Report of AAF & AHIPA

Y. Mori

Kyoto Univ., Res. React. Inst.

Workshop on Applications of High Intensity Proton Accelerator

NOv. 20-22, 2009, FNAL

workshop on AHIPA

Workshop on Applications of High Intensity Proton Accelerators

October 19-21, 2009
Fermi National Accelerator Laboratory, Batavia, IL, USA

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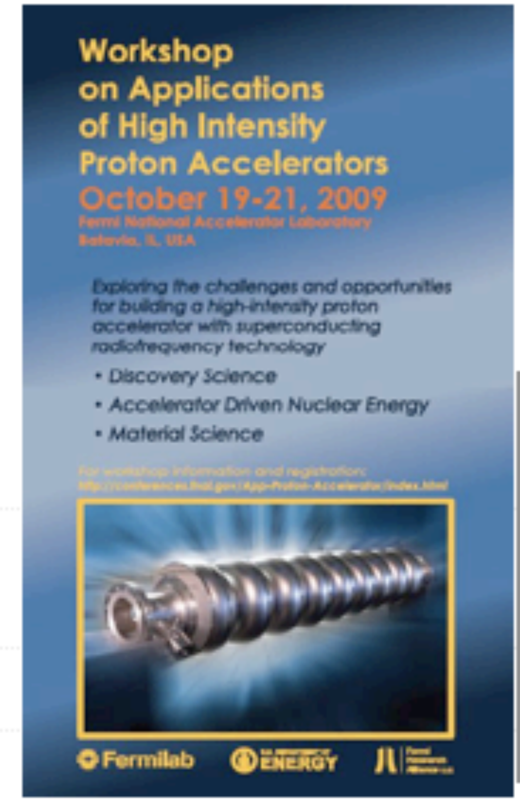
Welcome to the Workshop on Applications of High Intensity Proton Accelerators home page

Recent advances in superconducting rf technology have made possible the construction of high-intensity proton accelerators (10 Milliamp current or higher) at energies exceeding 1 GeV. Fermilab is developing a design of a High Intensity Proton Linac (Project-X) to support future High Energy Physics Programs. The workshop proposes to bring together researchers working in areas as diverse as

- Production of high intensity proton beam for Neutrino, Muon and Kaon Physics ,Muon Collider and Neutrino Factory
- Accelerator based solutions to Nuclear Energy and Transmutation of waste including Accelerator Driven Subcritical Systems
- Nuclear and Material Science and Material Production



Fermilab's future accelerator R&D program is focused on SRF Linac for Project-X, ILC, and any future machine. The present design of the Project-X linac is to provide 2 MWatt of pulsed beam power at 8 GeV. The workshop will cover topics related to challenges in the design of high-power CW and pulsed linear accelerators, targetry as well as design of systems to collect pions to achieve muon beams leading to a neutrino factory. The workshop is timed to enable the design of Project-X and other projects (SPL,...) to give due consideration to these future upgrade possibilities.

The proposed workshop is to focus ONLY on SRF Linac approaches and how it can be used (or have enough design hooks) for future accelerator applications. We want to discuss this in the light of our present program.

We encourage you to register and make your travel plans early as the number of rooms we have reserved in the local hotel is limited.

We look forward to seeing you in Fermilab.

Organized by: University of Illinois at Chicago | Fermilab | Illinois Institute of Technology | Argonne National Laboratory | University of Illinois at Urbana-Champaign | Northern Illinois University | Northwestern University | Fermi Research Alliance, LLC | University of Chicago

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working groups

Science:

•WG1: SRF Linac for Neutrino, Muon and Kaon Physics
Charge– Investigate the use of a multi megawatt proton linac for neutrino, muon and kaon physics.

•WG2: SRF Linac for Muon Collider and Neutrino factory
Charge—Investigate the use of a multi megawatt proton linac to target, phase rotate and collect muons for muon collider and neutrino factory.

Energy:

•WG3: SRF Linac driven subcritical systems (ADS)
Charge—Work out the parameters of a proton linac that is suitable for ADS applications. Investigate pulse structure, beam power, accelerator reliability issues.

•WG4: SRF Linac driven subcritical core
Charge—Examine target issues, reactor design options, feedback to the accelerator, core safety issues, core power.

Nuclear and Material Science and Material Production:

•WG5: Nuclear and Material Science and Material Production
Charge—Investigate the use of a high intensity proton accelerator for nuclear and material science and material production. Investigating the issues of radiation hardness. Specific areas to be addressed are neutrino factory targetry, ADS Reactor interface. Survey the existing knowledge of materials and their radiation hardness.

Accelerator:

•WG6: Project X SRF Linac parameter working group
Charge—Investigate common accelerator parameters with WG1-WG5.

Fermilab SRF Linac Development

Steve Holmes

Workshop on High Intensity Proton Accelerators
October 19, 2009

U.S. DEPARTMENT OF ENERGY

Fermilab

Outline

- Strategic Context/Evolution of the Fermilab Complex
- Project X Goals and Initial Configurations
- Research, Design, and Development Plan
- Relationships to other Programs

Project X website: http://projectx.fnal.gov/

Strategic Context: Fermilab and the World Program

Fermilab currently operates the highest energy collider, and the highest power long baseline neutrino beam, in the world.

Strategic Context: Fermilab and the World Program

Fermilab currently operates the highest energy collider, and the highest power long baseline neutrino beam, in the world.

In 2009:

- **LHC will capture the energy frontier**
- **J-PARC will initiate a competitive neutrino program**

Evolution of the Fermilab Accelerator Complex

- A multi-MW Proton Source, Project X, is the linchpin of Fermilab's strategy for future development of the accelerator complex.
- Provides long term flexibility/opportunities
  - Energy Frontier:

    Tevatron → ILC or Muon Collider

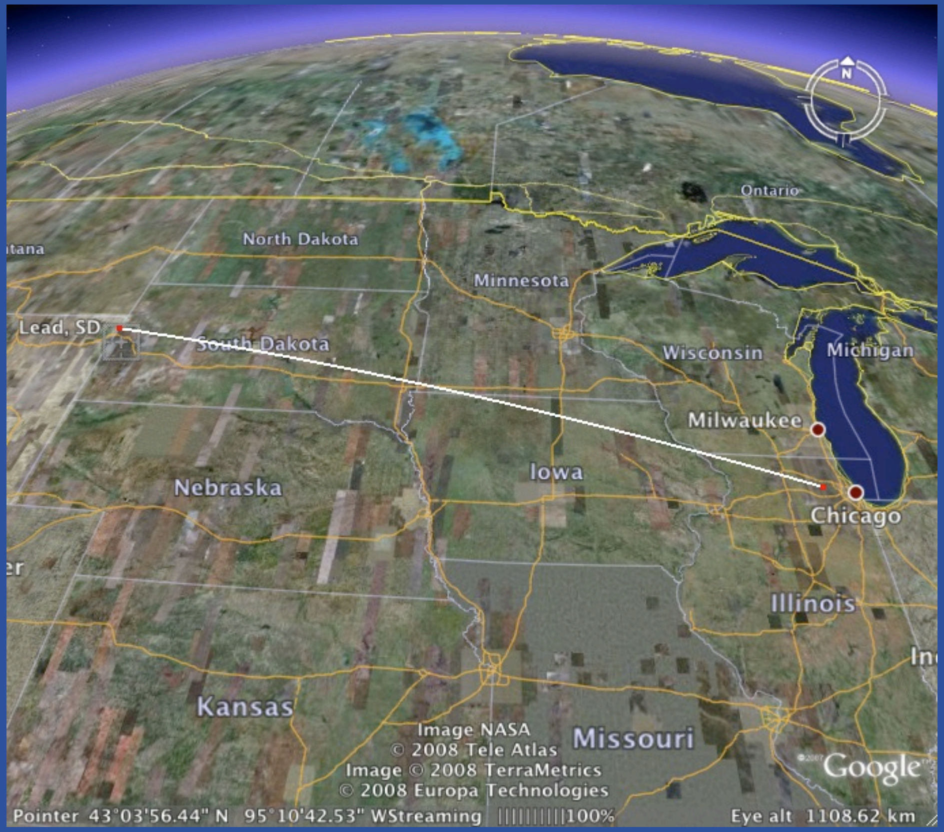
    - Technology alignment
    - Fermilab as host site for ILC or MC
  - Intensity Frontier:

    NuMI→ NOνA→ LBNE/mu2e→ PX → NuFact

    - World leading program in neutrino physics and other beyond the standard model phenomena

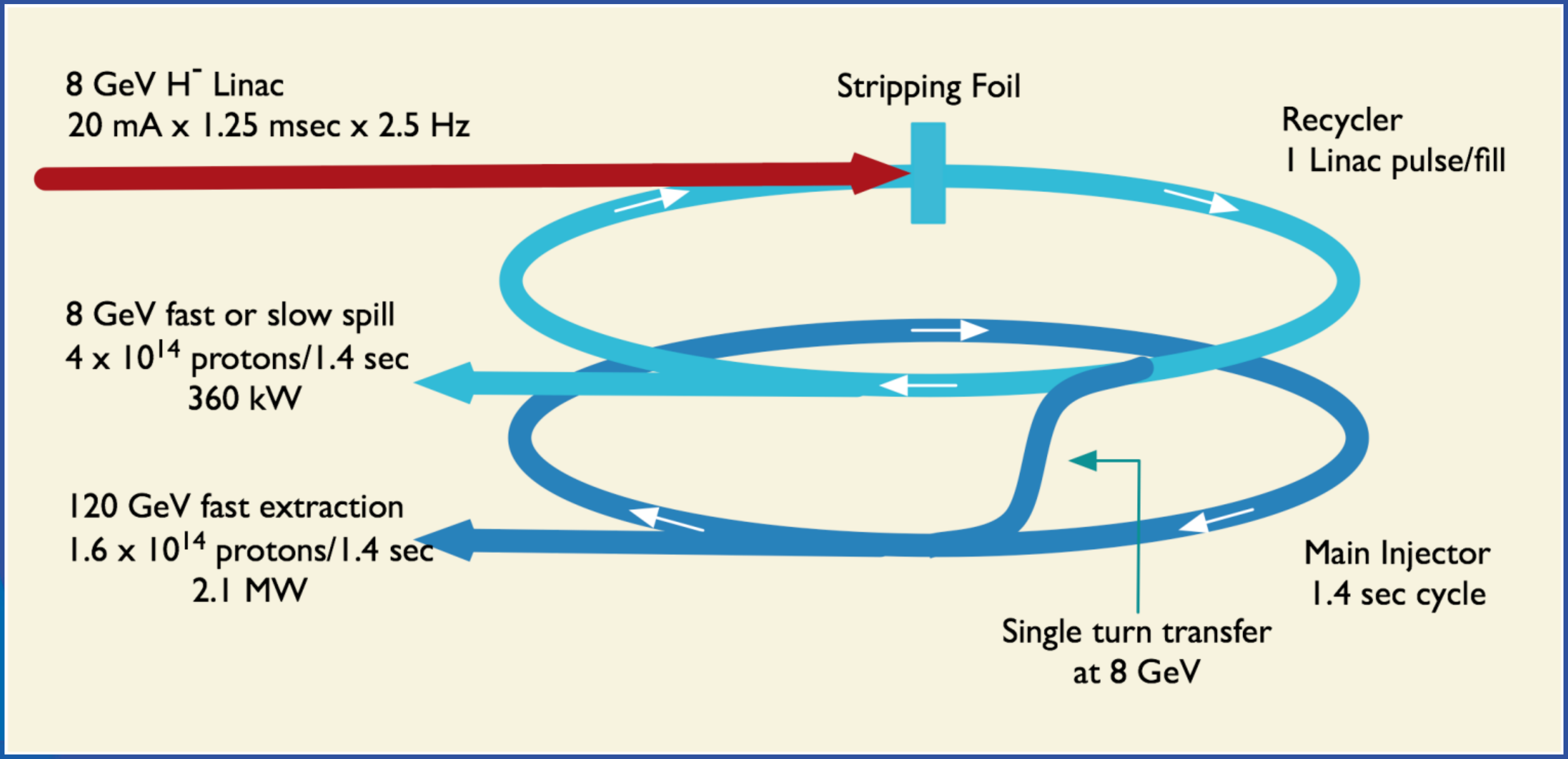
Mission Need

- Mission need for a multi-MW proton source (P5):
  - Long baseline neutrino oscillation experiments
    - ➢2 MW proton source at 60 - 120 GeV
  - High intensity, low energy precision experiments with kaons and muons
    - ➢Few × 100 kW simultaneous with neutrino operations
  - Platform for a future muon Facility – Neutrino Factory or Muon Collider
    - ➢Upgrade potential to 2-4 MW at ~5 - 15 GeV.



Initial Configuration-1

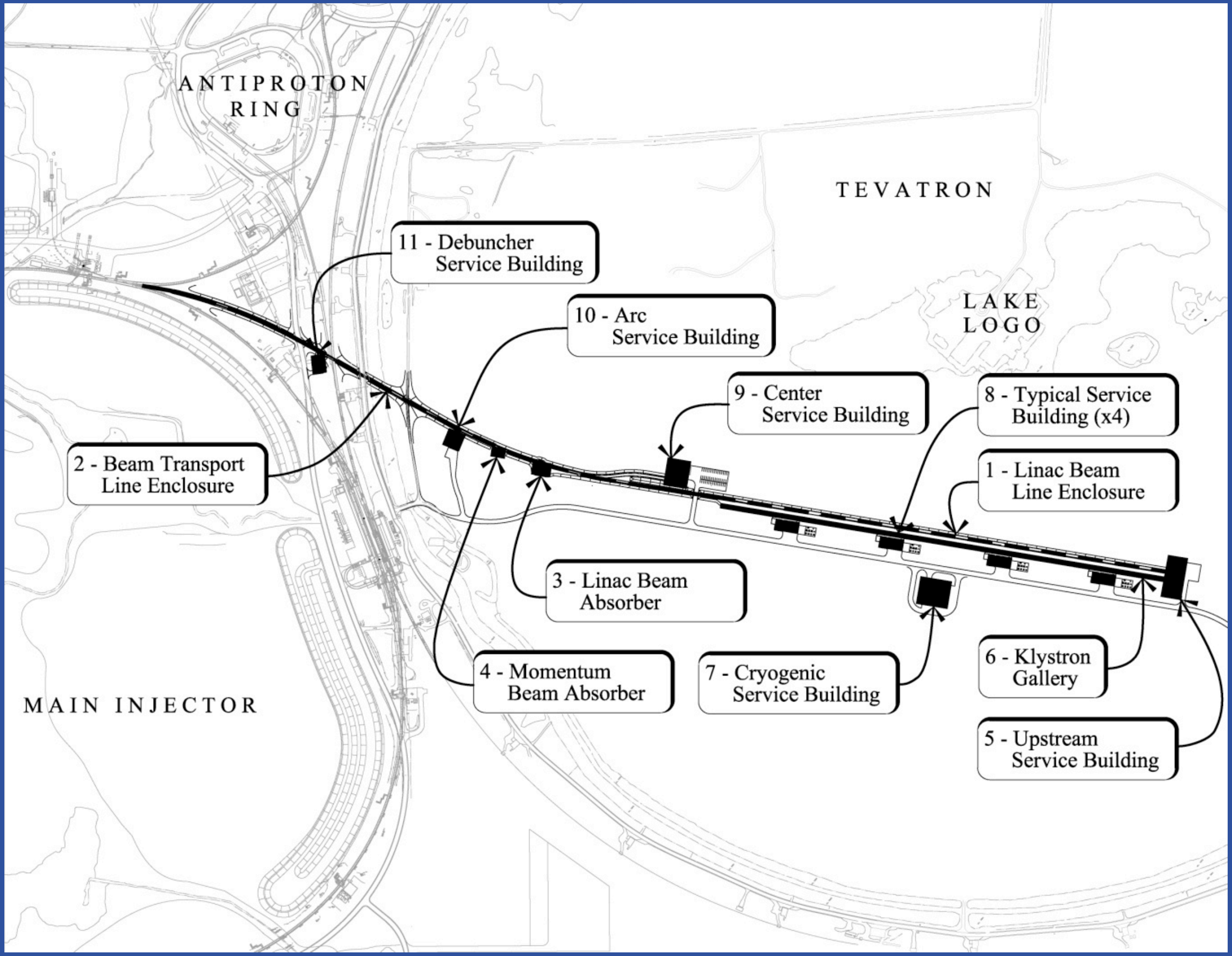
- Project X Design Criteria
  - >2 MW of beam power over the range 60 – 120 GeV;
  - Simultaneous with >150 kW of beam power at 8 GeV;
  - Compatible with future upgrade to 2-4 MW at 8 GeV



Initial Configuration-1 Performance Goals

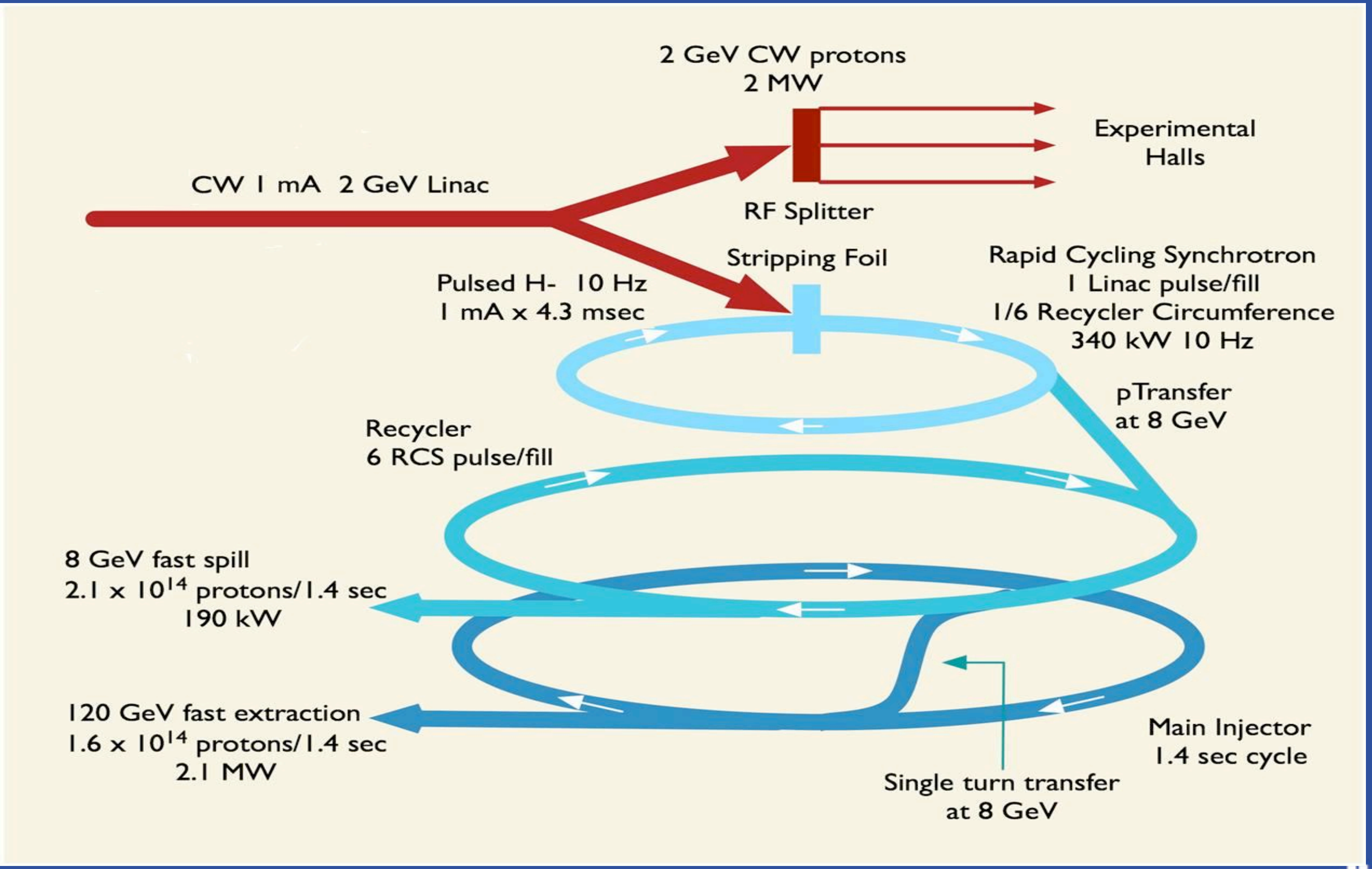
Linac		
Particle Type	H^-	
Beam Kinetic Energy	8.0	GeV
Particles per pulse	1.6×10^{14}	
Linac pulse rate	2.5	Hz
Beam Power	500	kW
Recycler		
Particle Type	protons	
Beam Kinetic Energy	8.0	GeV
Cycle time	1.4	sec
Particles per cycle to MI	1.6×10^{14}	
Particles per cycle to 8 GeV program	1.6×10^{14}	
Beam Power to 8 GeV program	360	kW
Main Injector		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.4	sec
Particles per cycle	1.6×10^{14}	
Beam Power at 120 GeV	2100	kW

Initial Configuration-1
Provisional Siting



Initial Configuration - 2

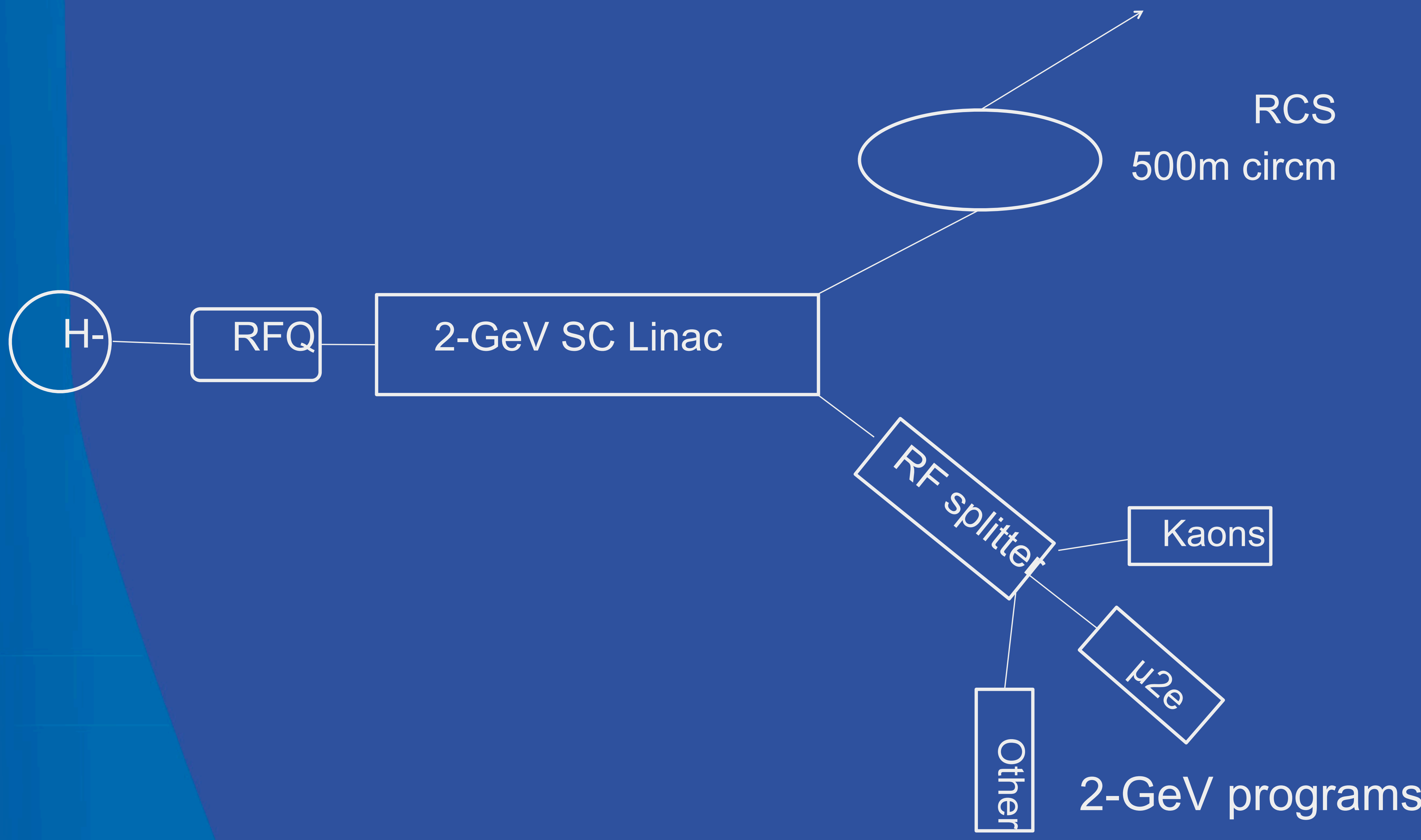
- Project X Design Criteria
  - 2 MW of beam power over the range 60 – 120 GeV;
  - Simultaneous with 2 MW beam power at 2 GeV;
  - Compatibility with future upgrades to 2-4 MW at 8 GeV



Initial Configuration-2 Performance Goals

Linac		
Particle Type	H^-	
Beam Kinetic Energy	2.0	GeV
Average Beam Current	1.0	mA
Linac pulse rate	CW	
Beam Power	2000	kW
Beam Power to 2 GeV program	1920	kW
RCS		
Particle Type	protons	
Beam Kinetic Energy	8.0	GeV
Cycle time	0.1	sec
Particles per cycle to MI	2.6×10^{13}	
Beam Power to 8 GeV program	200	kW
Main Injector/Recycler		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.4	sec
Particles per cycle	1.6×10^{14}	
Beam Power at 120 GeV	2100	kW

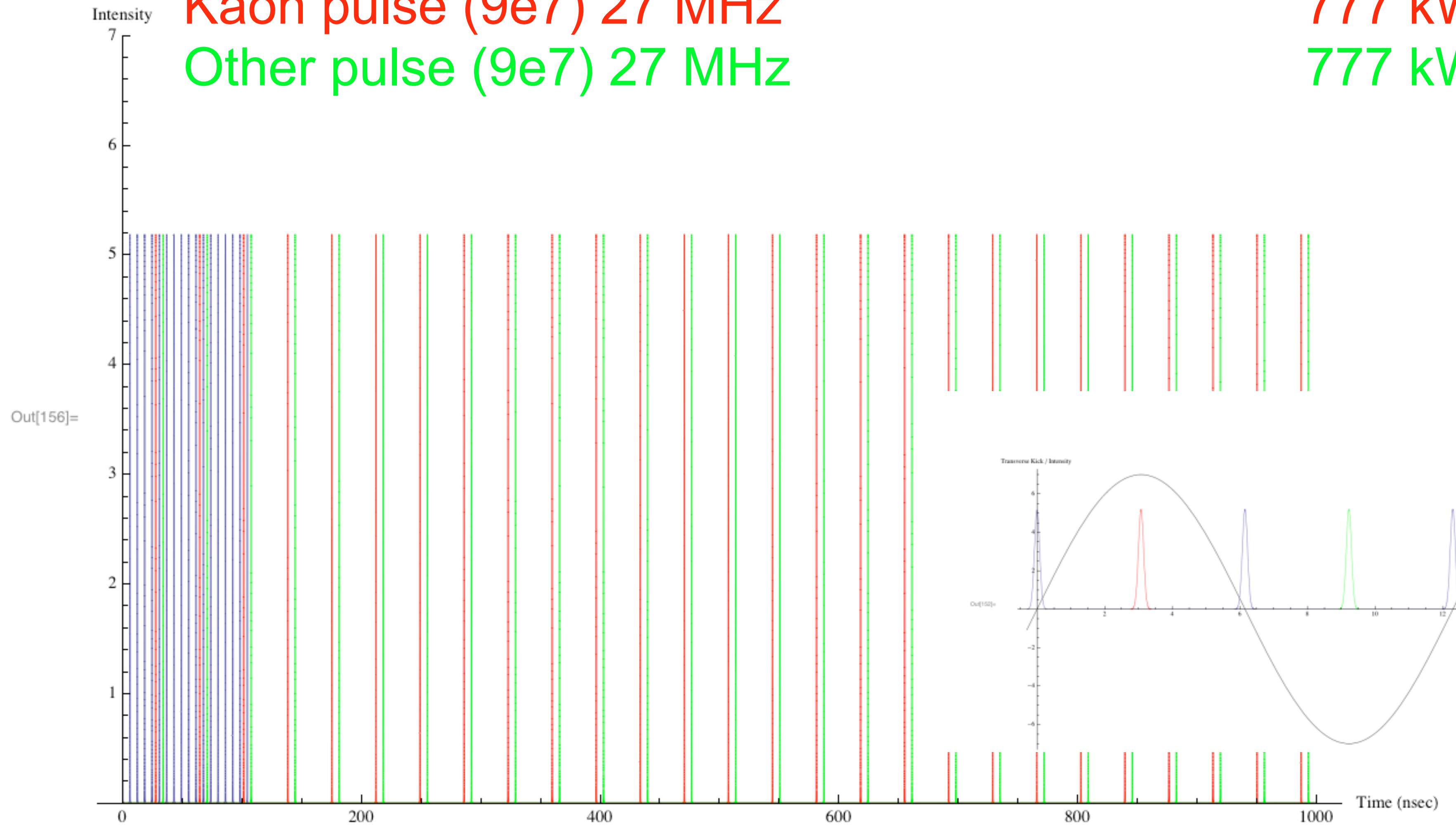
Initial Configuration-2



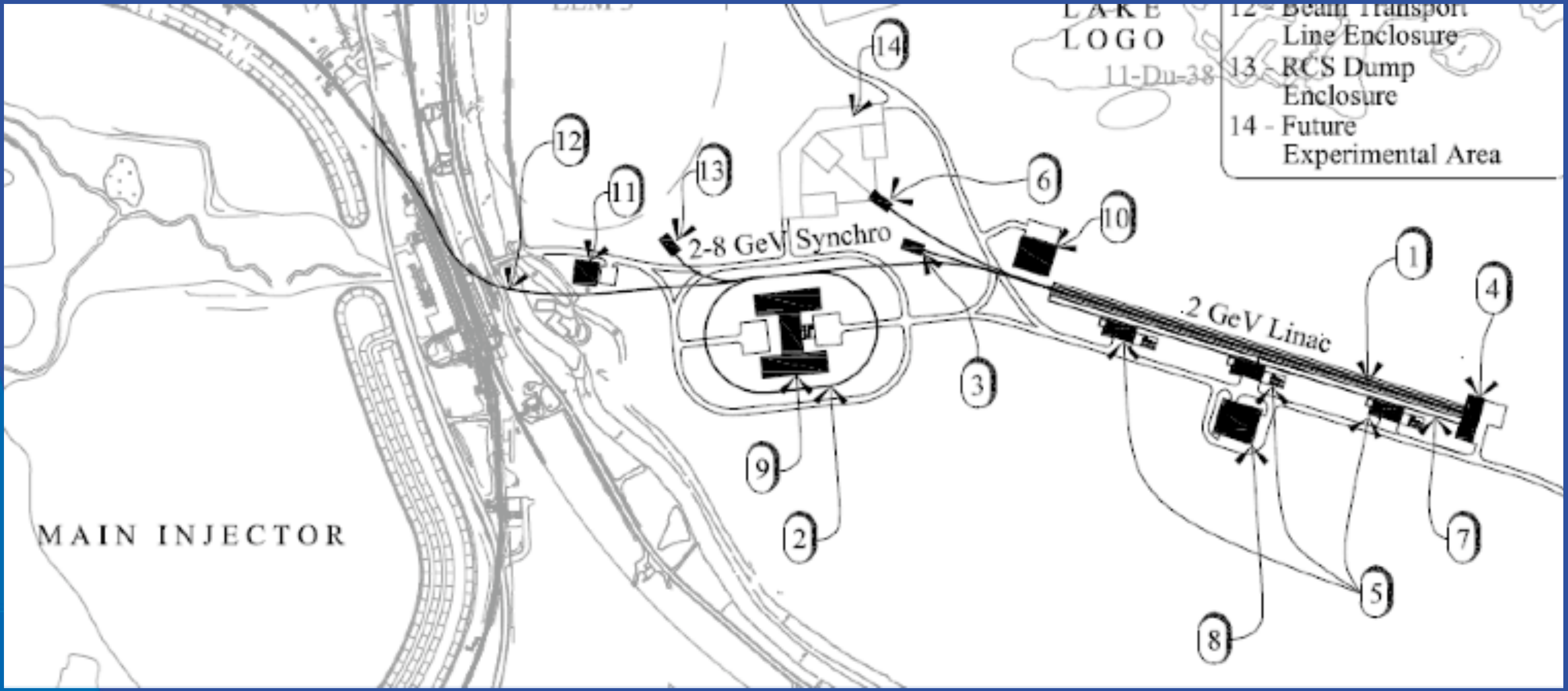
Initial Configuration-2
Operating Scenario

1 μsec period at 2 GeV

mu2e pulse (9e7) 162.5 MHz, 100 nsec	518 kW
Kaon pulse (9e7) 27 MHz	777 kW
Other pulse (9e7) 27 MHz	777 kW



Initial Configuration-2
Provisional Siting



Near-term Strategy

- Develop an Initial Configuration Document
  - Meeting the high level design criteria
  - Released V1.1, March 2009: available at http://projectx.fnal.gov/
- Revise/update the current RD&D Plan
  - Based on the ICD-1
  - Released V2.2, March 2009 following mid-February AAC evaluation
- Create a preliminary cost range estimate
  - Based on the ICD-1
  - Complete and subject of Director's Review March 16-17, 2009

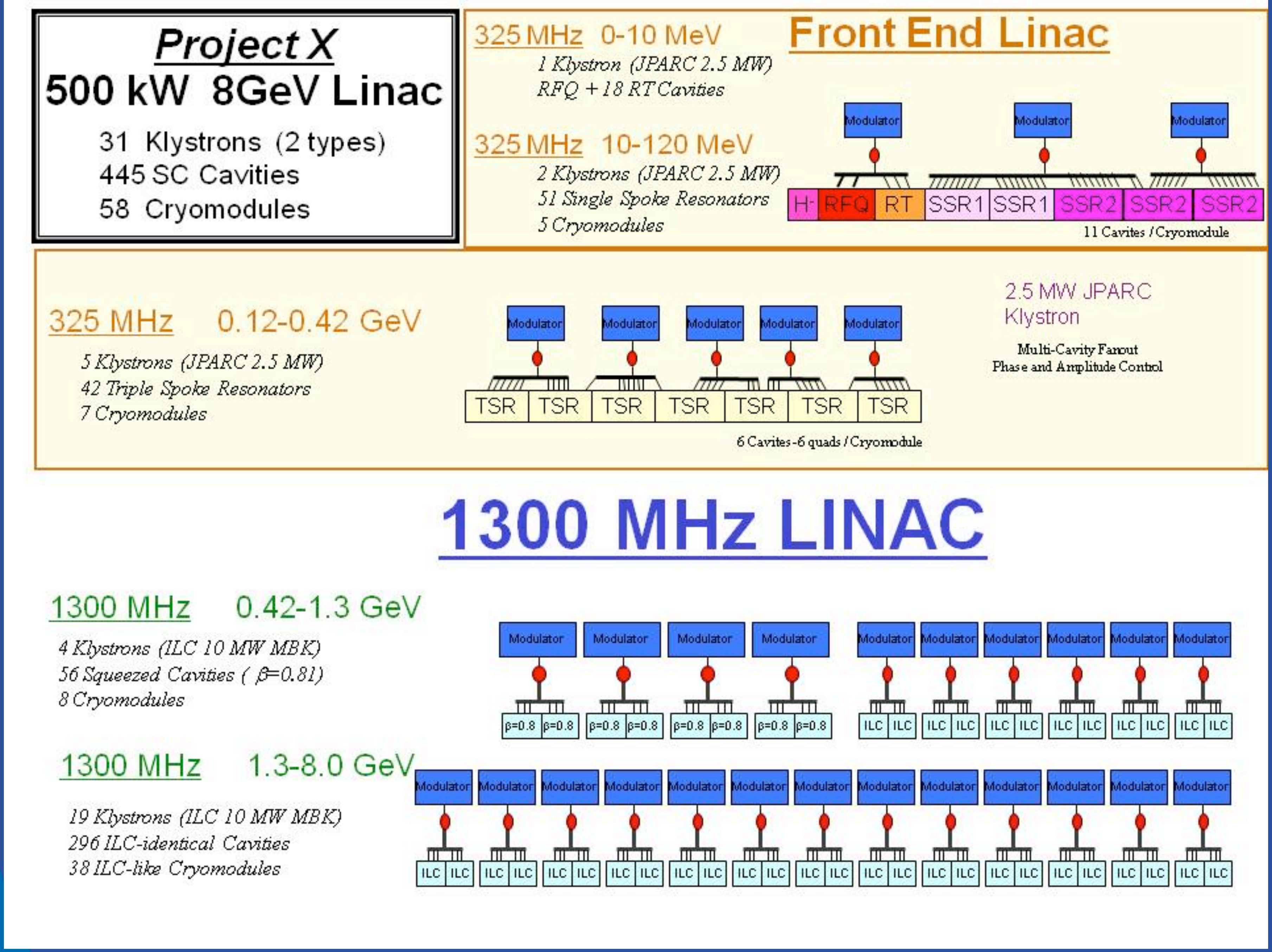
Near-term Strategy

- Establish design criteria and operating scenarios for alternative configurations
  - Alternative configuration (ICD-2) under development
- Establish a multi-institutional collaboration for the RD&D phase
  - Collaboration established
- CD-0 in 2010
  - Based on: ICDs, preliminary cost estimates, P5 mission definition
  - Coordinated with very long baseline (LBNE) and mu2e

Research Design and Development (RD&D) Plan

- Primary goal is to complete a fully developed baseline scope, cost estimate, and schedule in 2012-13 (CD-2).
  - Design and technical component development;
  - Undertaken by a multi-institutional collaboration capable of executing both the RD&D plan and the follow-on construction project
- Secondary goals:
  - Coordinate Project X and ILC SCRF development programs;
  - Retain alignment with Neutrino Factory and Muon Collider programs

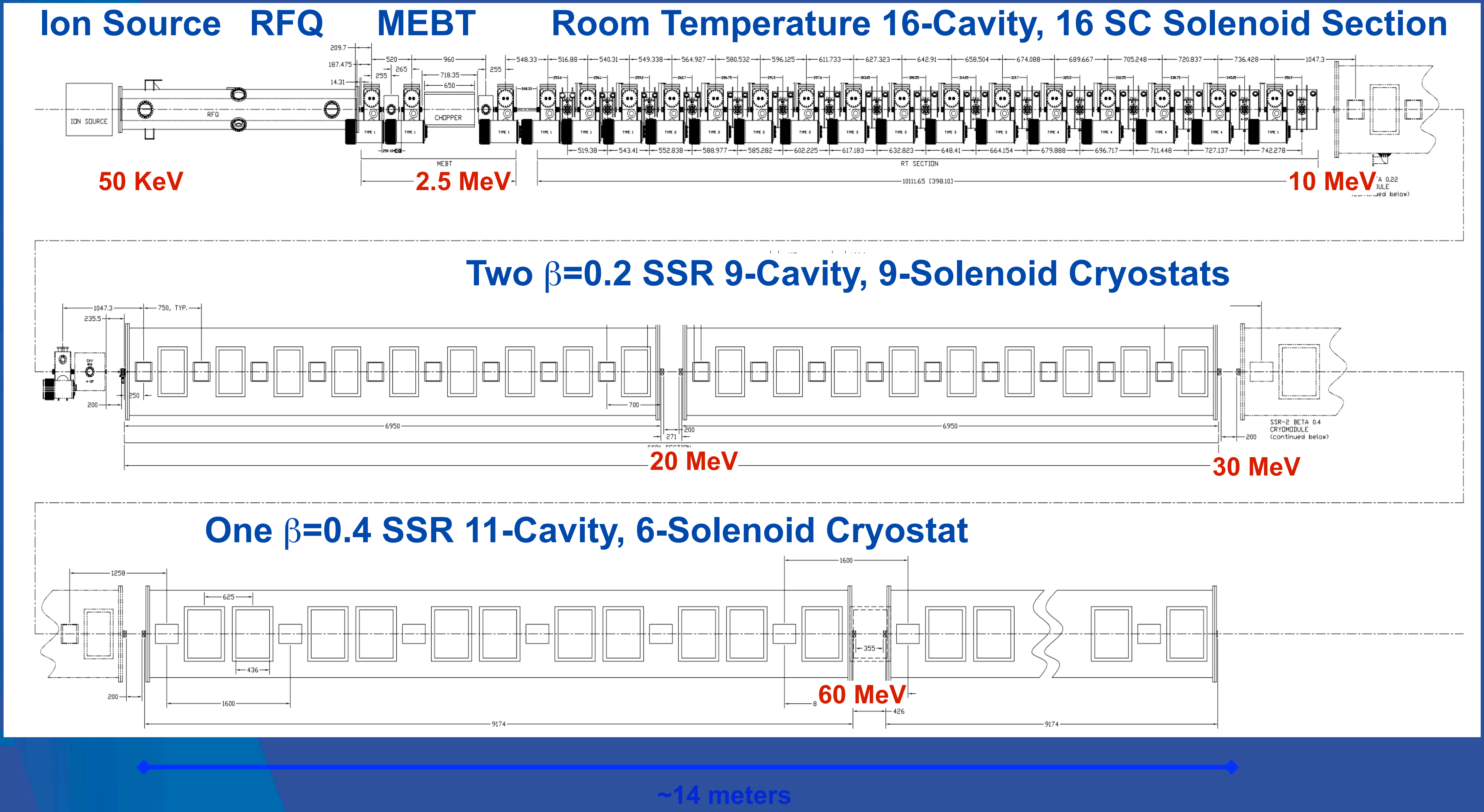
Technology Map (ICD-1)



Joint PX/HINS Strategy

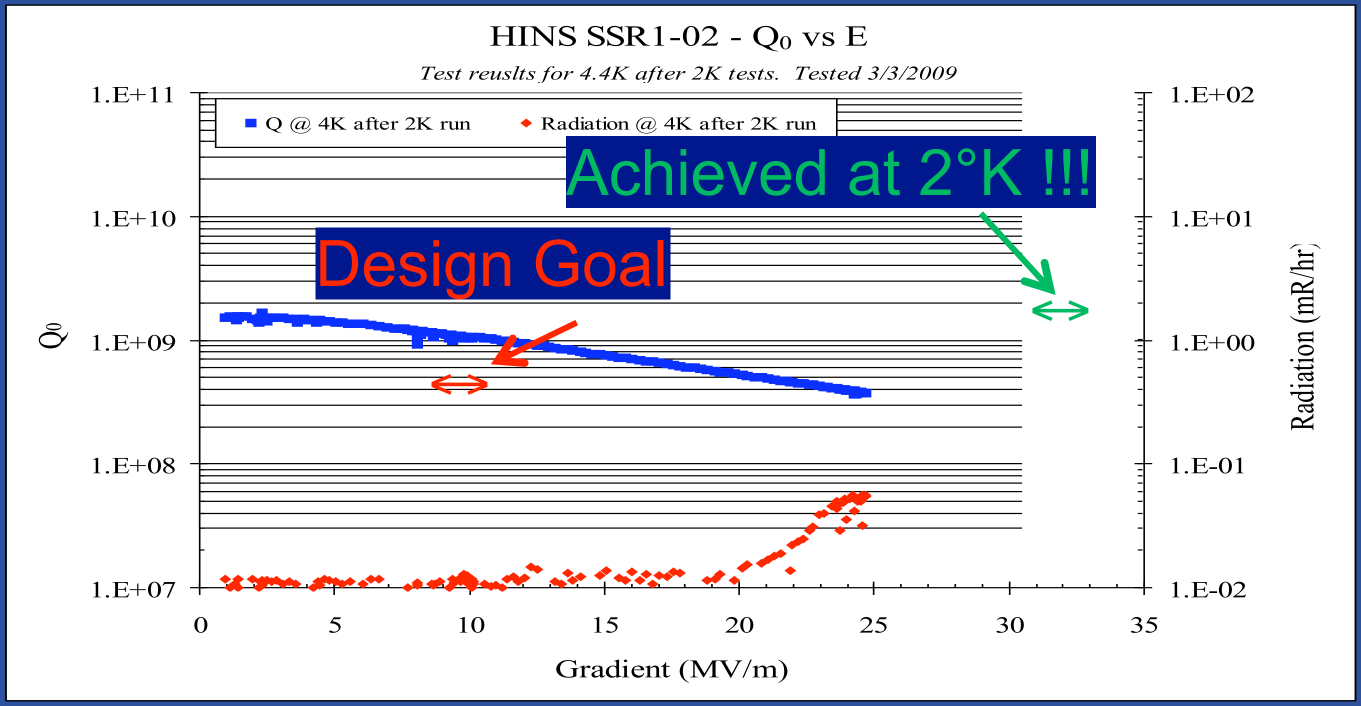
- The High Intensity Neutrino Source (HINS) program was established to pursue a new approach to high intensity, low energy ion acceleration.
- HINS is a candidate for the Project X front end.
  - Designed for 27 mA x 1 msec x 10 Hz
- Primary goals:
  - Accelerate axially symmetric beam (solenoidal focusing) to 30 MeV, utilizing superconducting rf technology beyond 10 MeV
  - Demonstrate vector modulators for phase/amplitude control of individual cavities fed by a common rf source
  - Demonstrate high-speed (nsec) beam chopping at 2.5 MeV
- Goal is to complete facility (@30 MeV) in ~2012

Joint PX/HINS Strategy



HINS Status

- Ion source (H+) installed and operating
- RFQ received and under rf testing
- Room temperature spoke resonators tested
- Prototype VMs tested
- Two β = 0.22, 325 MHz, SSRs successfully tested
  - Goal: >10 MV/m @ Q0>5E8 @ 4 K



Fermilab

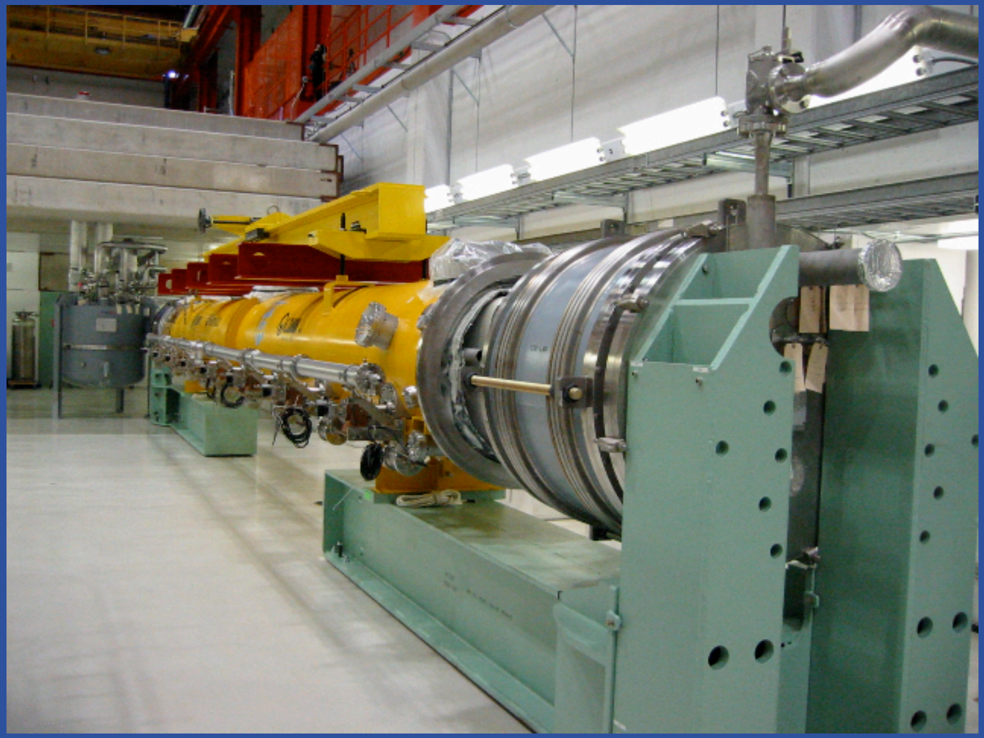
Joint PX/ILC/SRF Strategy

- Project X shares 1.3 GHz technology with ILC
  - ICD-1/ICD-2 requires 46/20 ILC-like cryomodules. In detail they will not be identical to ILC:
    - Beam current: (3×ILC charge/pulse, ICD-1)
    - Focusing required in all CMs
    - Gradient: 25/16 MV/m
- 4 year construction period

  ⇒ 1 CM/month
- Close coordination with GDE
  - Common development effort
  - Shared facilities for assembly and testing
  - Yield vs gradient is key metric

Joint PX/ILC/SRF Strategy

- Industrialization
  - Production of 1 CM/month represents a significant step beyond current capabilities; however, the production rate remains well below that required by ILC.
  - Could represent initial phase of (U.S.) industrialization buildup for ILC
- Cryomodule Assembly Plan
  - CM1: TESLA Type III (2009)
    - DESY supplied cavities
  - CM2: TESLA Type III (2009)
    - U.S. supplied cavities
  - CM3: Type IV.1 (2011)
    - Project X preliminary
  - CM4: Type IV.2 (2012)
    - Project X prototype



Collaboration Plan

- Multi-institutional collaboration established to execute the Project X RD&D Program.
  - Organized as a “national project with international participation”.
    - Fermilab as lead laboratory
    - International participation via in-kind contributions, established via bi-lateral MOUs. (First MOU with India in place)

Collaboration Plan

- (National) Collaboration MOU for the RD&D phase outlines basic goals, and the means of organizing and executing the work. Signatories:

ANL	ORNL/SNS
BNL	MSU
Cornell	TJNAF
Fermilab	SLAC
LBNL	ILC/ART

- Collaborators to assume responsibility for components and sub-system design, development, cost estimating, and potentially construction .

Working Timeline (technically limited)

- FY2010
  - CD-0: Mission Need
  - Initiate work on Conceptual Design Report
- FY2012
  - CD-1: Initial Baseline Range
- FY2013
  - CD-2: Baseline Project
- FY2014
  - CD-3: Initiate Construction
- ~FY2014~2018
  - Construct

Other Synergies

- We are well aware that the technology we are developing is broadly applicable beyond Elementary Particle Physics:
  - Accelerator Driven Energy Systems
  - Rare isotope production for nuclear physics
  - Neutron Sources (e.g. SNS)
  - X-ray FELs
  - Energy recovery linacs
  - Muon facilities for materials research…
- Hence, this workshop

Summary

- Project X is central to Fermilab’s strategy for future development of the accelerator complex:
  - Energy Frontier: Aligned with ILC technology development; Fermilab as potential site for ILC or a Muon Collider
  - Intensity Frontier: World leading program in neutrinos and rare processes; Fermilab as potential Neutrino Factory site
- Initial configurations established
  - >2 MW at 60-120 GeV, simultaneous with up to 2 MW at 2 GeV
- Strong technology synergies with many other applications
- Work done in this workshop will be carried forward into the DOE Accelerators for America Workshop next week

Symp. on Acclerators for America's Future

Oct. 25-27, 2009, Washington

Symp. on AAF

ACCELERATORS FOR AMERICA'S FUTURE

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The Spallation Neutron Source at Oak Ridge National Laboratory helps researchers improve such areas as medicine, material science and agriculture.

The *Symposium on Accelerators for America's Future* will examine the challenges for identifying, developing and deploying accelerators to meet the nation's needs in basic science, medicine, energy and the environment, national security, and industry.

Features

Workshop on Applications of High Intensity Proton Accelerators
October 19-21, 2009
Fermilab, Batavia, IL
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U.S. Particle Accelerator School
By providing specialized accelerators physics and engineering course that are not often available at universities, the USPAS has helped train thousands of students.
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Joint ICFA Advanced Accelerator and Beam Dynamics Workshop
The Physics and Applications of High Brightness Electron Beams 2009
November 16-19, 2009
Read more »

News

Symposium on "Accelerators for America's Future"
Nov. 5, 2009
AIP: FYI
The attendance, as well as the presentations from a diverse range of speakers, demonstrated the great interest there is in the potential of accelerators in areas such as medicine, industrial applications, and energy, as well as in new accelerator technologies.
Read more »

Director's Matters: Big tools for science
Nov. 2, 2009
AIP Matters
These tools of science, which have existed for almost a century, have had considerable impact on both science and the economy in ways that many outside of the physics community are unaware.
Read more »

Symposium on Accelerators for America's Future

October 26, 2009
Washington Marriott
Wardman Park,
Washington DC

Sponsored by the Office of High Energy Physics of the US Department of Energy's Office of Science

Chairs: Walter Henning, Argonne Distinguished Fellow, ANL and Charles Shank, Director, LBNL (Retired)

Exploring the challenges and opportunities for the development of accelerators to meet the nation's needs in:

- Discovery Science
- Medicine and Biology
- Industrial Applications and Production
- Energy and Environment
- National Security

Agenda, Slides and Videos

Working group

- WG1:Discovery Science
- WG2:Medicine and Biology
- WG3:Industrial Applications and Production
- WG4:Energy and Environment
- WG5:National Security

ACCELERATORS FOR AMERICA'S FUTURE

Energy and Environment Working Group

Stuart Henderson, ORNL
Steve Holmes, FNAL
October 27, 2009

U.S. DEPARTMENT OF ENERGY

Working Group Membership

Andrzej Chmielewski, Inst. Nuc. Chem., Warsaw

William Cooper, UC Irvine

John Galambos, ORNL

Pascal Garin, IFMIF-EVEDA

Yousry Gohar, ANL

Frank Goldner, DOE

Gordon Jarvinen, LANL

Rolland Johnson, Muons Inc.

Rick Kurtz, PNNL

Shekhar Mishra, FNAL

Yoshi Mori, Kyoto Univ.

Tim Myers, AES

Sergei Nagaitsev, FNAL

Eric Pitcher, LANL

Jean-Pierre Revol, CERN

Buzz Savage, DOE

Peter Seidl, LBNL

Richard Sheffield, LANL

Scope

The Energy and Environment Working Group considers current and potential future applications of accelerators to address the world's energy and environmental challenges.

- **Applications of Accelerators in Power Generation and Nuclear Waste Transmutation**
  - *Accelerator-driven systems for nuclear waste transmutation and the generation of electrical power, either as a byproduct of transmutation, or through burning of thorium-based fuel*
- **Applications of Accelerators in the Development of Materials for Advanced Nuclear Fusion/Fission Power Systems**
  - *the use of accelerators to produce radiation environments that are needed to further the development of high-performance materials for nuclear applications.*
- **Applications of Accelerators for Fusion Energy**
  - *Accelerator-based inertial confinement fusion*
- **Applications of Accelerators for Cleaner Air and Water**
  - *the use of accelerators for flue-gas treatment, the treatment of waste-water, drinking water and groundwater.*

Working Group Charge

For each of these applications the Working Group aims to answer the following key questions:

- What is the potential benefit and impact on society?
- What are the accelerator requirements?
- What is the present state-of-the-art accelerator performance?
- What areas of accelerator R&D are required to achieve the required accelerator parameters, and what are their relative priorities?
- What barriers stand in the way of deploying this accelerator technology within a 20 year time frame?
- What strategies can overcome the barriers to deployment?
- How can the gap between basic accelerator R&D and commercial technology deployment be bridged?
- Where would increased investment yield the greatest benefit?

Our Product

Our work for the next two days will focus on answering the charge questions and documenting those answers in a ~10 page report

– We are encouraged to include one figure per page

We have asked the following to take the lead in moderating a discussion of, and summarizing the response to, the charge questions

- **ADS/ATW: Richard Sheffield**
- **Materials Irradiation: Eric Pitcher**
- **Fusion Energy: Peter Seidl**
- **Environmental Applications: Bill Cooper**

Agenda

Tuesday Morning

- Presentations on E&E Working Group Scope

Tuesday Afternoon

- Presentations on E&E Working Group Scope
- Parallel Discussions in 4 groups
- Brief summary of Discussions (~20min)

Wednesday Morning

- Reports from each of the four groups (moderator) and group discussion of the response to the charge

Wednesday Afternoon

- Preparation of Closeout Presentation

Report Outline

1. Introduction [1p.]

Set the scene: energy demand, trends, nuclear fuel cycle, greenhouse gas emissions, air and water quality; general discussion of accelerators as potentially useful tools in the energy/environment equation.

2. Needs and Opportunities [4p.]

For each application,

- *Discuss the need, significance, and potential benefit to and impact on society*
- *Summarize the present status, and the existing capabilities and development efforts in the US, and worldwide*

2.1 Applications of Accelerators in Power Generation and Nuclear Waste Transmutation [1.25p.]

This section covers accelerator-driven systems for nuclear waste transmutation and the generation of electrical power, either as a byproduct of transmutation, or through burning of thorium-based fuel

2.2 Applications of Accelerators in the Development of Materials for Advanced Nuclear Power Systems [1p.]

This section covers the use of accelerators to produce radiation environments that are needed to further the development of high-performance materials for advanced nuclear systems.

2.3 Applications of Accelerators in Fusion Energy [0.75p]

This section covers accelerator-based inertial-confinement fusion (heavy-ion fusion).

Report Outline, cont'd

3. Challenges [5p.]

For each application, discuss

- *R&D requirements and their relative priorities,*
- *barriers to deployment (political, technical, cost, …)*
- *potential strategies for overcoming those barriers;*
- *the potential role of industry and commercial involvement;*
- *the possibility of public/private partnerships to advance R&D and increase the adoption of accelerator technology for this application*
- *areas in which increased investment would yield the greatest benefit*

3.1 Applications of Accelerators in Power Generation and Nuclear Waste Transmutation [1.5p]

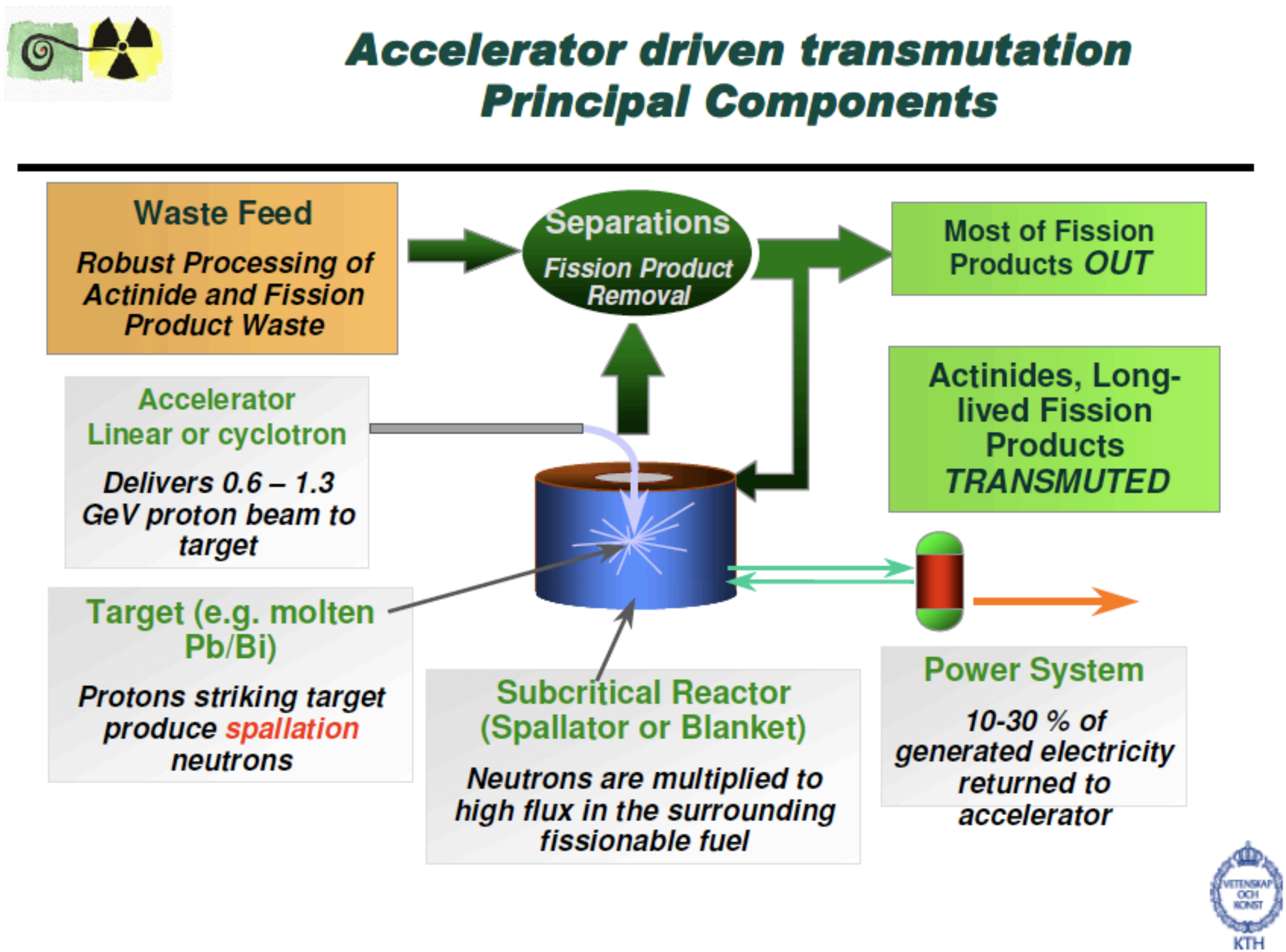
3.2 Applications of Accelerators in the Development of Materials for Advanced Nuclear Power Systems [1.25p.]

3.3 Applications of Accelerators in Fusion Energy [1p.]

3.4 Applications of Accelerators for Cleaner Air and Water [1.25p]

4. Principal Findings [1p.]

Beam power efficiency for ADSR



Required power efficiency

Required power efficiency

$$P_{e-power} \approx \varepsilon_{th-e} \times \frac{S}{1-k_{eff}} P_{beam} \; : \varepsilon_{th-e} \text{(thermal to electric)}$$

$$\eta_{accelerator} = \frac{P_{beam}}{P_{acceleraotr}} > \frac{P_{beam}}{P_{e-power}} \approx \frac{1-k_{eff}}{\varepsilon_{th-e} \times S}$$

$$\eta_{accelerator} \sim 0.25 \quad (\varepsilon_{th-e} = 0.2, k_{eff} = 0.95, S \sim 1)$$

Power Efficiency of Accelerator >25%

AC Power requirements for a Superconducting 1 GeV 10 MW Linac/Al Moretti– Preliminary

There are 87 Superconducting cavities at 4 K and 18 cavities at room temperature plus Rt. RFQ at 325 MHz and 50 ILC superconducting cavities at 1.8 K to reach 1 GeV. I have used data from reports of the PD, XFEL and Cryo group to derive this AC Power Table below. All Cavities and RFQ are made superconducting in this case.

klystron	Eff = 64 %	Power to Beam 10 MW	Mains Power 15.6 MW
Water tower cooling	Eff=80 %	15.6 MW/.80	7 MW
4 Deg Load	6100 W	AC Power ratio 200/1	1.2 MW
2 K Load	1250	AC Power ratio 800/1	1 MW
70 K load	5580	AC Power ratio 20/1	0.1 MW
HOM 2 K load	116	AC Power ratio 800/1	0.1 MW
		TOTAL	25 MW

ACCELERATORS FOR AMERICA'S FUTURE

Energy and Environment Working Group Report

Stuart Henderson, ORNL
Steve Holmes, FNAL

October 28, 2009

U.S. DEPARTMENT OF ENERGY

Working Group Membership

Andrzej Chmielewski, Inst. Nuc. Chem., Warsaw

William Cooper, UC Irvine

John Galambos, ORNL

Pascal Garin, IFMIF-EVEDA

Yousry Gohar, ANL

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There are Tremendous Challenges in Energy and the Environment

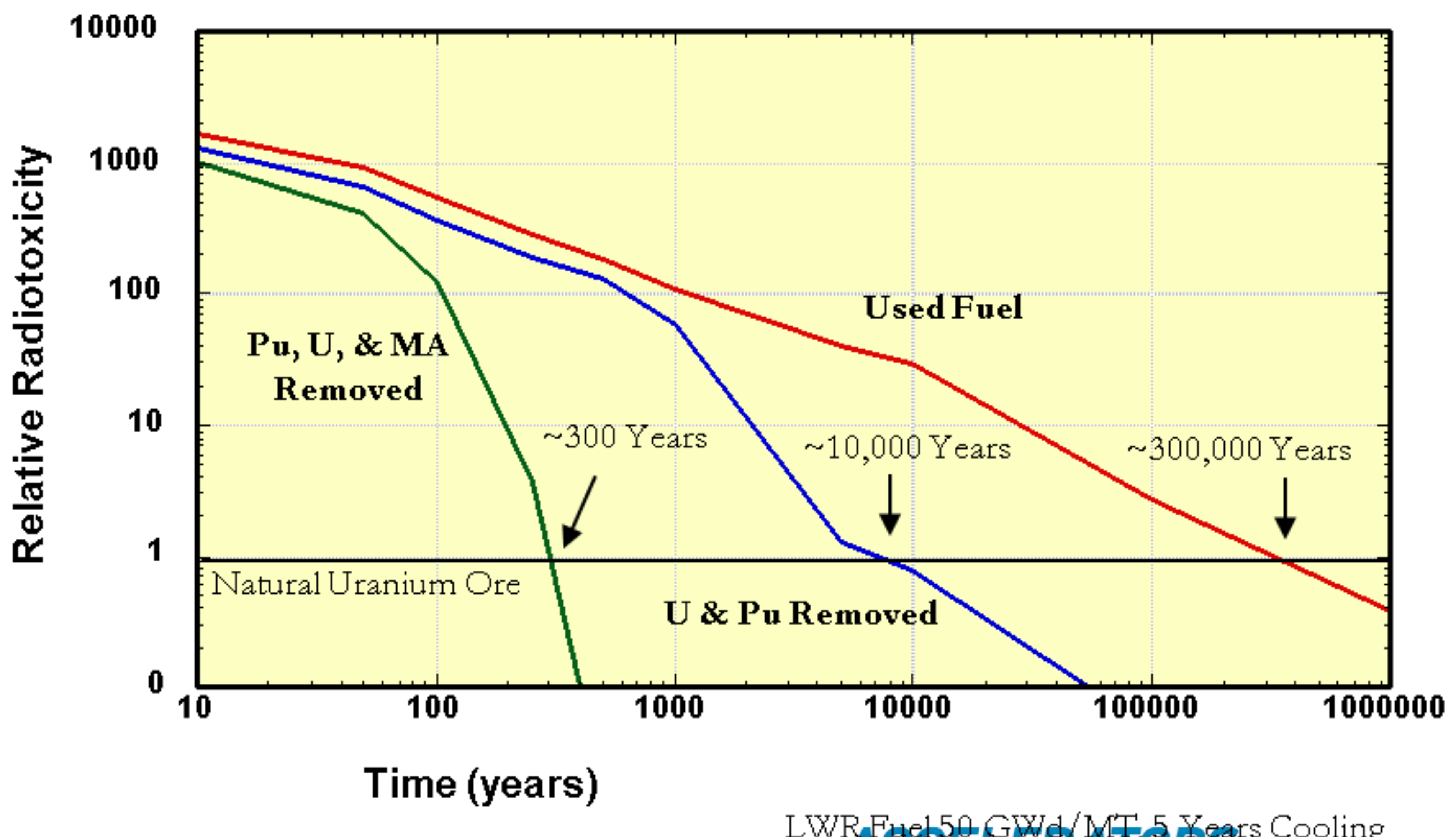
- **Projections from 2006 to 2030 (Energy Information Administration 2009)**
  - World marketed energy consumption is projected to increase by 44%
  - World net electricity consumption increases by 77%
  - Coal consumption increases by 50%
  - Nuclear power generation increases by 40%, but drops from 15% to 12% of total
  - World CO_2 emissions increase by 40%
  - Two-thirds of the human population will live under water-stress conditions

What Can Accelerators Offer Society in Energy and the Environment?

- **Sustainable and safe energy sources with manageable waste, proliferation control and greatly reduced carbon footprint**
- **Development of materials to enable future energy systems**
- **Cleaner air and water**
- **Accelerators already provide important tools for advancing the basic science of materials needed to meet the nations energy and environmental challenges:**
  - Advanced materials are being developed for solar energy, bioenergy, grid technologies, energy storage, carbon sequestration, hydrogen storage, made possible by the “Modern Ships of Discovery”

Accelerator-Driven Systems

- ADS offers the potential of reducing long-term radiotoxicity of nuclear waste, exploiting the residual energy content in spent fuel or using alternative fuels (e.g. Th) to generate electrical power
- ADS is ideally suited to burn the most problematic components in spent fuel (minor actinides)
- There are very active programs in Europe, Japan, China, India, Brazil, but no US program
- ADS includes Four Major Technology Elements: Separations & Waste Forms, Fuel Forms, Accelerators, and Transmuters



Requirements and R&D for ADS

Accelerator requirements are beyond the state-of-the-art

- Beam: 10-50 MW, ~1-2 GeV cw protons
- Losses: < 1 W/m for hands-on maintenance
- Beam trips: (0.3 < t < 100 s) < 1000/year

  (t > 100 s) < 30/year

Accelerator R&D program needs to focus on

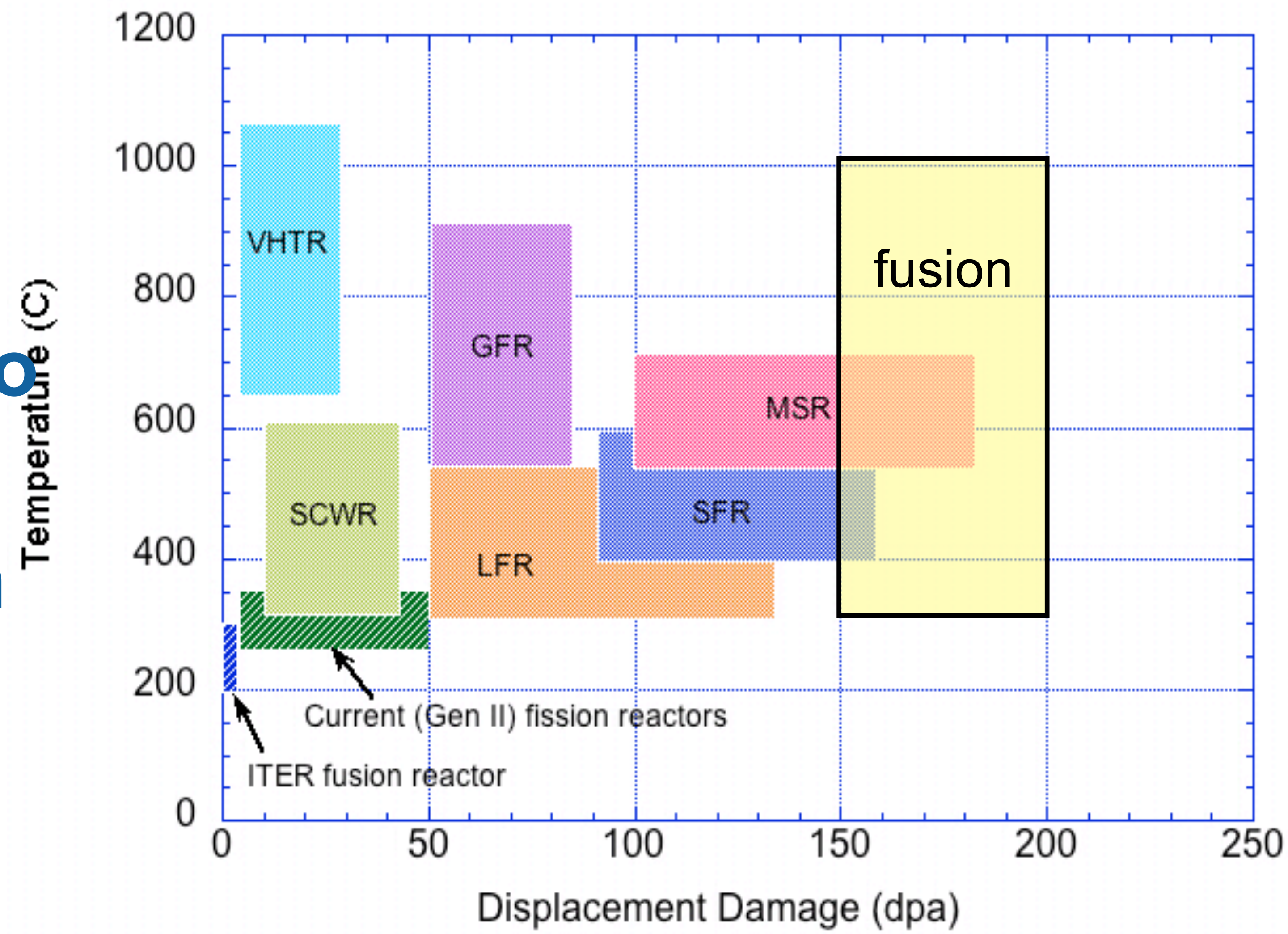
- Accelerator reliability which is well beyond levels typically found in accelerators for physics research
- Beam loss control and mitigation at <1W/m
- High intensity sources and low energy acceleration with high beam quality
- Many other R&D areas beyond the realm of accelerator R&D: subcritical reactor design and interface, separations processes, advanced fuel cycle design

Issues and Barriers

- Lack of buy-in from the US Nuclear Power industry
- ADS is by definition multidisciplinary, (nuclear power, waste management, accelerators, fuel processing, environment) and doesn't have a natural owner or champion.
- Accelerator design is intimately-related to spallation target/sub-critical reactor design and interface

Materials Irradiation

- **New materials are needed to advance nuclear energy**
- **High-temperature, radiation resistant materials for fusion/fission**



- **Development requires an intense neutron source beyond the present capabilities**
  - Two approaches: 40 MeV D-Li stripping, spallation source at GeV level
  - Fusion needs high energy neutrons for He/H generation
- **The relevant "Ship of Discovery" is still in port**

Accelerator Requirements and R&D

Accelerator Requirements:

- CW, high power, high reliability and availability beams
- Beamloss < 1 W/m for hands-on maintenance
- Rad-damage up to 50 dpa/year.
- Accel power ranges from > 2 MW for spallation, > 10 MW D-Li stripping

Faults minimized to maintain constant material temperature

Needed accelerator R&D:

- Modest extrapolation from today's capabilities
- Emphasis is on beam dynamics for low beamloss and high reliability

Materials Irradiation capability is a recognized need, and offers an opportunity for synergistic efforts between stakeholders

Inertial Fusion Energy: carbon-free, energy independence

Beam parameters

- target: several MJ/pulse, 10 Hz, 10 nsec pulse length, 1 mm radius, A > 100
- injector: 1 amp/beam at injector, 20 usec duration
- Most beam manipulations have been demonstrated in separate experiments, either scaled or driver scale.

Synergies : ATW: if fusion/fission hybrid (+ energy) & Materials irradiation testing

Needed accelerator R&D:

- Design of a demonstration power plant accelerator.
- Integrated beam manipulations capable of target physics experiments
- Beam loss understanding and mitigation to allow hands-on maintenance.
- System component reliability demonstrated at scale.
- Cost-effective component fabrication

NIF ignition will lead to a renewed interest in a variety of IFE approaches

Environmental Applications of Accelerators

Cleaner Air and Water: radiation processing of

- Flue gases for SO_2, NOx, VOCs
- Water for biological and chemical control

Accelerator needs for flue gas: 0.8 MeV, ~1 MW total installed power per ~50 MW plant

Accelerator needs for water: <5 MeV, ~0.4 MW (small) – 10's MW (large)

Accelerator capability exists; further development is best done in industry

- Further cost-reduction would catalyze economic viability

U.S. lags behind the world on pilot/demonstration projects

- Flue gas treatment pilot plants exist in: Poland, Bulgaria, China
- Water treatment industrial scale system operates in Korea

Enormous opportunities are held up in the "Valley of Death" between technology development and deployment

- **Bridging between accelerator Industry and stakeholders needs creative approaches for demonstration, outreach, education and training**
- **Opportunity for public/private partnerships**

Energy and Environment Specific Findings

- There are many fertile areas of opportunity and innovation
- Beam loss understanding and mitigation at <1W/m (ADS, Fusion, Materials) is required
- Accelerator reliability beyond levels typically found in physics research (All)
- High intensity sources and low-energy acceleration with high beam quality (All)
- Economic analysis (ADS, Fusion, Environment)
- Industrial buy-in (ADS, Fusion, Environment)
- Inter-office, Inter-agency & international cooperation (All)
- Creative approaches are needed to bridge the “Valley of Death”

Proposed General Findings

There are strong synergies with other applications via

- High intensity, high efficiency, low loss sources – w/ Discovery Science, Security, Medical
- Beam dynamics for low loss acceleration and high beam-quality – same
- Superconducting radio-frequency cavities, superconducting magnets and related advanced technologies – Discovery Science, Security, Medical

Cross cutting issues

- Inter-office, Inter-agency & international cooperation (All)
- "Valley of Death" will require creative partnerships

$$T = C / \beta c$$

$$C = 2\pi r$$

$$r = r_0 \left(\frac{p}{p_0} \right)^{\alpha}$$

$$\alpha = \frac{1}{k+1}$$

$$T = \frac{2\pi r_0 \left(\frac{p}{p_0} \right)^{\alpha}}{\beta c} = \frac{2\pi r_0 {p_0}^{-\alpha} p^{\alpha}}{\beta c} = \frac{2\pi r_0 \left(\beta_0 \gamma_0 \right)^{-\alpha} \left(\beta\gamma \right)^{\alpha}}{\beta c} = \frac{2\pi r_0 \left(\beta_0 \gamma_0 \right)^{-\alpha}}{c} \frac{\left(\gamma^2 - 1 \right)^{-\frac{\alpha}{2}}}{\frac{\left(\gamma^2 - 1 \right)^{\frac{1}{2}}}{\gamma}} = \frac{2\pi r_0 \left(\beta_0 \gamma_0 \right)^{-\alpha}}{c} \gamma \left(\gamma^2 - 1 \right)^{-\frac{\alpha+1}{2}}$$