed to build MYRRHA, the first ADS demonstration reactor
- **India**: National nuclear power strategy is based on Thorium; ADS is needed to breed U-233
- **China**: Announced development program to build 1 GW ADS by 2032
- **US**: renewed interest, but no funded R&D program in ADS
  - Fermilab's Project X can play a role in developing ADS should it become a priority



Finally

- Thorium holds the promise as a real, game-changer in Nuclear Energy
- Thorium has significant advantages on both the front-end of the fuel cycle (resource availability, utilization and cost) and on the back-end of the fuel cycle (waste, proliferation)
- Reactor concepts help to address serious concerns from the public (intrinsic safety, waste minimization, potential to burn spent fuel)
- The potential of particle accelerators in the fuel cycle, and in deploying thorium energy, has become much stronger in the last decade as significant technological advances have been achieved

Thorium may well be the future of Nuclear Energy

Backup Materials

ADS Technology Readiness Assessment

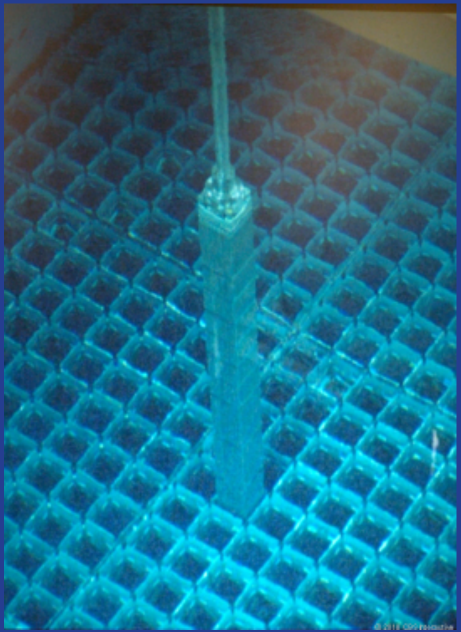
		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance			
	Reliability			
Accelerating System	RF Structure Development and Performance			
	Linac Cost Optimization			
	Reliability			
RF Plant	Performance			
	Cost Optimization			
	Reliability			
Beam Delivery	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			

Green: "ready", Yellow: "may be ready, but demonstration or further analysis is required", Red: "more development is required".

Fuel Flexibility

The control margin that allows critical reactor operation is provided by delayed neutrons:

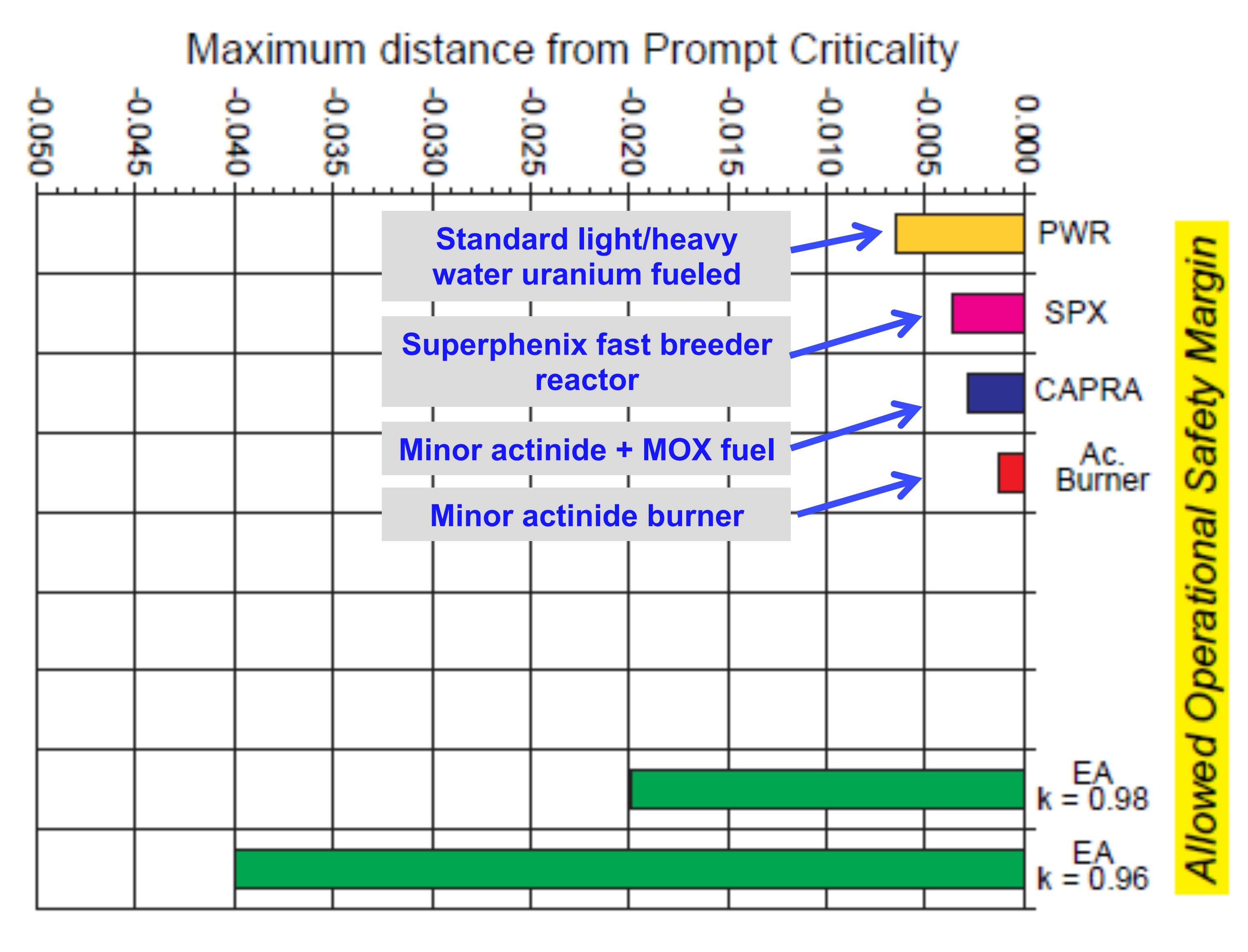
- Prompt neutrons from U-235 fission reproduce in ~1 msec
- ~0.65% of neutrons produced in U-235 fission are delayed with mean emission time ~5 seconds
- Power reactors operate in a “prompt sub-critcal, delayed critical mode”



Accelerator driven systems are ideally suited to burning fuels which are problematic from the standpoint of critical reactor operation, namely,

- fuels that would degrade neutronic characteristics of the core to unacceptable levels due to small delayed neutron fractions and short neutron lifetimes, such as minor actinide fuel.
- Additionally, ADS allows the use of non-fissile fuels (e.g. Th) without the incorporation of U or Pu into fresh fuel.

Margin to Prompt Criticality



Nuclear is in the News

THE WALL STREET JOURNAL.

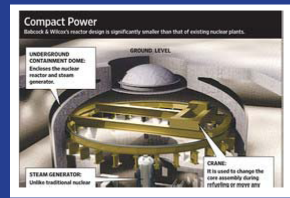
U.S. NEWS | MARCH 4, 2010, 9:34 A.M. ET

Energy Department Files to Withdraw Yucca Mountain License Application

APRIL 17, 2010

Nuclear's Fall—and Rise

As some environmentalists begin to offer more support, the future of nuclear power in the U.S. still depends on whether it makes economic sense



BUSINESS | FEBRUARY 18, 2010

Small Reactors Generate Big Hopes

NOVEMBER 29, 2010

Playing the Nuclear Card

As China looks to wean itself off coal, CLP Holdings sees a big opportunity

ASIA NEWS | MARCH 15, 2011, 11:55 A.M. ET

Japan's Nuclear Crisis Escalates

Damage Spreads to Fourth Reactor; Prime Minister Warns of Radiation Release, Tells Residents in 18-Mile Zone to Stay Indoors

INDIA NEWS | NOVEMBER 18, 2011, 6:34 P.M. ET

Indian, U.S. Leaders Meet on Nuclear Law

BUSINESS | JANUARY 26, 2012, 6:40 P.M. ET

Panel Urges Quick Action for Nuclear Waste Plan

BUSINESS | FEBRUARY 10, 2012

Agency Clears Reactors

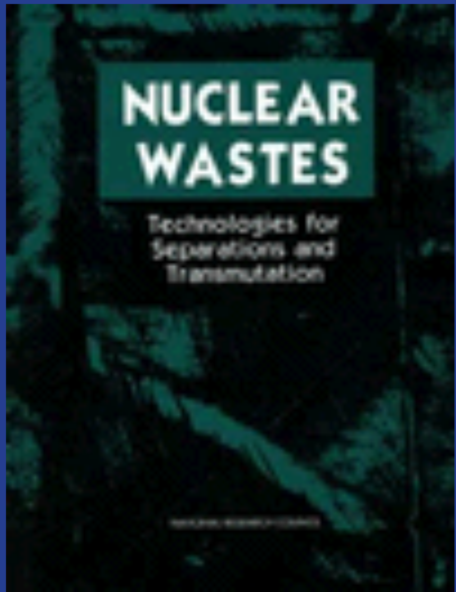
Electrical Power Production

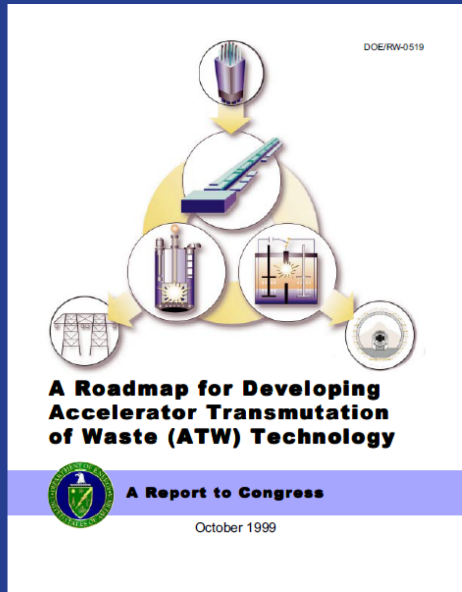
- A waste transmutation facility also generates substantial power which can be used to generate electricity.
- Many ADS concepts utilize Th-based fuel to take advantage of some of its benefits:
  - greater natural abundance,
  - proliferation resistance, and
  - significantly reduced production of transuranics which are a major source of radiotoxicity and decay heat relative to uranium-based fuel.

- An ADS system based on Th fuel would not require incorporation of fissile material into fresh fuel, and could operate almost indefinitely in a closed fuel cycle.
- Expanded use of Th-based fuels is actively pursued in several countries to investigate whether ADS can speed up the deployment of the ^{233}U-Th fuel cycle by breeding ^{233}U, which does not exist in nature.

ADS Activities in the US and World

Timeline of US ADS Activities





Early 1990s

ADS studies for advanced fuel cycles

1995

National Research Council Report evaluated one ADS concept

1999

Congress directs DOE to evaluate ATW concept and prepare Roadmap

2000

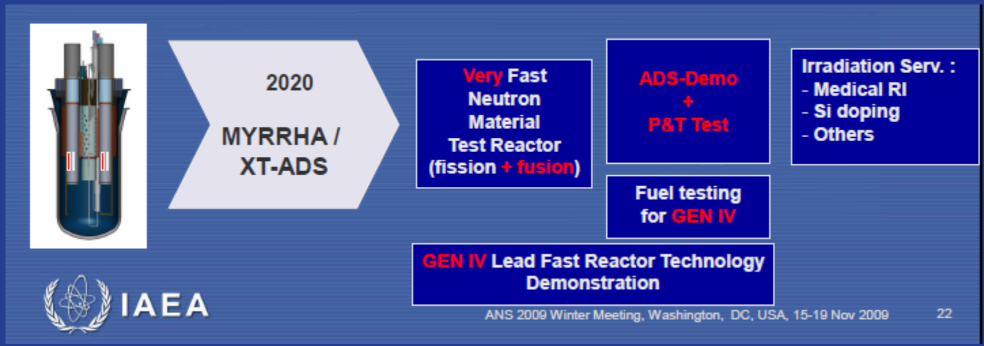
DOE Sponsors Advanced Acc. Applications

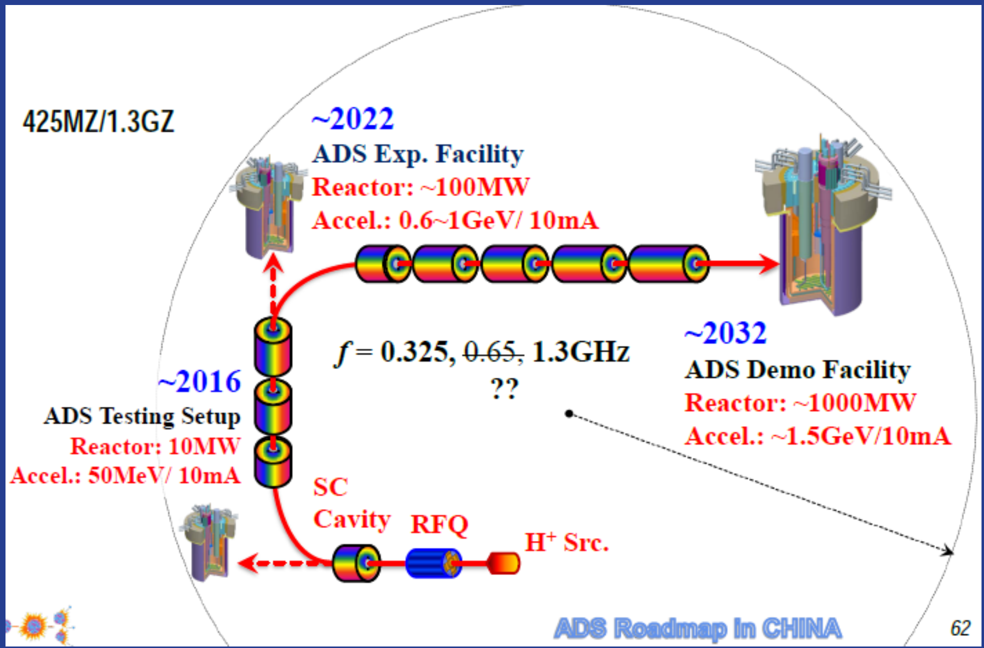
2003

DOE AAA program transitioned to AFCI; ADS work halted

Worldwide ADS Activities (Selected)

- Europe: MYRRHA
  - Belgian proposal to replace the current BR-2 research reactor with an ADS (85-MW core driven by a 2-MW accelerator)
  - Total Project Cost about 1B€, Belgium seeking international participation (MOU's with S.Korea & China)
- China: CAS announced ADS Roadmap to develop industrial scale system in two decades
- India: Objective to develop sustainable Th fuel cycle
  - ADS enables Th-U233 breeding





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ADS System Requirements

Range of Missions for Accelerator Driven Systems

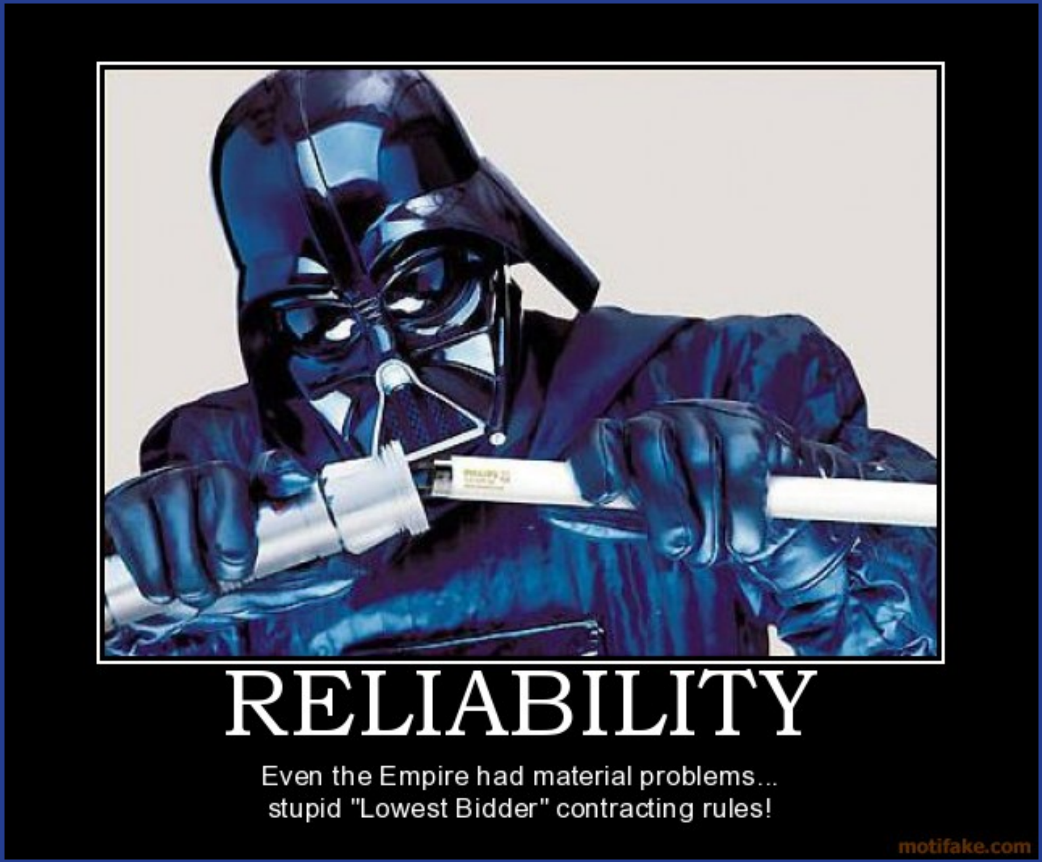
Transmutation Demonstration and Experimentation →	Industrial-Scale Transmutation →	Industrial-Scale Power Generation w/ Energy Storage →	Industrial-Scale Power Generation w/o Energy Storage
• Accelerator sub-critical reactor coupling • ADS technology and components • M.A./Th fuel studies	• Transmutation of M.A. or Am fuel • Convert process heat to another form of energy	• Deliver power to the grid • Burn MA (or Th) fuel • Incorporate energy storage to mitigate long interruptions	• Deliver power to the grid • Burn MA (or Th) fuel

Time, Beam-Trip Requirements, Accelerator Complexity, Cost →

Reliability

More than any other requirement, the maximum allowable beam trip frequency has been the most problematic, and in many ways has been perceived as a "show-stopper"

Conventional wisdom held that beam trips had to be limited to a few per year to avoid thermal stress and fatigue on the reactor structures, the target and fuel elements



Beam Trip Requirements in EUROTRANS Studies ca. 2009

Eur. Phys. J. Special Topics **176**, 179–191 (2009)

DOI: 10.1140/epjst/e2009-01157-8

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Regular Article

Prospects for transmutation of nuclear waste and associated proton-accelerator technology

A.C. Mueller

National Institute for Nuclear and Particle Physics, CNRS, 75016 Paris, France

Table 4. Main specifications for the proton beam. The listed requirements are for driving the technology-demonstrator XT-ADS compared to the industrial prototype EFIT.

	XT-ADS	EFIT
Max. beam intensity	2.5–4 mA	20 mA
Proton energy	600 MeV	800 MeV
Beam entry	Vertical from above	
Allowed beam trips (>1 sec)	<5 per 3-month operation cycle	<3 per year
Beam stability	Energy: ±1%, Intensity: ±2%, Size: ±10%	
Beam time structure	CW, including zero-current periods (200 μs), repeated at low rate	

Recent Beam Trip Duration Analyses

- **Recent detailed analyses of thermal transients in the subcritical core lead to beam trip requirements that are much less stringent than previously thought**
- There are three analyses based on transient response of reactor components using modern FEA methods: JAEA, MYRRHA and Argonne

JAEA Analysis: H. Takei et. al., Proc. 5th OECD/NEA HPPA

- Four criteria depending on the beam trip duration *T*

Beam trip duration *T*	Acceptable Frequency	Remarks
$0 < T < 5$ sec.	10^5 / 2 year 10^6 / 40 year (25,000 / y)	Beam window life time Fatigue failure of reactor structure
$5 < T < 10$ sec.	10^5 / 40 year (2,500 / y)	Fatigue failure of reactor structure
10 sec. $< T <$ 5 min.	10^4 / 40 year (250 /y)	Fatigue failure of reactor structure
$T >$ 5 min.	Once a week (50 /y)	System availability

Understanding of Beam Trip Requirements Has Improved Greatly

- Improved understanding results in
  - ~2 order of magnitude relaxation of requirements for "short" trips and
  - ~1 order of magnitude relaxation for "long" trips
- Updated Beam-Trip Rate requirements, while still very challenging, appear manageable with
  - modern linac architecture,
  - appropriate redundancy and
  - utilization of reliability engineering principles
- More work is required to bring these components together with high reliability at > 10 times the beam power of today's accelerators, **but "getting from here to there" is achievable**

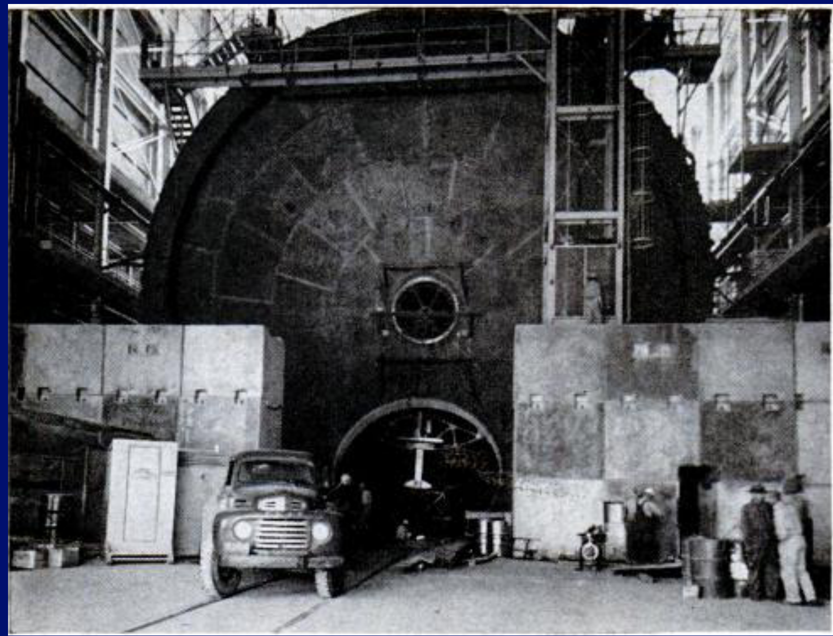
ADS Parameters and Requirements Depend on the Mission

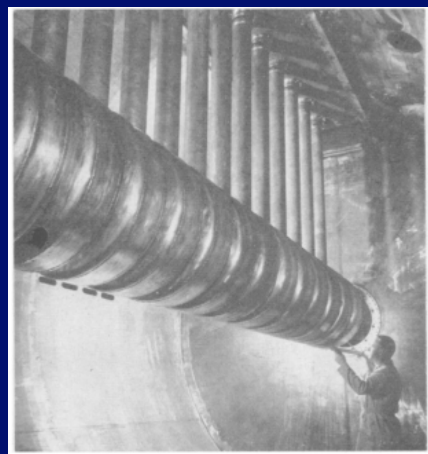
	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1-2 MW	10-75 MW	10-75 MW	10-75 MW
Beam Energy	0.5-3 GeV	1-2 GeV	1-2 GeV	1-2 GeV
Beam Time Structure	CW/pulsed (?)	CW	CW	CW
Beam trips (t < 1 sec)	N/A	< 25000/year	<25000/year	<25000/year
Beam trips (1 < t < 10 sec)	< 2500/year	< 2500/year	<2500/year	<2500/year
Beam trips (10 s < t < 5 min)	< 2500/year	< 2500/year	< 2500/year	< 250/year
Beam trips (t > 5 min)	< 50/year	< 50/year	< 50/year	< 3/year
Availability	> 50%	> 70%	> 80%	> 85%

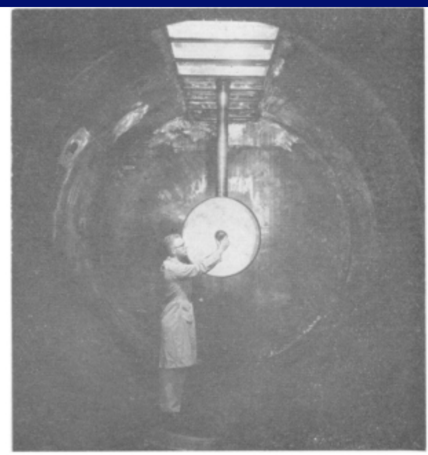
ADS Technology Development and Readiness

The Beginning: the Materials Testing Accelerator Program

- MTA Program at UCRL (early 1950s) marks the birth of high-power hadron accelerator field
- Goal: Breed Pu-239, U-233 and H-3 with a 350 MeV, 0.25 Amp deuteron beam (Livdahl, Proc. LINAC81 p.5).
- The Mark I accelerator : 12 MHz drift-tube linac (60 ft. diameter!), eight 40 ton drift tubes, delivered ~50 mA at ~10 MeV (briefly)
- Two other accelerators built, based on 48.6 MHz (12 ft. dia.) DTLs. The A-48 produced 30mA, 7.5 MeV deuterons

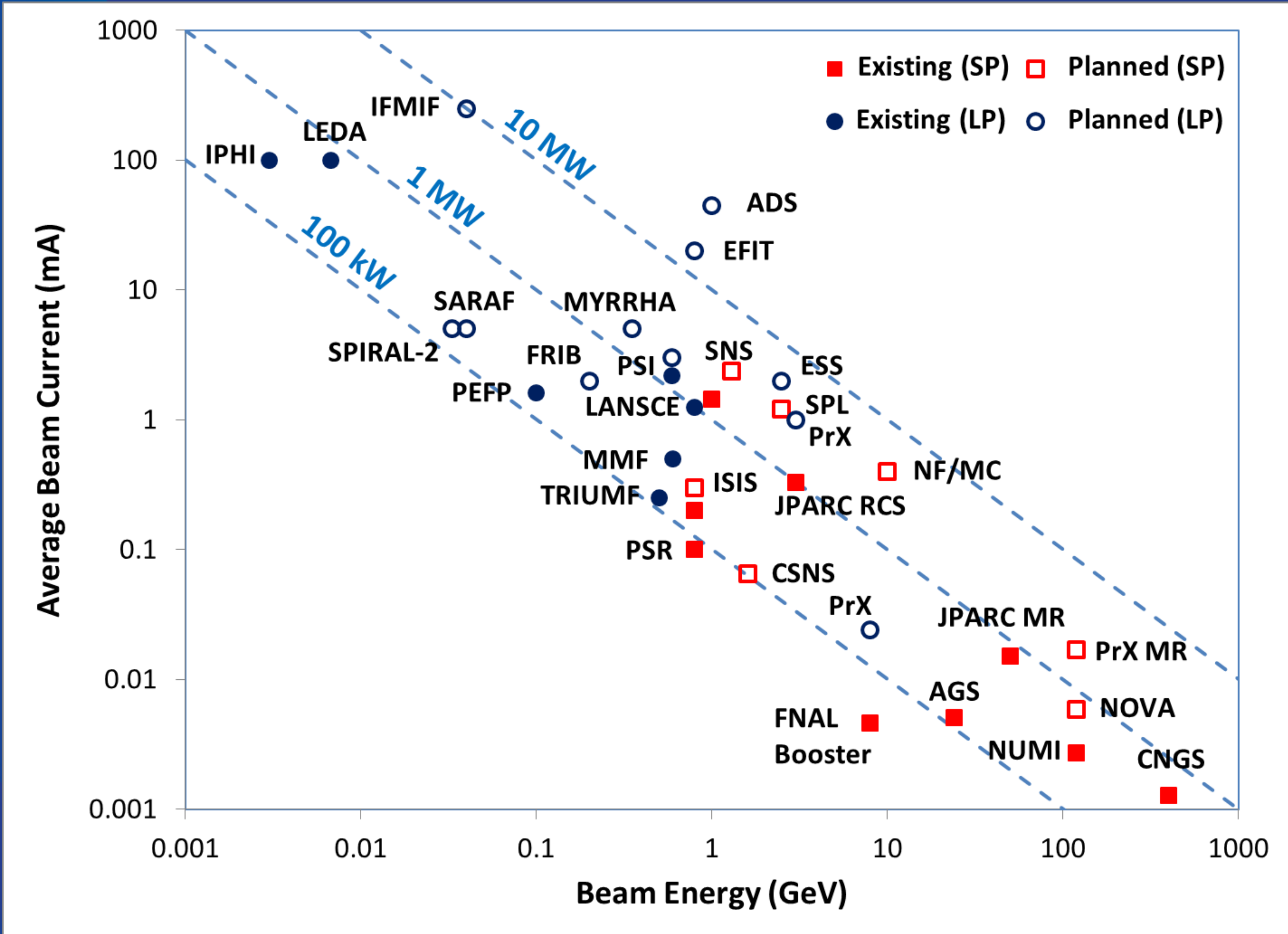






- Numerous fundamental limits were encountered

The Beam Power Landscape: Planned



Accelerator Technology Choices

- Three technologies have demonstrated MW-class performance
  - Cyclotron – PSI
  - NC Linac – LANSCE
  - SC Linac – SNS
- In the range of 5-10 MW, both cyclotron (at its limits) and linear accelerator technology are applicable.
  - Perhaps FFAGs will be capable someday.
- Various studies have concluded that SCRF technology has far greater beam power potential than cyclotron technology, and that it is the technology of choice for the > 10MW beam power required to drive GW-level subcritical cores
- Further, SCRF has the capability for achieving very high reliability as it lends itself to implementing a robust independently-phased RF cavity system.
  - potential for fault tolerance and rapid fault recovery

Challenges for High Power Proton Accelerators for ADS

- Producing high-quality beams (high brightness, low halo) in the injector system at high duty factor
- Accelerating high beam currents to high energy
  - high-power CW RF systems, structures and components; for RF efficiency and practicality, SCRF is the technology of choice
- Transporting high power beams while maintaining beamloss at a level where routine maintenance is possible (<1 Watt/m)
  - Acceleration of beams from keVs to GeVs with little emittance growth, and minimization of halo growth
  - Understanding and control of collective effects that have the potential to generate large-amplitude particles
  - Systems for collimation, machine protection
- Target systems capable of handling extreme power densities (~MW/liter) and extreme radiation environments (~ 10^5 Rem/hr beam off)

ADS-Relevant Technology Development in the Last 10-15 Years

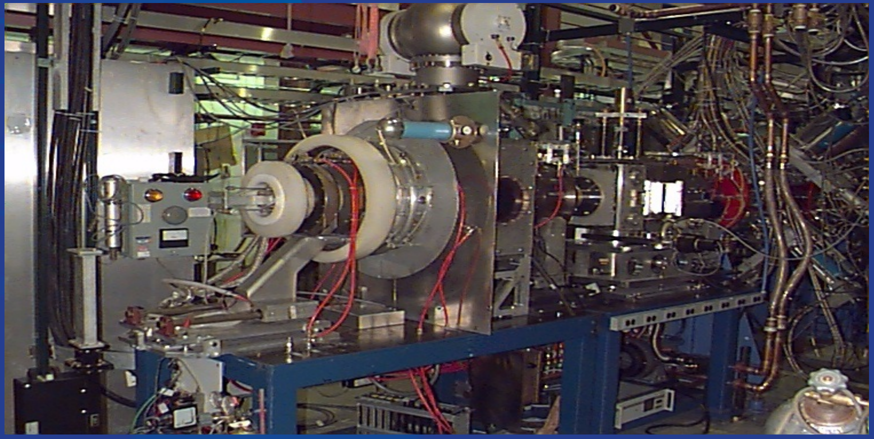
- Key technologies have been demonstrated
  - High-power Injector technology has been built and *demonstrated ADS-level performance* (Low-Energy Demonstration Accelerator at Los Alamos)
  - SRF structures have been built which cover a broad range of velocities (from v/c=0.04 to 1). Use of SRF offers potential to achieve high reliability
  - Liquid-metal target systems have operated with MW proton beams (Pb-Bi loop - MegaPIE @ PSI, liquid Hg @ SNS and J-PARC)
- Modern, MW-class high power proton accelerators exist (Spallation Neutron Source)

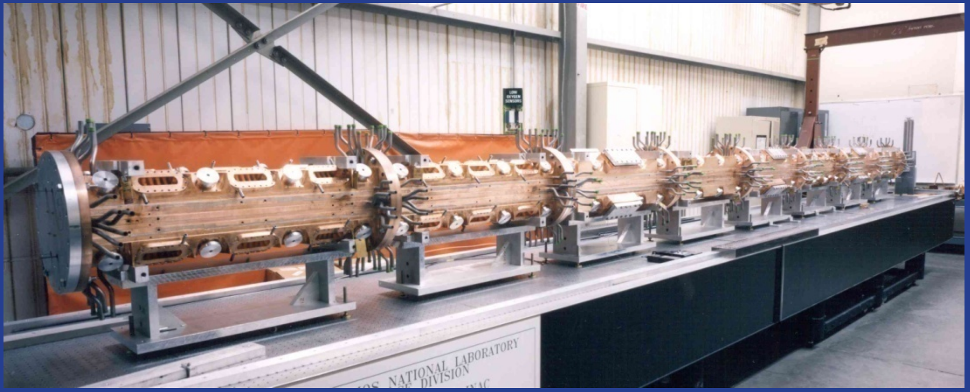
Key technologies of relevance for ADS applications that existed only on paper ~15 years ago have since been developed and demonstrated

Front-End System Technology: Low-Energy Demonstration Accelerator (LEDA)

- Full power performance demonstrated for a limited operating period.
  - 20 hours at 100 mA CW
  - 110 hours at > 90 mA CW
- RMS beam emittances measured; reasonable agreement with simulation
- No long-term operations for reliability/availability evaluation

Performance demonstrates injector capability needed for ~100 MW ADS





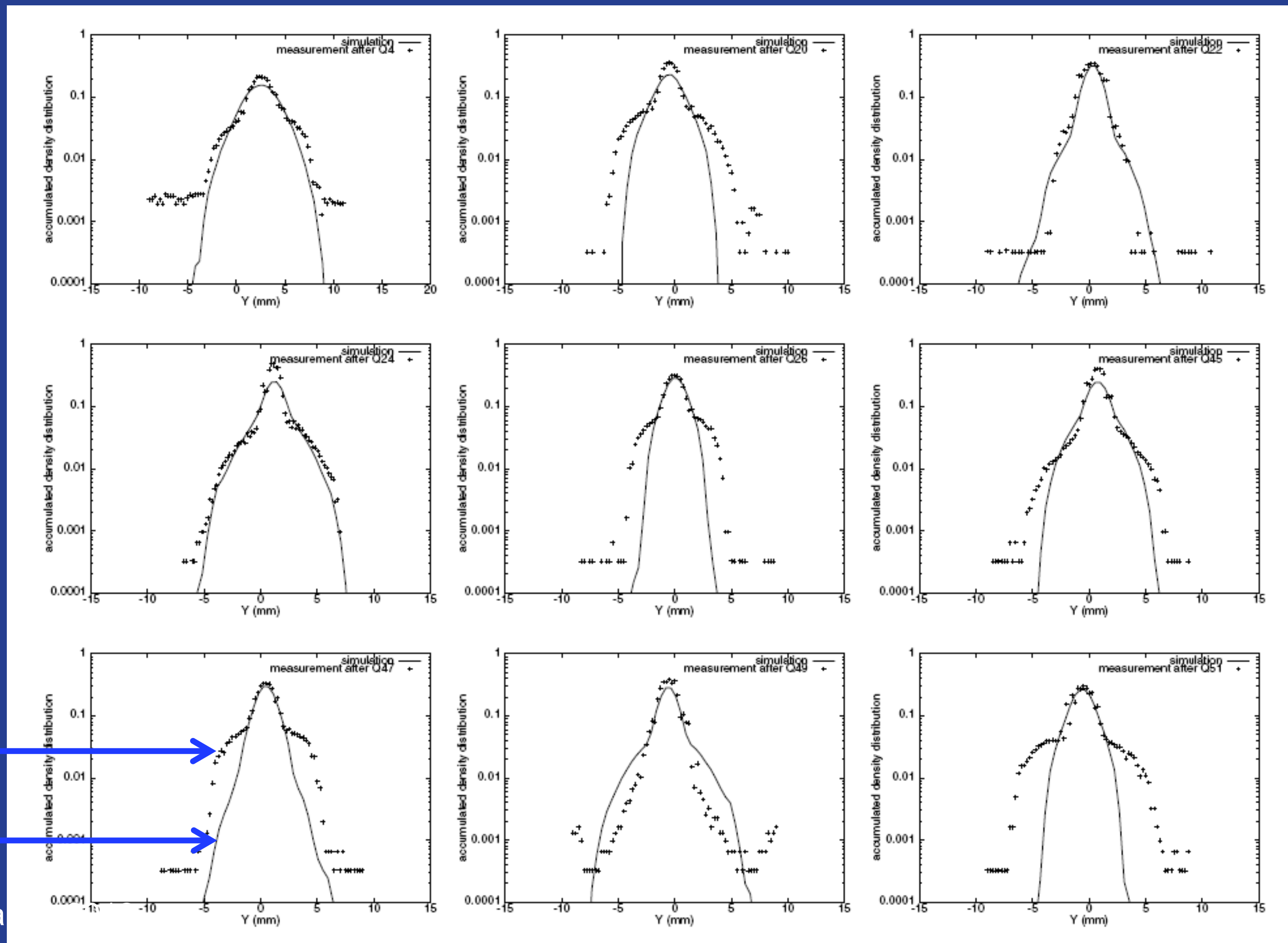
Fermilab

State of the Art in Halo/Emittance Growth Measurement and Simulation

- LEDA measurements and IMPACT code comparison: J. Qiang et. al., PRST-AB 5 (124201) 2002.
- 52 quadrupole focusing channel with intentionally mismatched, low-energy, high-intensity beam
- Plot shows vertical beam profile data (points) compared to simulation (line) at 9 locations
- Conclusion: Knowledge of input distribution is incomplete; inadequate to achieve quantitative agreement for mismatched beams

Data

Simulation



SILHI: Source of Light Ions for High Intensity at CEA-Saclay

- An ECR-based source (SILHI) was built and tested, extracting > 100 mA proton current
- The source was operated for ~1,000 hours to assess reliability and availability

Parameters	Déc. 97	Mai 99	Oct. 99	March 01	June 01
Energy (keV)	80	95	95	95	95
Intensity (mA)	100	75	75	118	114
Duration (h)	103	106	104	336	162
Beam off number	**53**	**24**	**1**	**53**	**7**
MTBF (h)	**1.75**	**4**	**n. appl.**	**≈ 6**	**23.1**
MTTR (mn)	**6**	**5.3**	**2.5**	**≈ 18**	**2.5**
Uninterrupted beam (h)	**17**	**27.5**	**103**	**25**	**36**
Availability (%)	**94.5**	**97.9**	**99.96**	**95.2**	**99.8**

SNS Can Be Considered an ADS Prototype

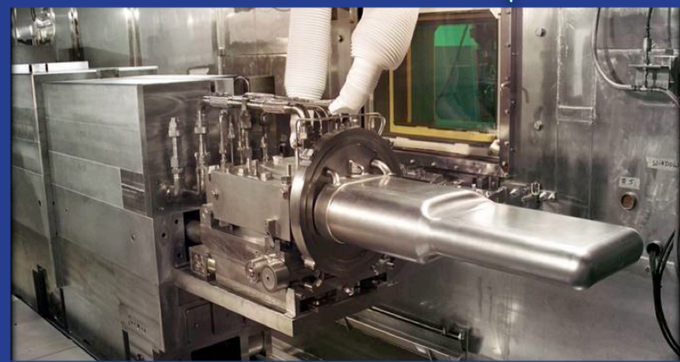
Front-End: Produce a 1-msec long, chopped, H- beam

1 GeV LINAC

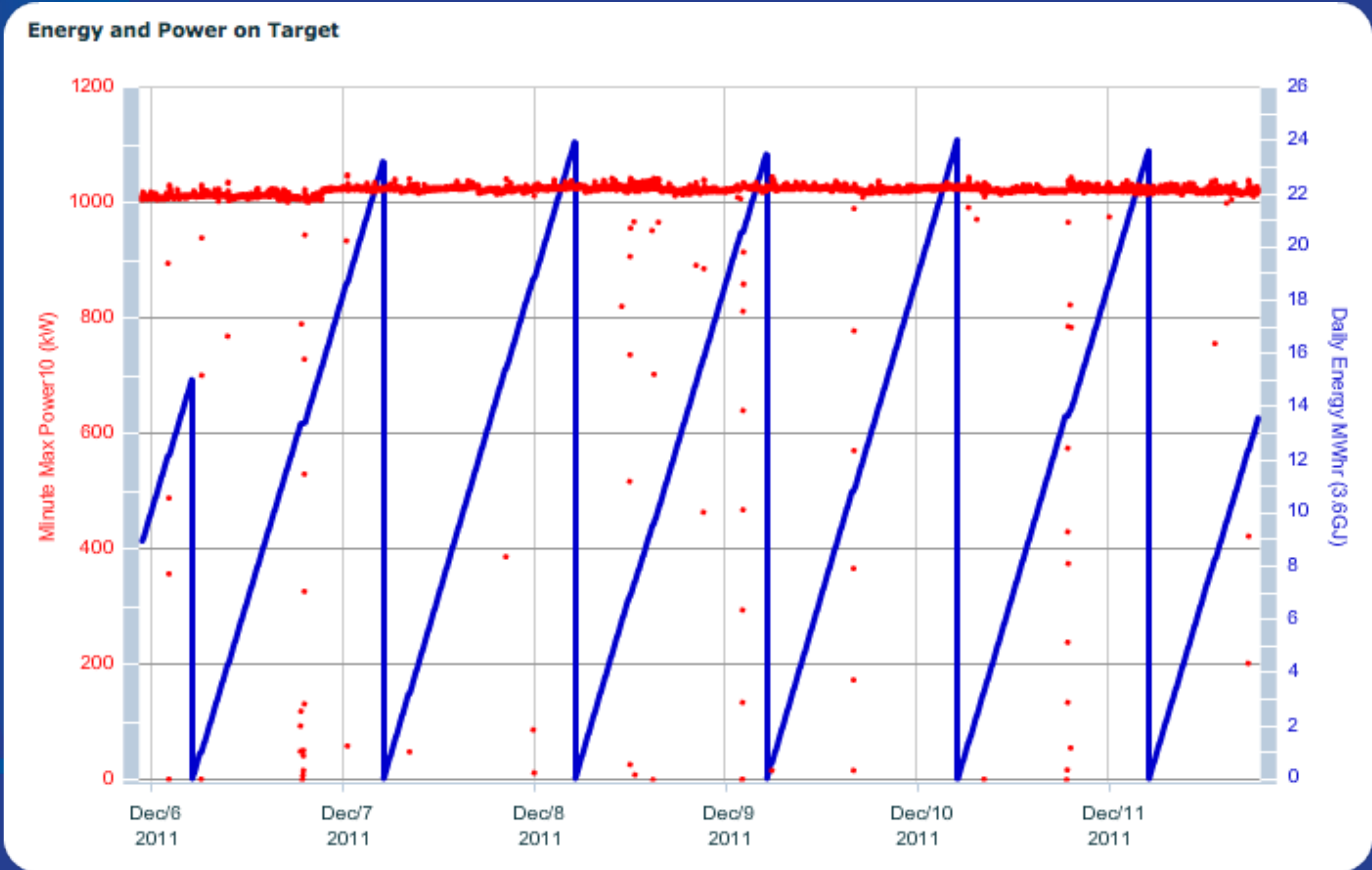
Accumulator Ring: Compress 1 msec long pulse to 700 nsec

Liquid Hg Target

High power RF



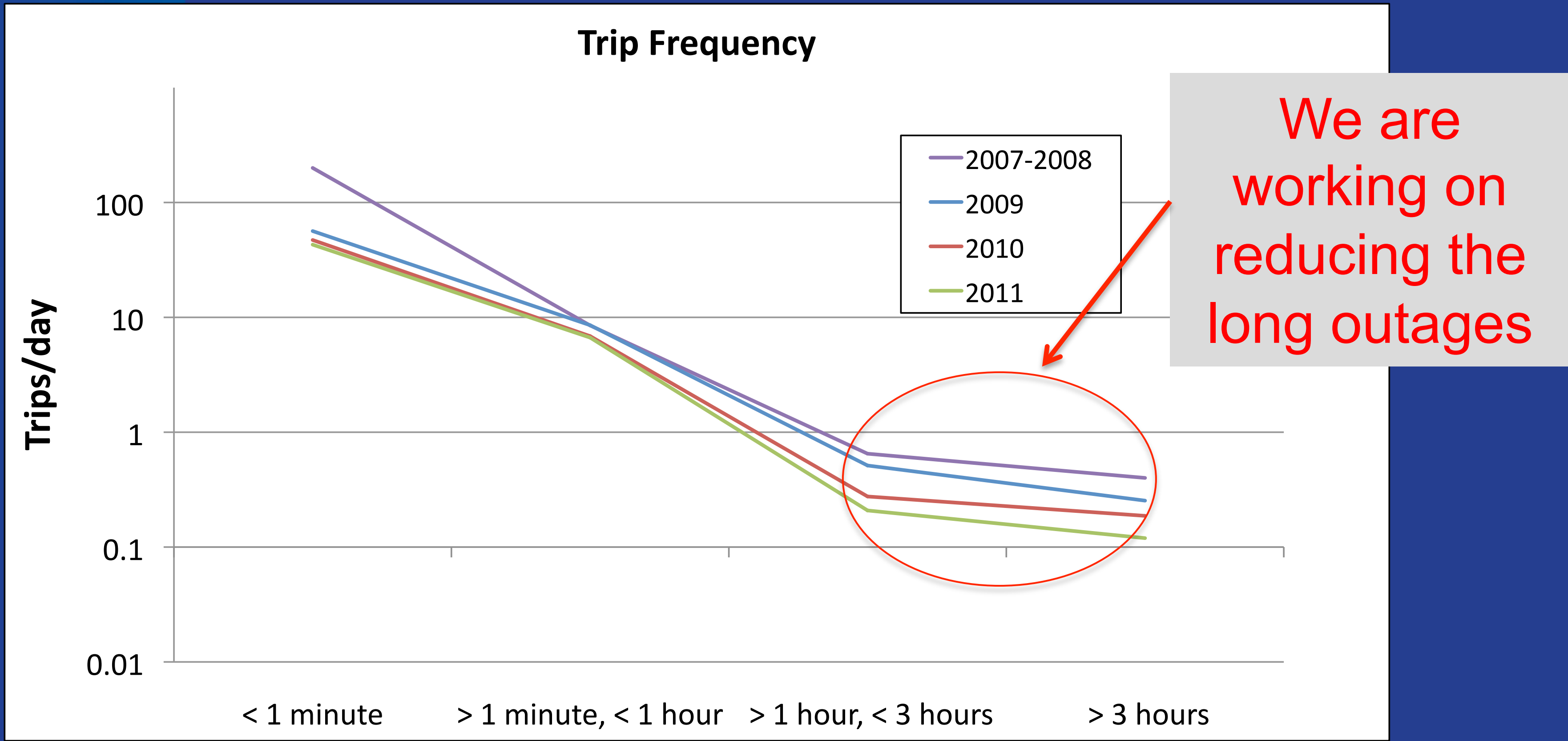
Performance of SNS, a MW-class Proton Linear Accelerator



Fermilab

Trip Rates at SNS

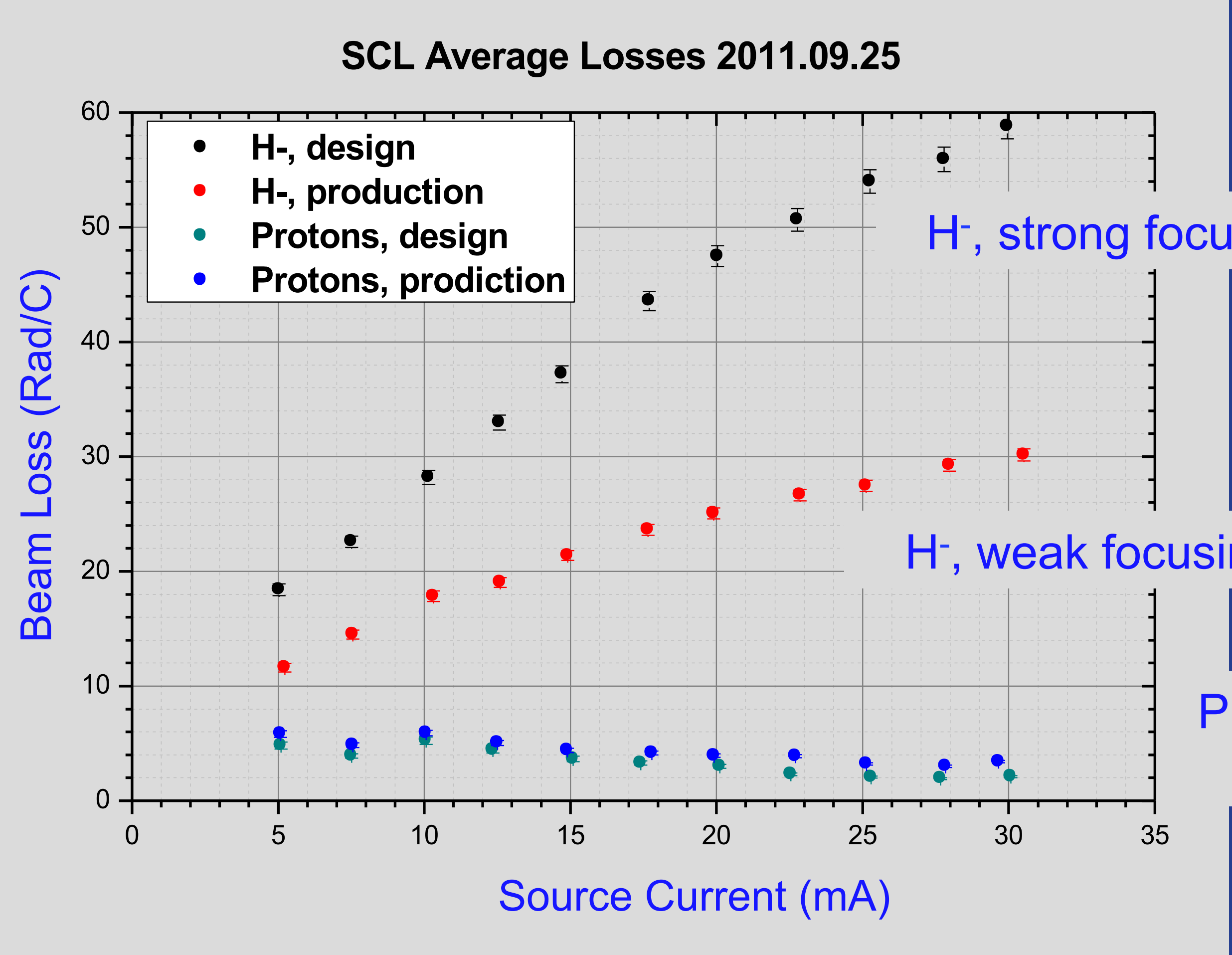
Courtesy J. Galambos



- SNS is focusing on reducing long outages – which affect the user program
  - Short trips are not a driver of downtime, and have received relatively little attention
- SNS was not designed for very low trip rates

Proton Beam Loss is much lower than H^-

Courtesy J. Galambos



A. Shishlo et al.

- Measured beam loss in the SNS linac is much lower for protons than for H^-
  - Trends are consistent with "Intra-beam stripping"

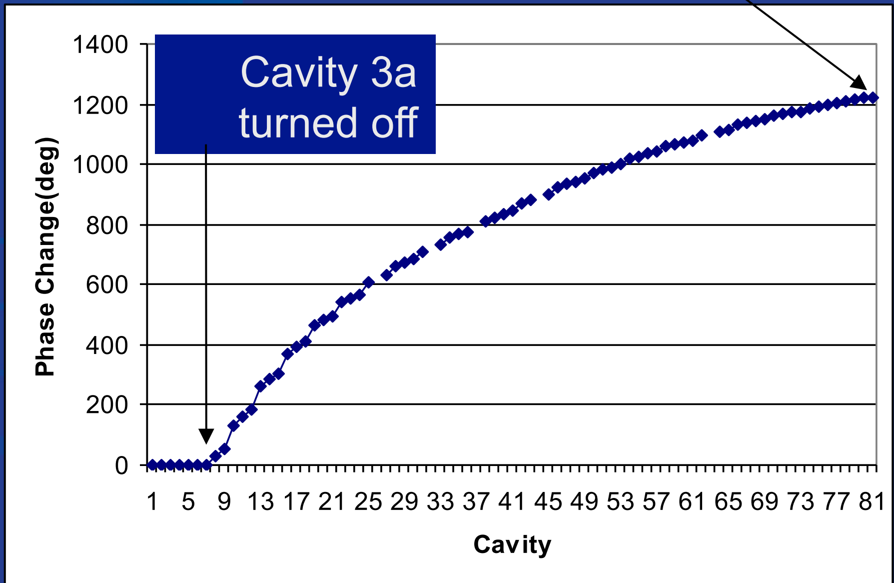
SNS Beam loss scales favorably for ADS

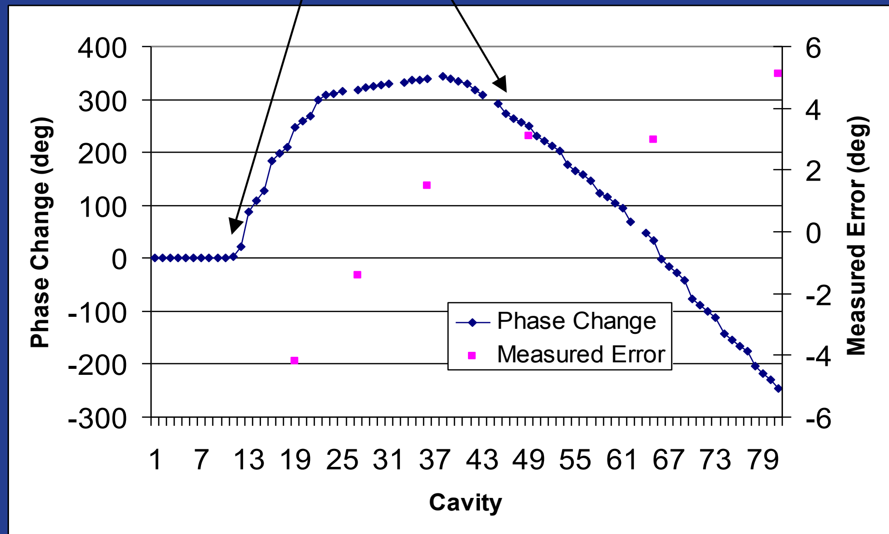
Superconducting Cavity Fault Recovery

- A cavity fault recovery scheme is developed to adjust downstream cavity setup, to accommodate upstream cavity changes
  - Uses a difference technique, with initial beam based measurements
  - Successfully demonstrated and used at SNS
    - Could work in < 1 sec if needed

Final cavity phase found within 1 degree, output energy within 1 MeV

Turned on cavity 4a, reduced fields in 11 downstream cavities





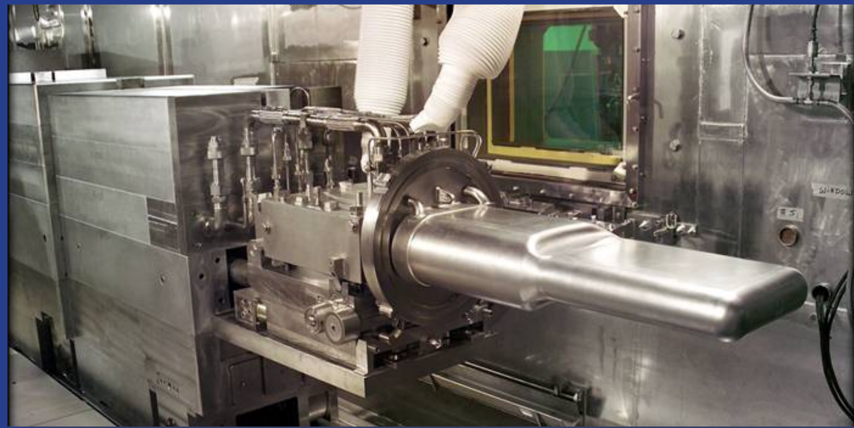
Courtesy J. Galambos

Target Systems- Requirements

- Maximize the number of neutrons *escaping* from the target per proton incident on it.
- Accommodate high deposited power density (~1 MW/liter).
- Relative to the subcritical core, contribute in an insignificant way to the dose received by workers and the public under design basis accident scenarios.
- Operate reliably for more than six months between target replacements.
- Be capable of being replaced within a reasonable (about one week) maintenance period.

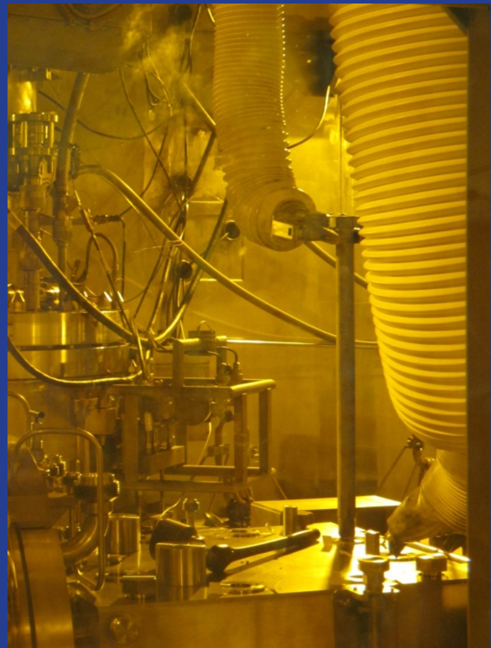
State of the Art: Operating MW-class Target Systems

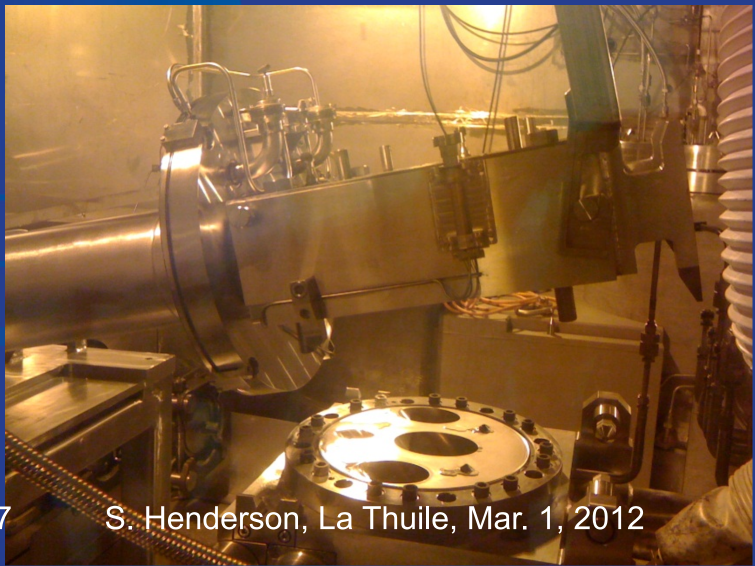
- Solid-target
  - SINQ at PSI (~1.2 MW “DC” beam)
- Liquid Hg
  - Spallation Neutron Source (1.1 MW pulsed)
  - Japan Proton Accelerator Research Complex (0.3 MW pulsed)
- Pb-Bi Eutectic target
  - MEGAPIE at PSI (0.8 MW)
- Spallation targets for ADS application well above 1 MW will likely use heavy liquid metal cooling to achieve compact designs.
  - The only example of lead or LBE cooling for high power is the Russian LBE submarine reactors which were designed for approximately 150 MW.

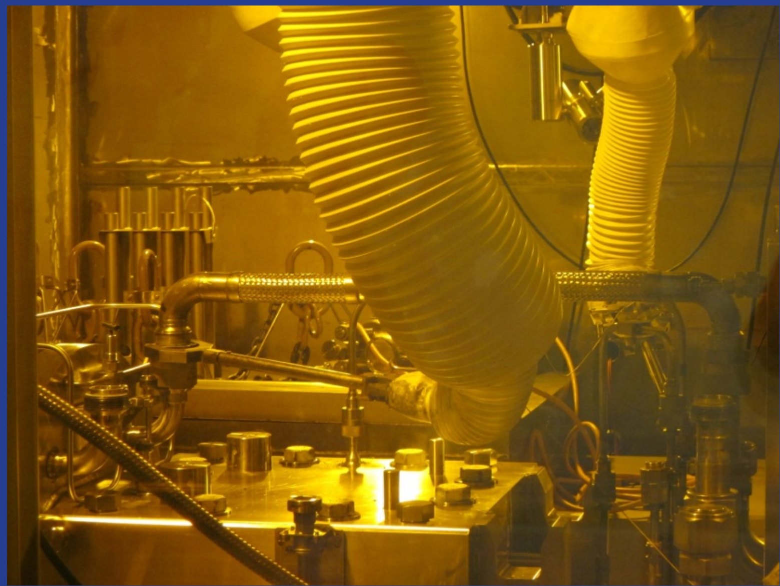


Fermilab

High Power Targets are Consumables (SNS Target Service Bay)







ADS Technology Readiness Assessment

		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			

Green: “ready”, Yellow: “may be ready, but demonstration or further analysis is required”, Red: “more development is required”.

What Does This Mean for Project-X?

Project X as a National Resource With Applications Beyond Particle Physics

- A multi-MW high energy proton accelerator is a national resource, with potential application that goes beyond particle physics
- Such facilities are sufficiently expensive that the U.S. will not invest in multiple facilities with duplicative capabilities
- We are engaging the potential user communities for utilization of high power proton beams beyond HEP:
  - Materials Irradiation, ADS Development, Cold muon source for materials science

Project X and Potential for ADS

- A demonstration facility that couples a subcritical assembly to a high-power accelerator requires 1-2 MW beam power in the GeV range
- The 3 GeV Project X CW Linac has many of the elements of a prototypical ADS Linac
  - High CW beam power in the right energy range
- The Project X CW Linac is ideally suited to power a demonstration facility with focus on:
  - Target system and subcritical assembly technology development and demonstration
  - Demonstration of transmutation technologies and support for fuel studies
  - Materials irradiation
  - High reliability component development, fault tolerant linac and rapid fault recovery development
- In Collaboration with Argonne have begun to formulate an experimental program on Pb-Bi spallation target characteristics and transmutation experiments
- In Collaboration with PNNL we are formulating a materials irradiation program and concept for a facility

Key Findings from the White Paper Working Group Report

1. There are active programs in many countries, although not in the U.S., to develop, demonstrate and exploit accelerator-driven systems technology for nuclear waste transmutation and power generation.
2. Accelerator-driven sub-critical systems offer the potential for safely burning fuels which are difficult to incorporate in critical systems, for example fuel without uranium or thorium.
3. Accelerator driven subcritical systems can be utilized to efficiently burn minor actinide waste.
4. Accelerator driven subcritical systems can be utilized to generate power from thorium-based fuels
5. The missions for ADS technology lend themselves to a technology development, demonstration and deployment strategy in which successively complex missions build upon technical developments of the preceding mission.

Key Findings from the White Paper Working Group Report

6. Recent detailed analyses of thermal transients in the subcritical core lead to beam trip requirements that are much less stringent than previously thought; while allowed trip rates for commercial power production remain at a few long interruptions per year, relevant permissible trip rates for the transmutation mission lie in the range of many thousands of trips per year with duration greater than one second.
7. For the tens of MW beam power required for most industrial-scale ADS concepts, superconducting linear accelerator technology has the greatest potential to deliver the required performance.
8. One of the most challenging technical aspects of any ADS accelerator system, the Front-End Injector, has demonstrated performance levels that meet the requirements for industrial-scale systems, although reliability at these levels has not yet been proven.

Key Findings from the White Paper Working Group Report

9. Superconducting radio-frequency accelerating structures appropriate for the acceleration of tens of MW of beam power have been designed, built and tested; some structure types are in routinely operating accelerator facilities.
10. Ten to one-hundred fold improvement in long-duration beam trip rates relative to those achieved in routine operation of existing high power proton accelerators is necessary to meet industrial-scale ADS application requirements.
11. The technology available to accelerator designers and builders of today is substantially different from, and superior to, that which was utilized in early ADS studies, in particular in the design which was considered in the 1996 National Research Council report.
12. Spallation target technology has been demonstrated at the 1-MW level, sufficient to meet the "Transmutation Demonstration" mission.

Key Findings from the White Paper Working Group Report

13. With appropriate scaling at each step along a technology demonstration path, there are no obstacles foreseen that would preclude the deployment of spallation targets at a power level (10 to 30 MW) needed to meet the application of ADS at an industrial scale.
14. Technology is sufficiently well developed to meet the requirements of an ADS demonstration facility; some development is required for demonstrating and increasing overall system reliability.
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.

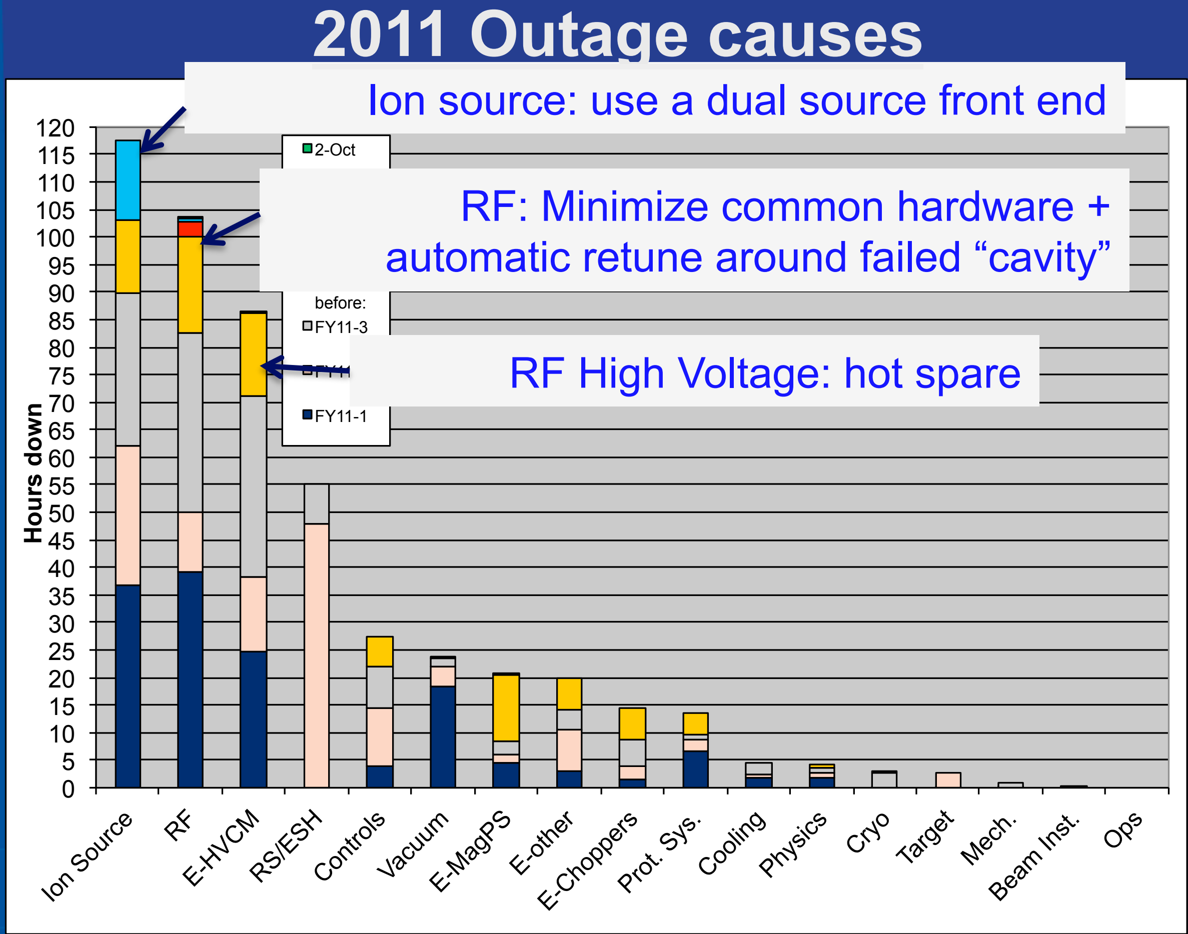
Annual Trip Rate Targets: ADS Development Path

* white paper: " *Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production"*

Trips/year	SNS Experience (2011)	ADS Transmutation Demonstration *	Industrial Scale ADS prototype*	Power Plant – no Energy Storage
t < 1s		NA	25000	25000
1s < t < 10 s	7200	2500	2500	2500
10 s < t < 5 min	3300	2500	2500	250
t > 5 min	550	50	50	3

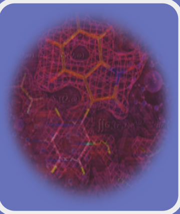
- Considering SNS was not designed to accommodate extremely low trip rates - not so far off !

We Know the SNS Reliability Weaknesses
Direction for ADS attention



- Some remedies are implementable at SNS (dual source front end)
- Others not easy – beyond the design envelope

Applications of High Power Proton Accelerators

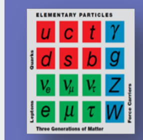


Materials Science

- Neutron Sources
- Muon Sources

Energy & Environment

- Materials Irradiation
- Accelerator Driven Systems

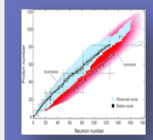


Particle Physics

- Proton Drivers for HEP

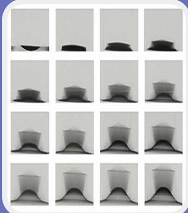
Medicine

- Isotope production



Nuclear Physics

- High-power ISOL
- Neutron, nuclear EDMs



National Security

- Proton Radiography

Applications of Accelerators: Materials Irradiation

- Materials for next generation fission reactors or fusion devices need an order of magnitude greater radiation resistance than those in use today

Zinkle and Busby, Materials Today 12 (2009) 12.

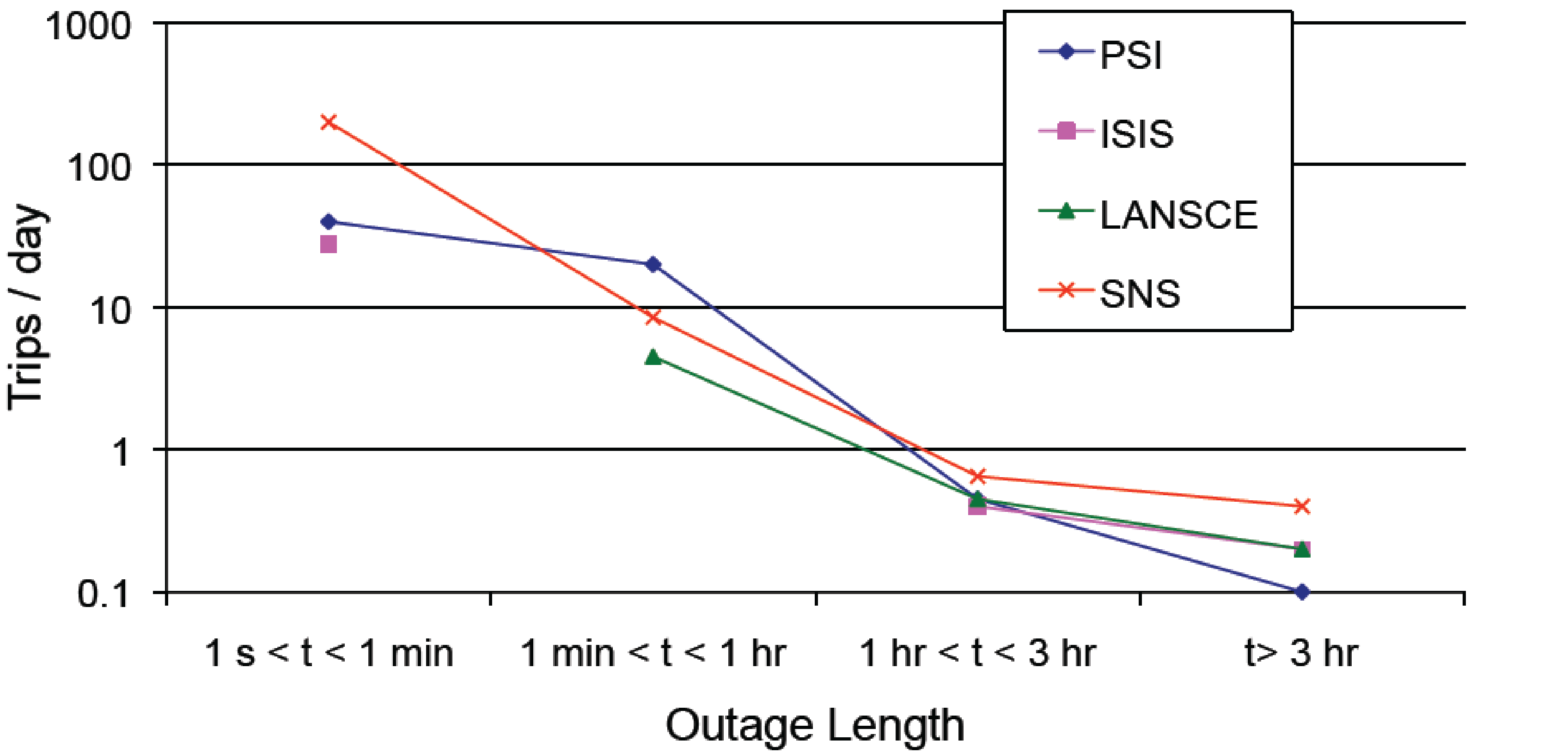
Fission reactors include very-high-temperature reactors (VHTR), supercritical water-cooled reactors (SCWR), gas-cooled fast reactors (GFR), lead-cooled fast reactors (LFR), sodium-cooled fast reactors (SFR), and molten-salt reactors (MSR).

Applications of Accelerators
Materials Irradiation

- Irradiation with energetic particles leads to atomic displacements
  - Atomic displacements leads to microstructural evolution, which results in substantial mechanical and physical property changes.
- Damage regime can be reached by accelerator-driven sources
- Very aggressive accelerator parameters are required to reach 20-40 dpa/yr
  - IFMIF: 250 mA x 40 MeV deuteron accelerator (10 MW beam power) using D-Li stripping
  - MW-class spallation neutron source

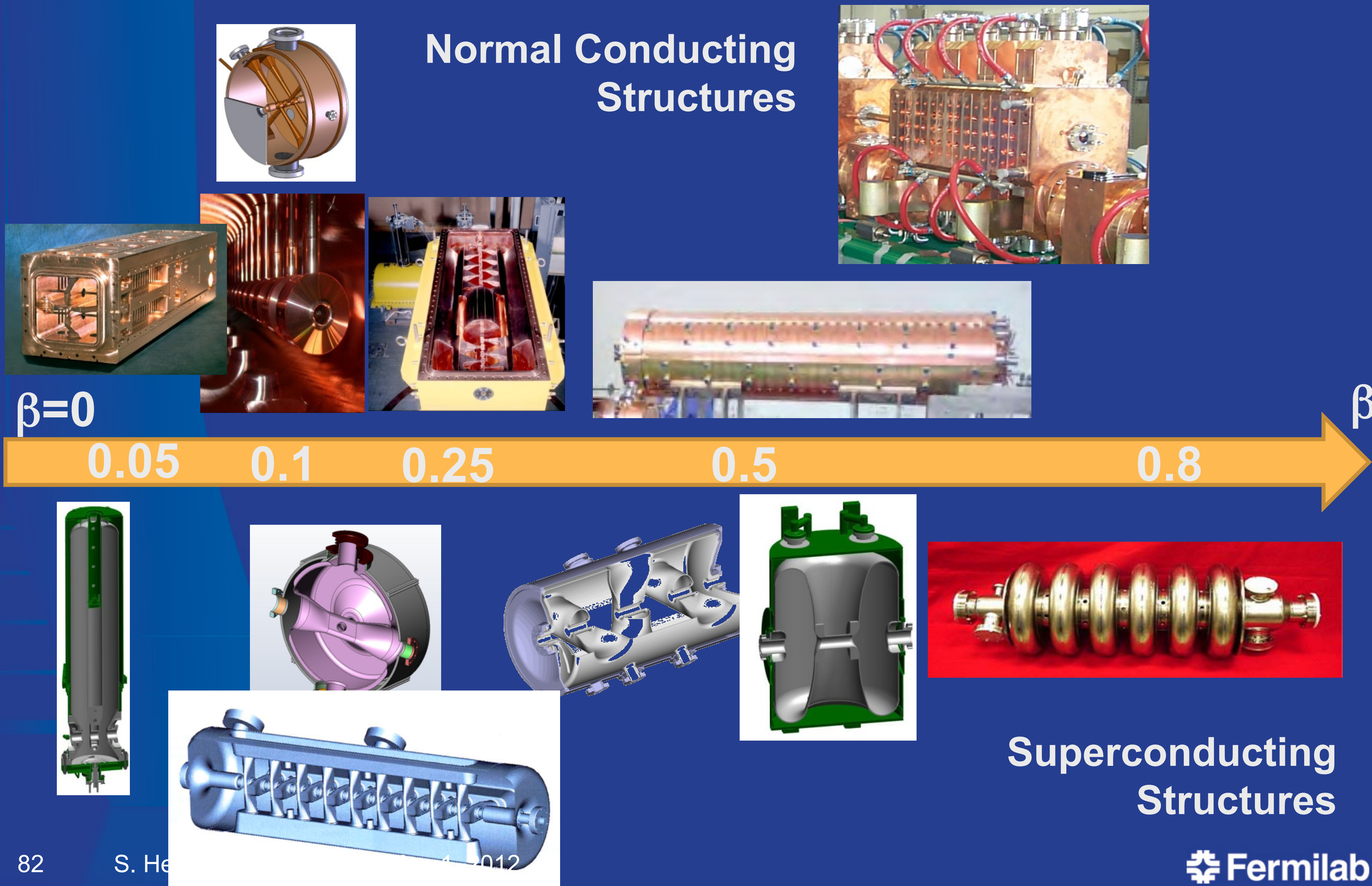
Beam Trip Duration Experience

- It is instructive to look at the experience, but one must keep in mind that operating proton accelerators were not designed for low trip rates



J. Galambos, HB2008, p. 489

A Zoo of RF Structures for β < 1 Acceleration

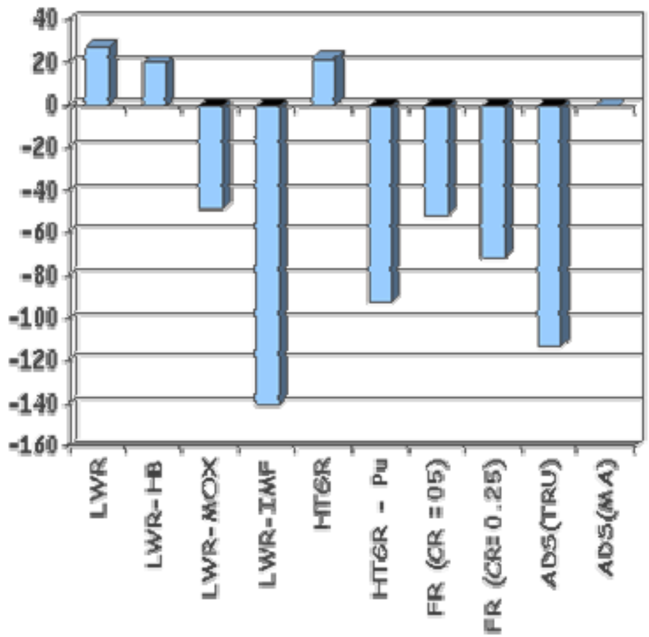


NRC Study (1996) Accelerator Parameters: Based on 1992 Normal-Conducting (coupled-cavity) Linac Design

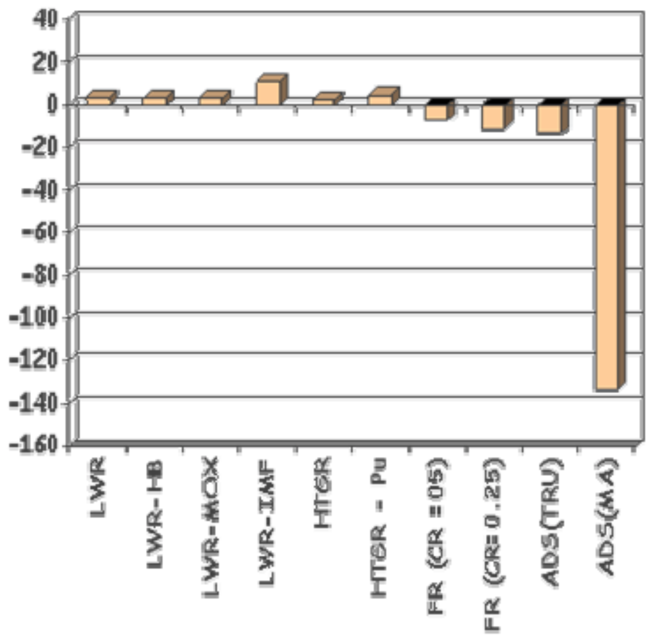
	ATW-1	ATW-2	Present Day
Beam Energy [MeV]	1600	800	1500
Beam Power [MW]	400	88	75
Accelerating Gradient	1 MV/m	1 MV/m	20 MV/m
Linac Length	1900 m	1000m	300 m

M. Cappiello, "The Potential Role of ADS in the U.S."

The ADS is most efficient at Minor Actinide Transmutation

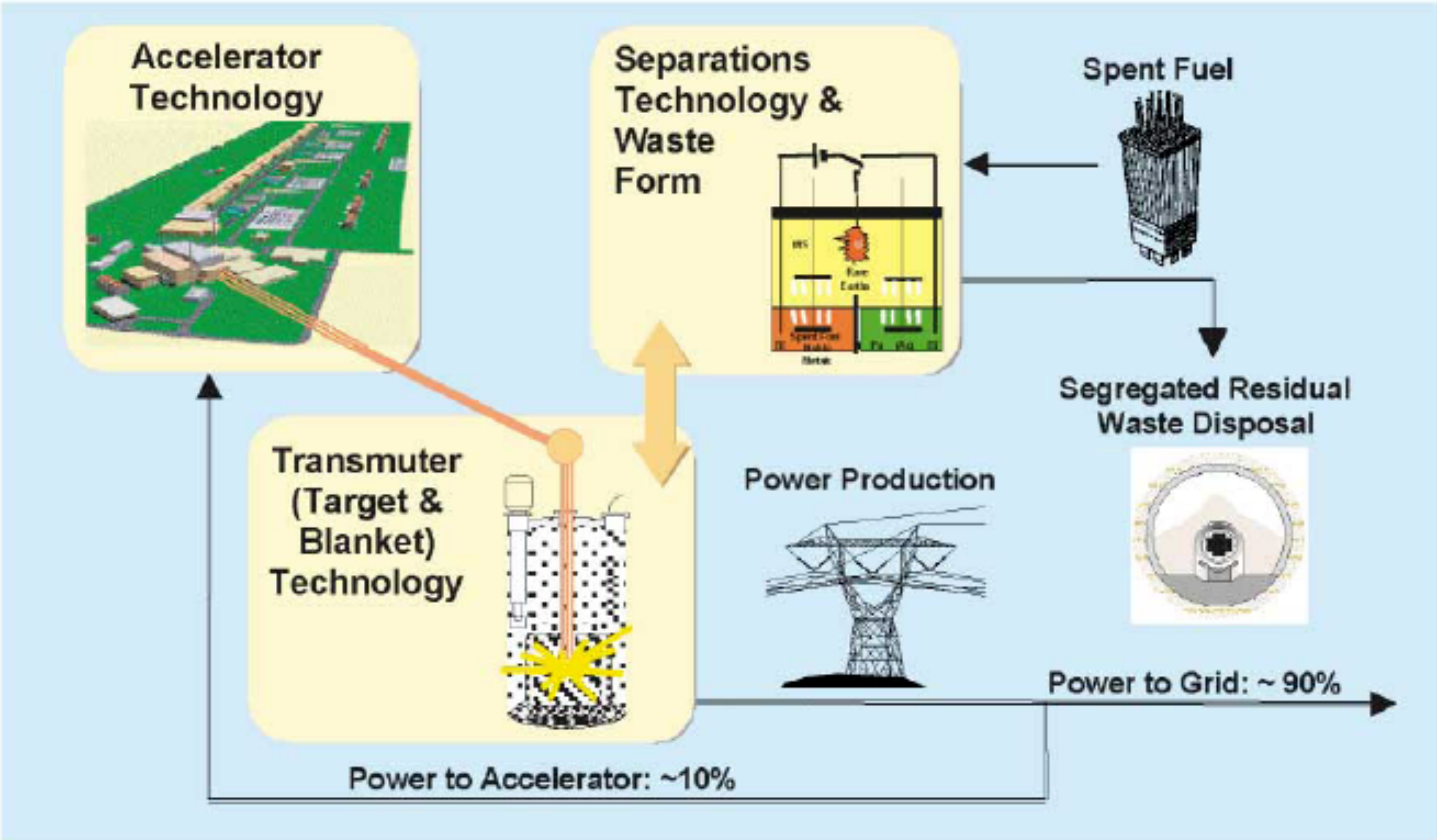


Pu Production Rate (grams / GWh)



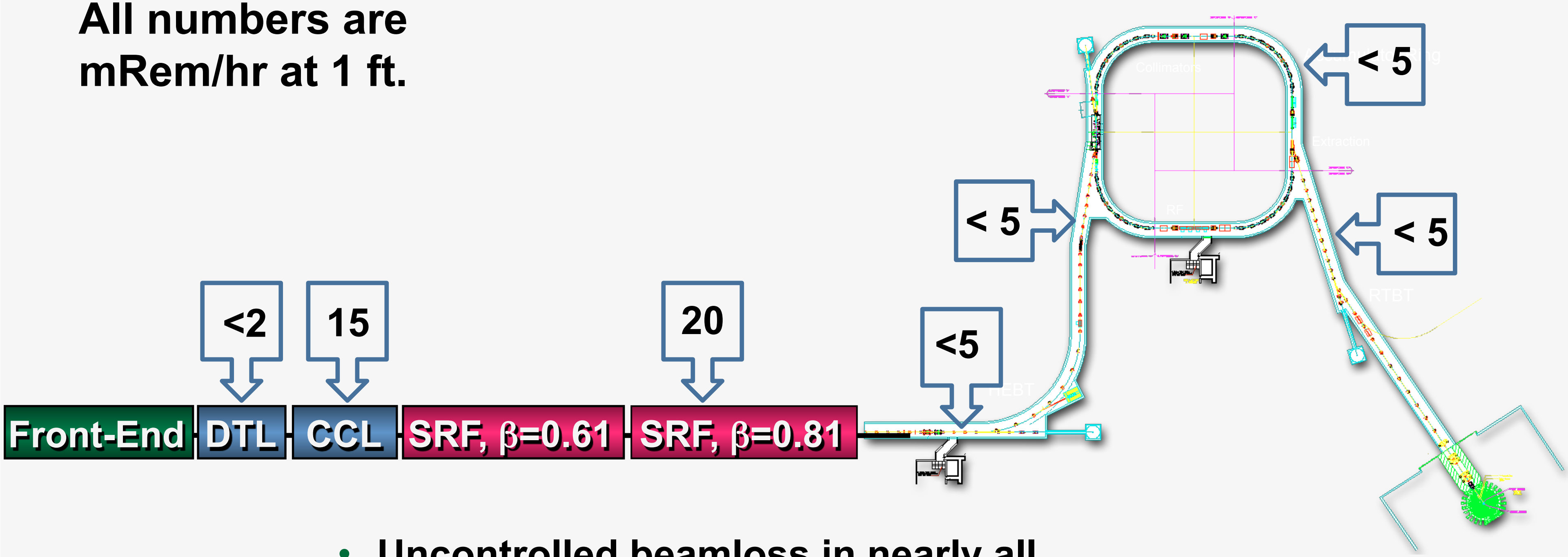
MA Production Rate (grams / GWh)

Components of an Accelerator Transmutation of Waste System



Beamloss: SNS Residual Activation after 1 MW Operation (Average by Region)

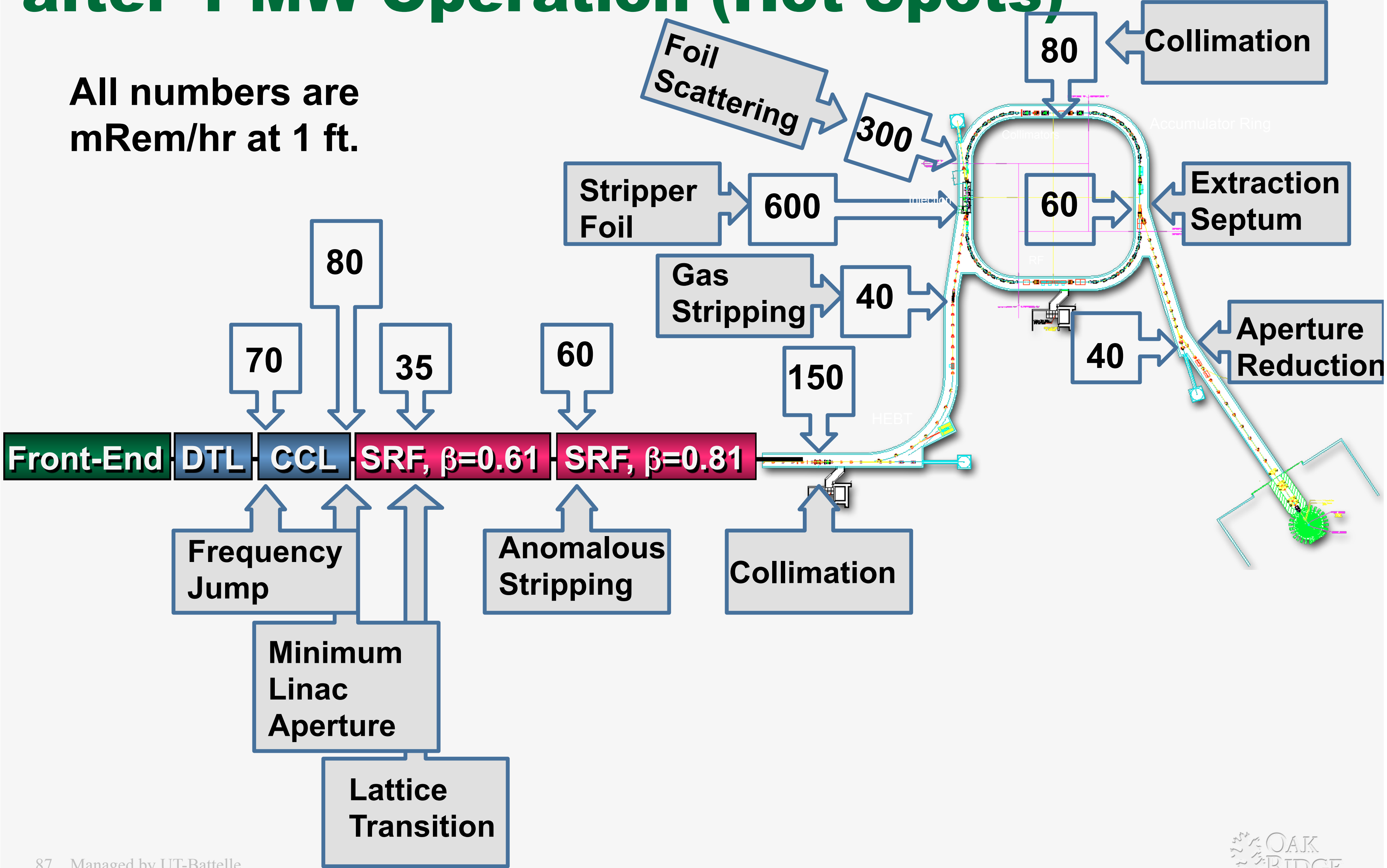
All numbers are mRem/hr at 1 ft.



- **Uncontrolled beamloss in nearly all regions of the accelerator is in line with expectations (< 1 W/m) at ~1 MW operation**
- **The SNS has not been limited by beam loss for ~2 years**

Beamloss: SNS Residual Activation after 1 MW Operation (Hot Spots)

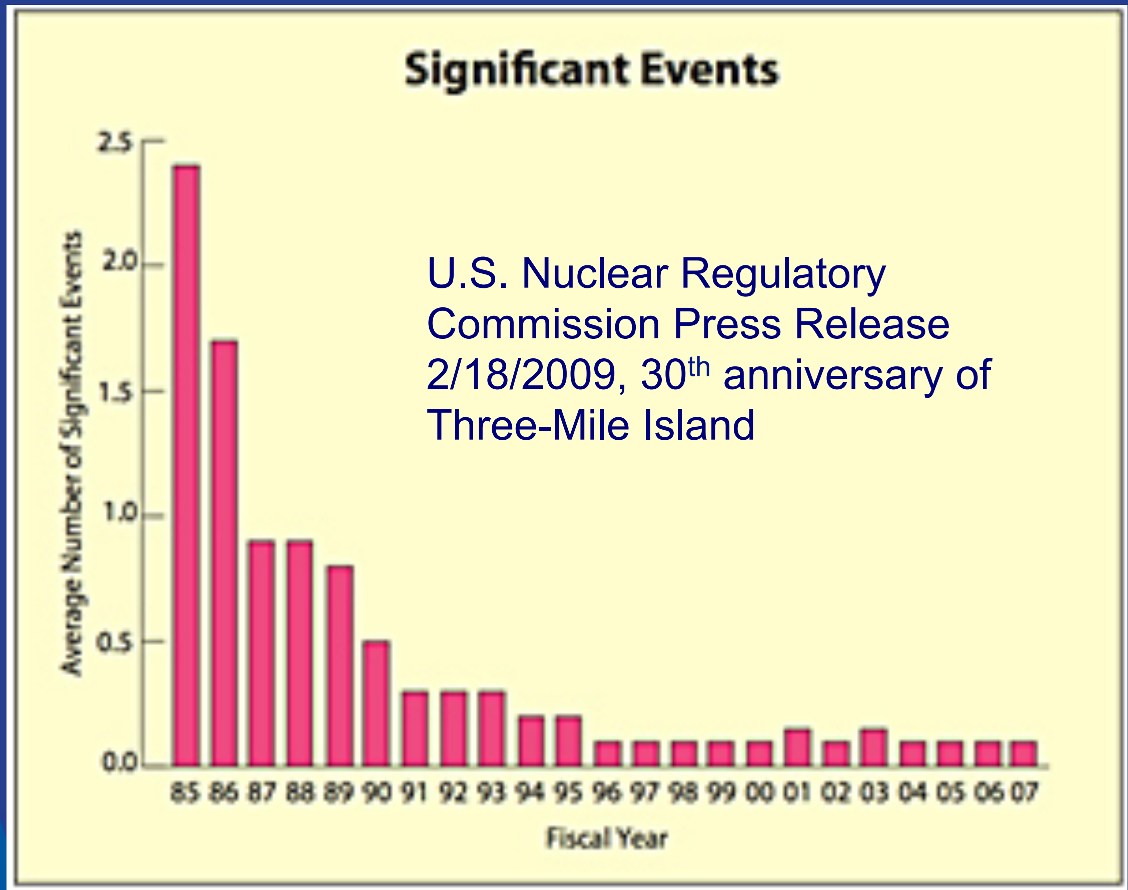
All numbers are mRem/hr at 1 ft.



Accelerator Technology – Existing Parameter Sets

	Transmutation Demonstration (MYRRHA [5])	Industrial Scale Facility driving single subcritical core (EFIT [10])	Industrial Scale Facility driving multiple subcritical cores (ATW [11])
Beam Energy [GeV]	0.6	0.8	1.0
Beam Power [MW]	1.5	16	45
Beam current [mA]	2.5	20	45
Uncontrolled Beamloss	< 1 W/m	< 1 W/m	< 1 W/m
Fractional beamloss at full energy (ppm/m)	< 0.7	< 0.06	< 0.02

Are Reactors Unsafe?



The White Paper

- In June 2010 DOE Office of Science tasked a Working Group with producing a White Paper assessing accelerator and target technology for Accelerator-Driven Systems (ADS)
- The White Paper was intended to make a hard-nosed assessment, addressing
  - the technical requirements for ADS
  - status and readiness of the technology
  - the R&D necessary to meet the requirements

…and to answer two underlying questions:

- Do the advances that have been made in Accelerator Technology in the last 10-15 years change the practicality of ADS?
- Is the technology to the point where a demonstration program is warranted?

The White Paper

"Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production"

http://www.science.doe.gov/hep/files/pdfs/ADSWhitePaperFinal.pdf

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- George Lawrence, LANL, retired
- Tom McManamy, ORNL
- Alex Mueller, CNRS-IN2P3
- Sergei Nagaitsev, FNAL
- Jerry Nolen, ANL
- Eric Pitcher*, LANL
- Bob Rimmer, TJNAF
- Richard Sheffield, LANL
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