SUMMARY WG3

SRF Linac Driven Subcritical Systems

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Challenges For CW Linacs

- **CW operation**
  - => dynamic heat load (rf losses) is dominant => refrigerator cost will be significant.
  - Make choices that will lower the heat load
  - RF power operating is also a significant part of the overall AC power
    - Choose matched Qext (microphonics should be tolerable)
    - Choose design options that lower microphonics risk
- **High Beam current (e.g. 1 - 10 mA)**
  - **Careful matching and beam halo**
  - Be prepared to extract and intercept HOM power
  - Need damping of Q's for HOMs to avoid beam blow up (halo?) ?
- **Preserve beam profile**
  - Good cavity alignment
  - Low kicks from couplers etc, esp for low energy end
  - Good amplitude and phase stability (e.g. Amplitude/phase stability ERL: 10^{-4}/0.02 deg)
  - RF distribution, low level rf control system issues
- **Operation**
  - High reliability, low trip rate.
    - Favors moderate gradients (e.g. 15 -20 MV/m)

H. Padamsee

Above Challenges Impact Design Choices For

- Cavity
- Input coupler
- HOM coupler
- Tuner
- Cryomodule
- Above issues valid for medium beta elliptical and high beta cavities

Prospects for a very high power CW SRF Linac

R. Rimmer
AHIPA09

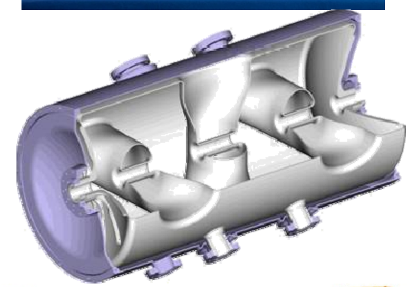
The good news:

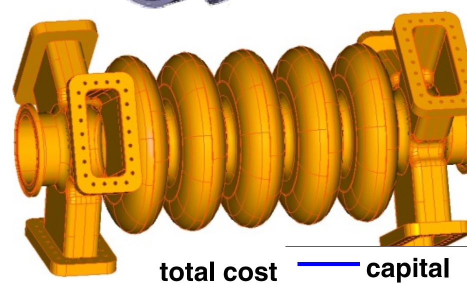
- Large SRF facilities work (CEBAF/SNS)
- Many proton driver cavities/couplers are in development worldwide
- SRF performance continues to improve
- 2K cryogenics are getting more efficient
- New CW RF sources continue to be developed
  - IOTs, multi-beam tubes, magnetrons
- Science case for new machines is very strong

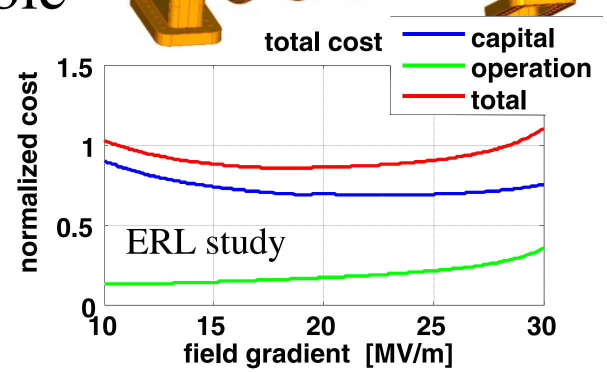
Prospects for a very high power CW SRF Linac

R. Rimmer
AHIPA09

- No show stoppers to running CW high-current
- Robust high-power couplers must be used
- Main challenges may be halo / beam loss / trip rate
- Q_o (residual resistance) is significant cost factor
- Cost "optimization" depends strongly on assumptions
- Low frequency preferred for ADS / high current
  - Large apertures, TV-band RF sources
- For project-X 650 MHz section may be desirable
- CW beam test facilities would be highly desirable
- Front end is the most challenging part
  - E.g. 30 mA CW HINS would address many critical issues!





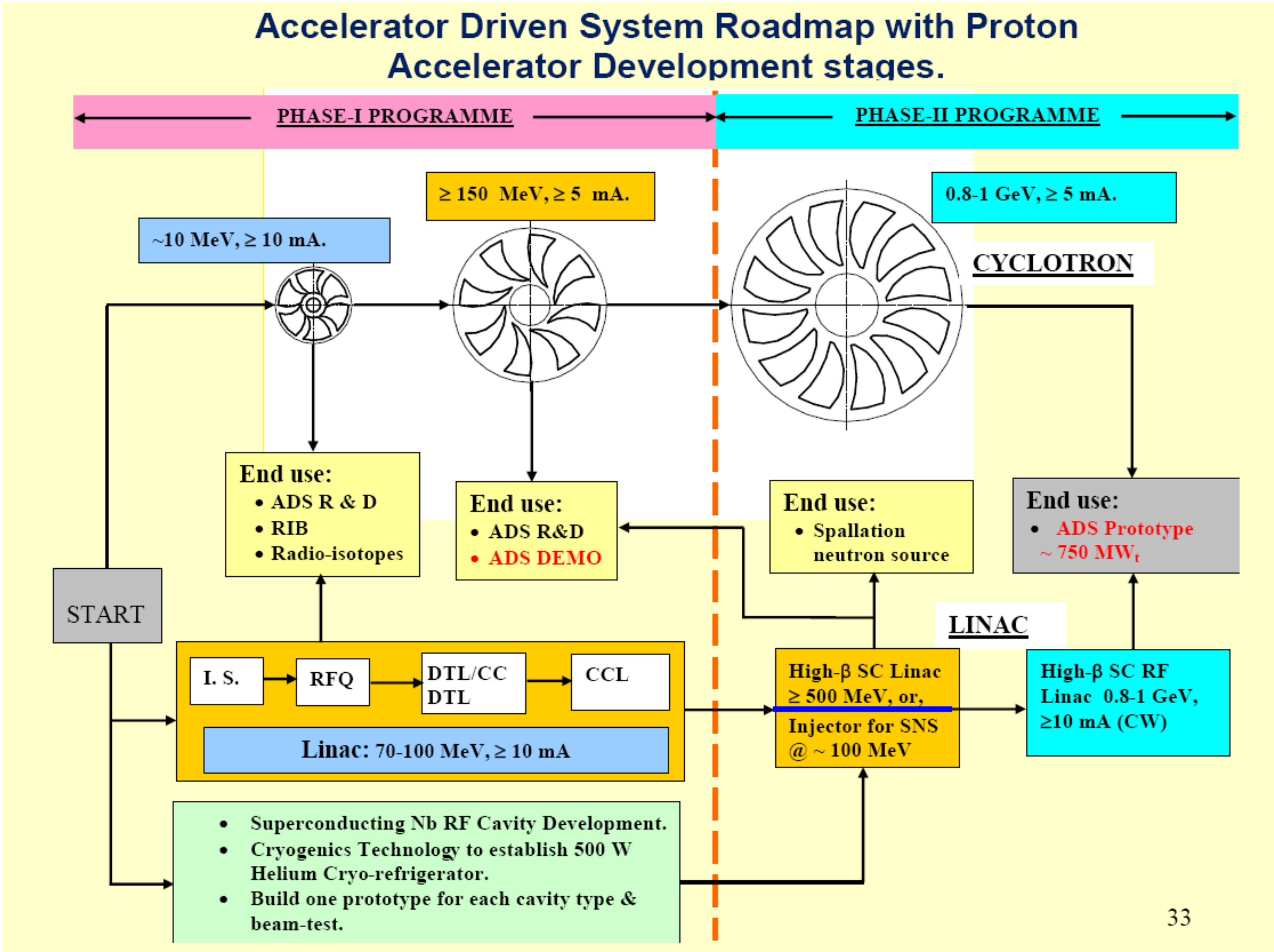


Technologies for ADS

- High power proton accelerator: 1 GeV, cw or high duty factor, high current
    - High beam current front-end
    - Superconducting RF cavities
    - RF power systems
- Molten heavy metal spallation target & associated process system.
    - High volumetric beam power density
    - Materials: irradiation and corrosion resistant
- Sub-critical reactor
    - Dedicated TRU transmuter fuel & fuel-cycle
    - Configuration: technology issues
    - Transients & safety studies

Ongoing Indian activities in ADS programme

- Design studies of a 1 GeV, 30 mA proton linac.
- Development of 20 MeV high current proton linac for front-end accelerator of ADS.
- Construction of LBE experimental loop for design validation and materials tests for spallation target module.
- Development of computational tools and data for neutronics of spallation target and coupled sub-critical reactor.
- Experimental validation of reactor physics codes and data with 14-MeV neutrons in sub-critical core at PURNIMA labs.
- Design studies for ADS experimental reactor



Accelerator Driven System Roadmap with Proton Accelerator Development stages.
PHASE-I PROGRAMME
PHASE-II PROGRAMME
≥ 150 MeV, ≥ 5 mA.
0.8-1 GeV, ≥ 5 mA.
~10 MeV, ≥ 10 mA.
CYCLOTRON
End use:
• ADS R & D
• RIB
• Radio-isotopes
End use:
• ADS R&D
• ADS DEMO
End use:
• Spallation neutron source
End use:
• ADS Prototype ~ 750 MWt
START
LINAC
I. S.
RFQ
DTL/CC DTL
CCL
Linac: 70-100 MeV, ≥ 10 mA
High-β SC Linac ≥ 500 MeV, or, Injector for SNS @ ~ 100 MeV
High-β SC RF Linac 0.8-1 GeV, ≥10 mA (CW)
• Superconducting Nb RF Cavity Development.
• Cryogenics Technology to establish 500 W Helium Cryo-refrigerator.
• Build one prototype for each cavity type & beam-test.
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Scheme of Proton Linac Development

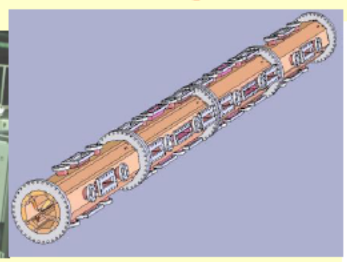
High current injector 20 MeV, 30 mA

Proton IS 50 keV → RFQ 3 MeV → DTL 20 MeV → Normal Conducting DTL/ CCDTL or Super-conducting → 100 MeV → SC Linac → 1 GeV

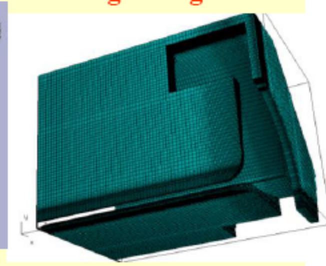
Design completed and fabrication is in progress

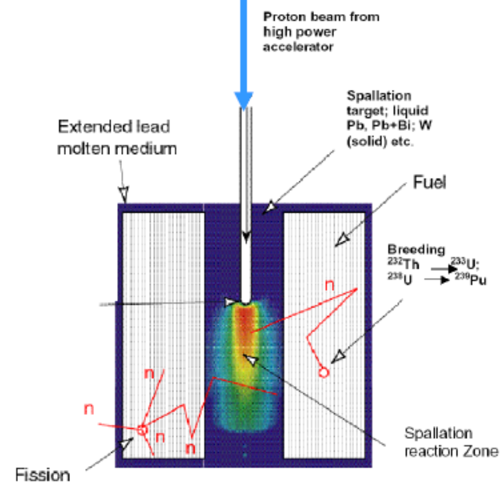
ECR Ion Source

RFQ

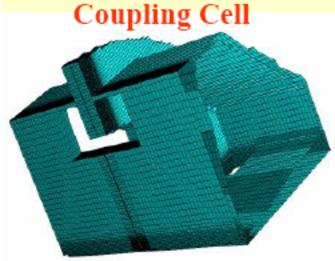


Beginning Cell

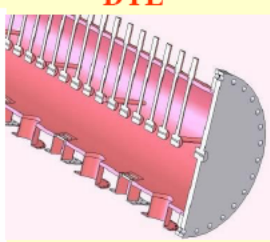




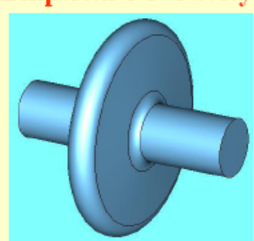
Coupling Cell



DTL



Elliptical SC Cavity



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Main points of presentation by V.C.Sahni

- DAE has a strong international partnership with Fermilab & CERN that is geared towards development of technology for High Intensity Proton Accelerator, especially SCRF technology and doing value engineering.

- The DAE-Fermilab collaboration has been promoted by Dr. Anil Kakodkar & Dr. Pier Oddone and over the last two and a half years approximately 10 DAE scientists have been hosted by Fermilab and each has spent many months.

- The collaboration has helped in setting up SCRF cavity fabrication facilities and carrying out design improvements such as simpler end group manufacture, economical arrangement for cavity mounting in a cryomodule etc.

- RRCAT has made an all solid state modulator for the linac4 project at CERN, which has been tested and ready for shipment to Geneva.

Main points of presentation by V.C.Sahni

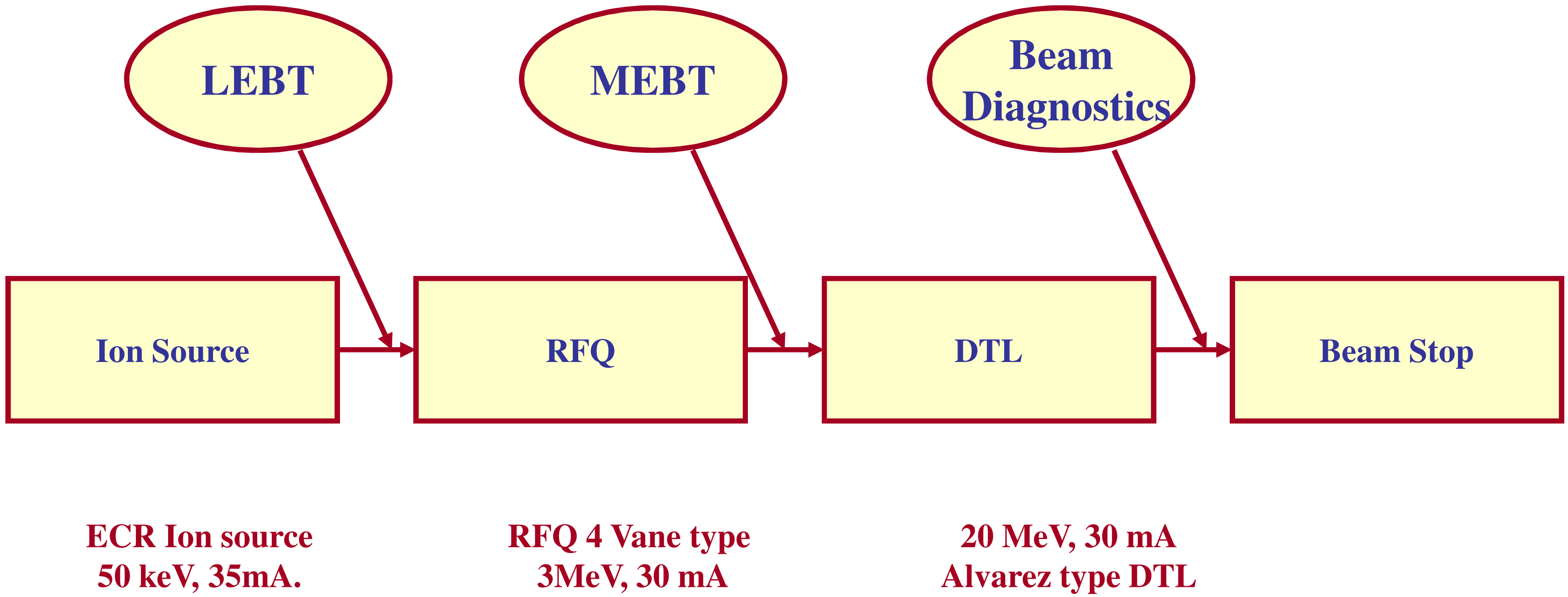
• BARC is currently engaged in constructing a Low Energy High Intensity Proton Accelerator (LEHIPA) OF 20MeV, 30mA that can serve as an injector for ADS program.

•The building to house LEHIPA will be available in early 2010 when sub systems such as ECR ion source, LEBT, RFQ, MEBT, DTL etc. will be installed in a phased manner over the next two to three years.

•The proton beam from this facility will also be carried to an AHWR critical facility to study the coupling to a reactor.

•In parallel work is being done on a 400KeV RFQ based 14MeV(D+T) neutron source that will be coupled to a natural Uranium light water moderated sub critical assembly for performing flux measurements etc.

Layout of BARC's 20 MeV Linac Section



LEBT : Low Energy Beam Transport System

RFQ : Radio Frequency Quadrupole

MEBT : Medium Energy Beam Transport System

DTL : Drift Tube Linac

V. C. Sahni

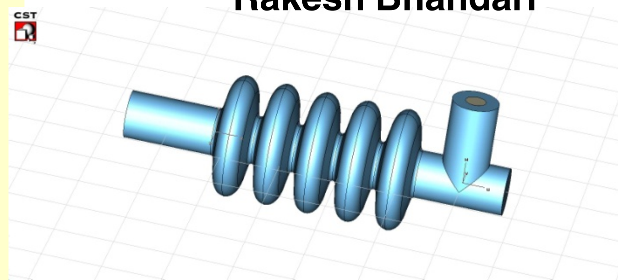
Rakesh Bhandari

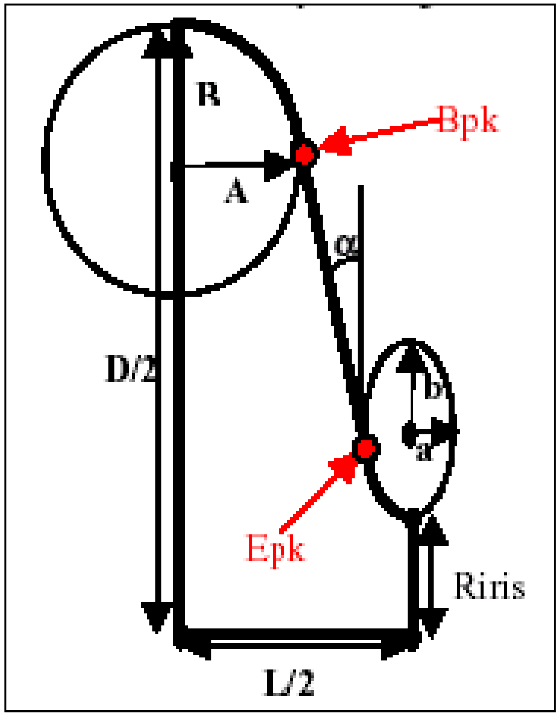
- Electromagnetic design of high-β 5-cell Superconducting rf linac cavity has been completed.

- Frequency : ~ 700 MHz

- An elliptical shape equatorial arc — eliminates multipacting, which limits the performance of cylindrical pill-box cavities.
  It makes distribution of the magnetic field along the surface more uniform and thus reduces B_{pk}. This in turn leads to higher accelerating gradients and lower losses.

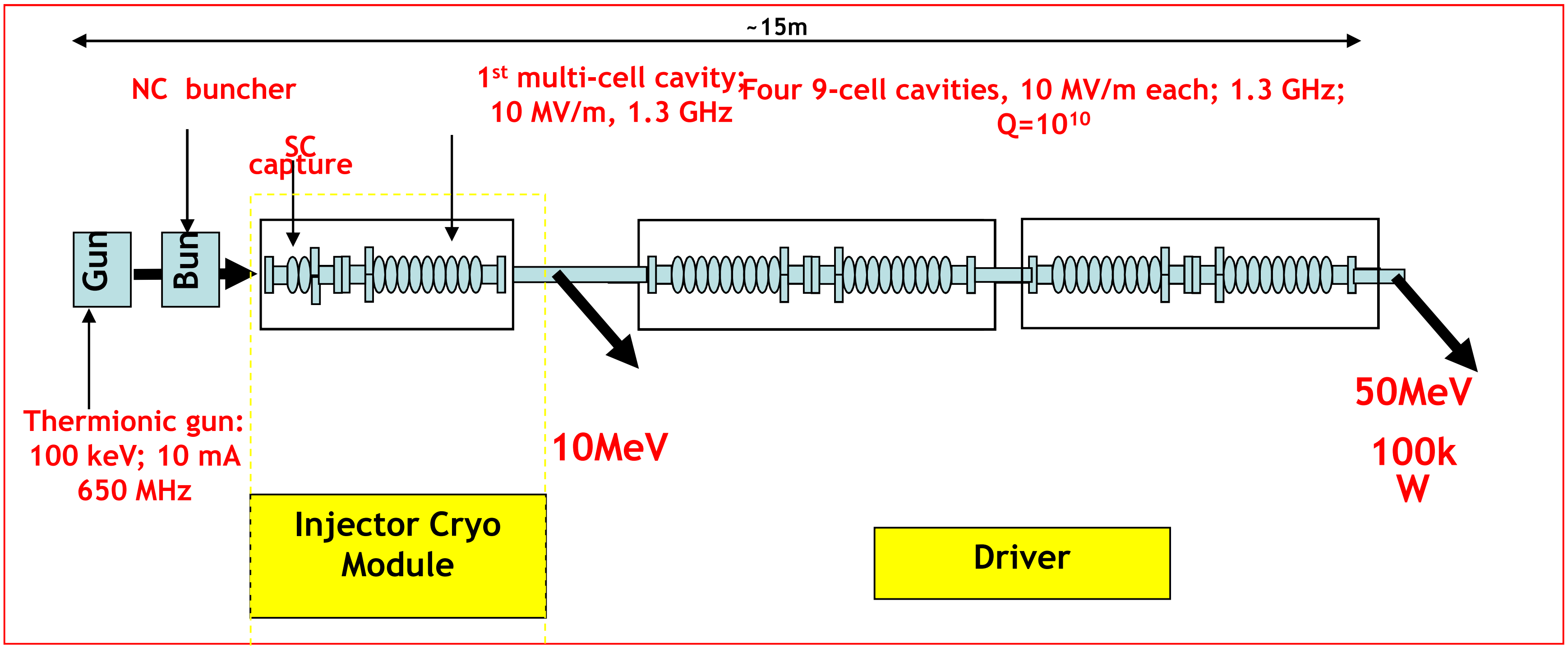
- The use of elliptic arcs in the Iris area of the cavity reduces the peak surface electric field (E_{pk}), which alleviates field emission.





Rakesh Bhandari

Schematic Layout of SC Electron Linac



**VECC-
TRIUMF MOU
(2008-12)
Phase 1**

Status
Beam dynamics design completed,
presently under technical review

CSNS CHINESE ACADEMY OF SCIENCES 中国散裂中子源

SUMMARY

1, High intensity proton accelerator has two applications in China: ADS and CSNS.
2, Five key technologies in high intensity proton accelerator for ADS are under development.
3, ADS basic study has gained support in two phases from the Ministry of Science and Technology.
4, CAS presented an ADS new proposal to the government in recent to speed up ADS from the present basic study to small-scale system construction. Five institutes of CAS joined in the new proposal.

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Five study fields in ADS programs

1. A high intensity injector
2. A high intensity RFQ accelerator

   supported by the Ministry of Science and Technology in ADS basic study programs

3. Medium beta SC cavity study

   supported by the Chinese Academy of Sciences

4. A SC lab for vertical test

   supported by IHEP, Beijing

5. Low beta SC cavity study

   supported by CAS

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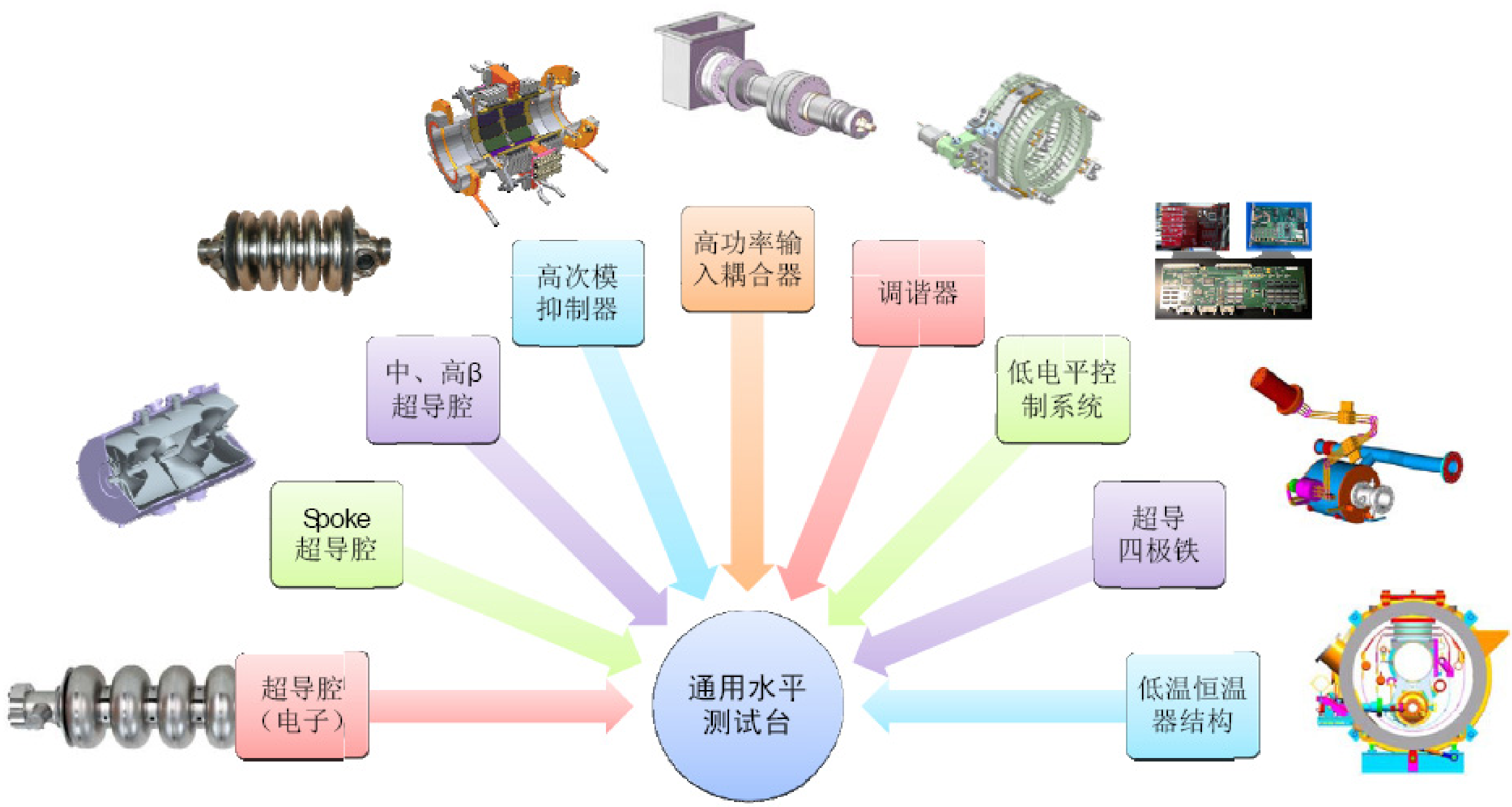
A larger SC lab planed at IHEP—A synthesize horizontal test stand for multipurpose

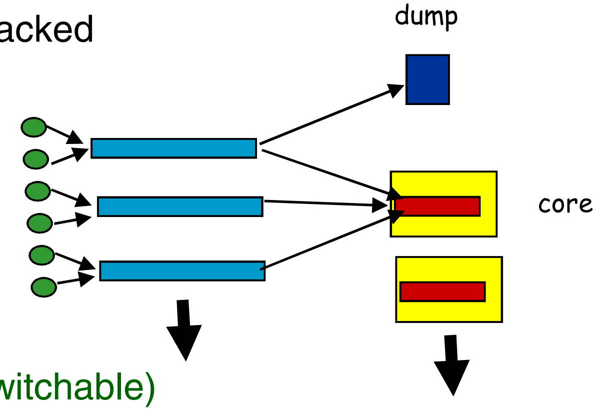


Differences Px vs ADS linac

- A 10 MW proton source to create neutrons for ADS might be similar to the 2 GeV 2 MW CW linac under consideration for Project X but there are significant differences:
- Commercial: Power Production is a business
  - Basic purpose of the linac is different
  - ADS Linac is part of a facility intended to make money vs acquire knowledge
- Optimization:
  - Research accelerators usually emphasize optimization of performance vs capital cost, availability, operating costs, efficiency, project risk, etc. (even though many of these also are important for a research accelerator)
  - Availability requirements for commercial power production are much higher vs a research accelerator like Project X. (but perhaps are more similar to ILC ?)
  - A commercial power plant will be built around this linac ➔ requires a very conservative design with low risk (must satisfy investors vs your colleagues or the DOE reviewers)
  - A company building an ADS linac would probably do a better job of optimizing capital costs vs operating cost with a long term view
    - easier for industry since they will borrow money to do this right vs research environment in which we want the project approved
    - ie DOE environment favors solutions with lower initial construction costs
- Maintenance and Operation: ADS linac must be operable and maintainable for long periods without large on-site laboratory accelerator staff

Differences, Development

- Reliability: (some requests seem extreme! < 5 trips/yr > 1 sec)
  - Cryogenics and RF power are likely weak points but can be attacked
  - Use high availability approach to control electronics
  - Avoid single point failures… e.g. beam pipe vacuum
  - A lot could be learned about reliability from Project X



- Redundancy:
  - Linacs with multiple sources (PX could develop this)
  - Multiple linacs in separate enclosures. (1needed/core , switchable)
  - Hot spare linac with power switched from dump to ADS core ?
  - Multiple independent cryo systems so one or more linacs could be off for maintenance
  - Px might then ~simulate <u>one</u> of these machines
- Operating Efficiency:
  - Need efficient wall plug to beam power efficiency (SRF)
  - Electrical power use for cryogenics will be important ➔ use high Q cavities, low operating gradients (BCS losses go as G**2/Q), efficient cryogenic cycles
  - Likely an optimal ADS machine would be lower frequency (cryo efficiency and rad losses)
  - Optimization of cavity gradient vs linac capital cost may be different for a high efficiency ADS linac vs a research linac

Project X Changes for a 10 MW Project X

- RF Power Source:
  - Project X upgrades to 10 MW at 2 GeV ➔ ~5 mA beam current ➔ 90 KW per 9-cell cavity
  - Need ~100-200 KW CW RF power source per cavity
  - High power IOT's are potentially attractive due to increased efficiency
    - ➢ but 200 KW IOT @ 1.3 GHz don't exist
    - ➢ Magnetrons might be very attractive if one could control phase and amplitude (SBIR)
- Main Cavity couplers
  - Present XFEL couplers can take ~ 5 KW, upgradable to >20 KW for Project X ICD-2
  - 100-200 KW coupler probably require a significant redesign of XFEL coupler
  - Constrained by the 40 mm port size in the ILC/Project X nine-cell elliptical cavities
- Front end changes:
  - Develop a reliable, redundant >10 ma CW proton source, higher current RFQ, etc.
- Controls, LLRF, Fast Fault Recovery
  - A real challenge given ADS availability requirements
  - ADS requirement ➔ keep beam on… machine protection ➔ turn beam off!
- 10 MW capable dumps and/or targets !
- Maintenance:
  - Activation at SNS, already an issue at 1 MW ➔control of losses in a 10 MW Project X!
  - Consider provisions for remote handling and maintenance of cryomodules?
  - Losses, and activation favor larger cavity apertures and lower frequencies than1.3 GHz

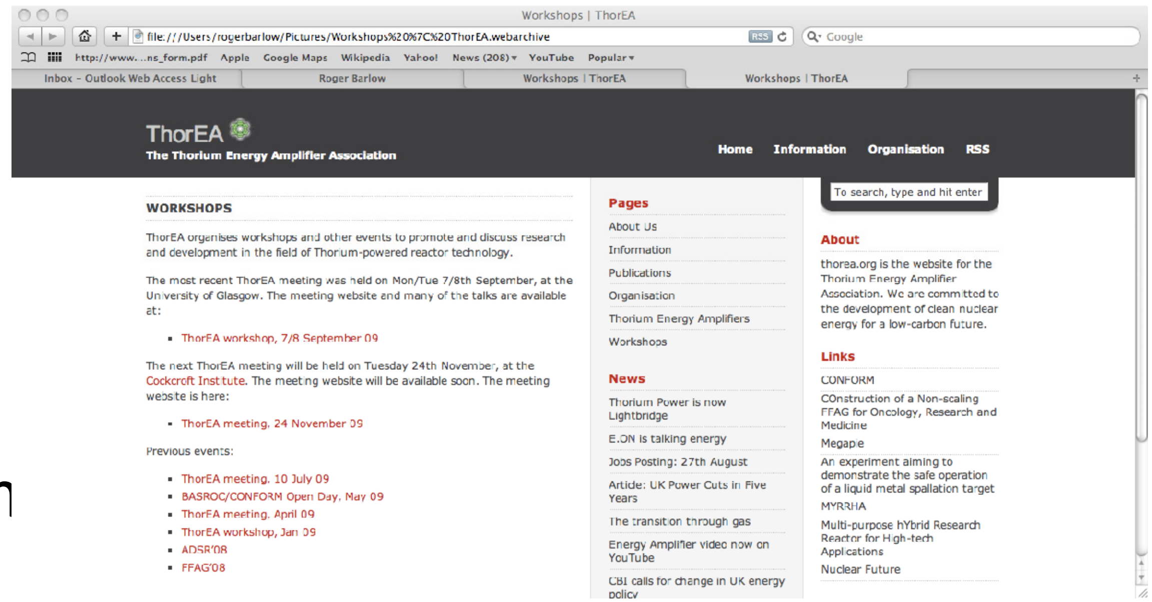
Summary

- The design choices for a commercial ADS linac will likely be much different that for a research accelerator like Project X
- Nevertheless, Project X can provide a lot of useful operational information to guide the design of ADS linac
  - Much of this information does not require Px be upgraded to 10 MW.
  - Provisions to upgrade Project X to 10 MW at some point would require inclusion of some expensive “hooks” early in the program
  - A 2 GeV 10 MW linac would be expensive and would require a serious potential user of this power to justify these hooks.

What it does(1)

Workshops

- Last one in Glasgow September 7-8
- Next one Daresbury November 24
- Talks accessible from the website



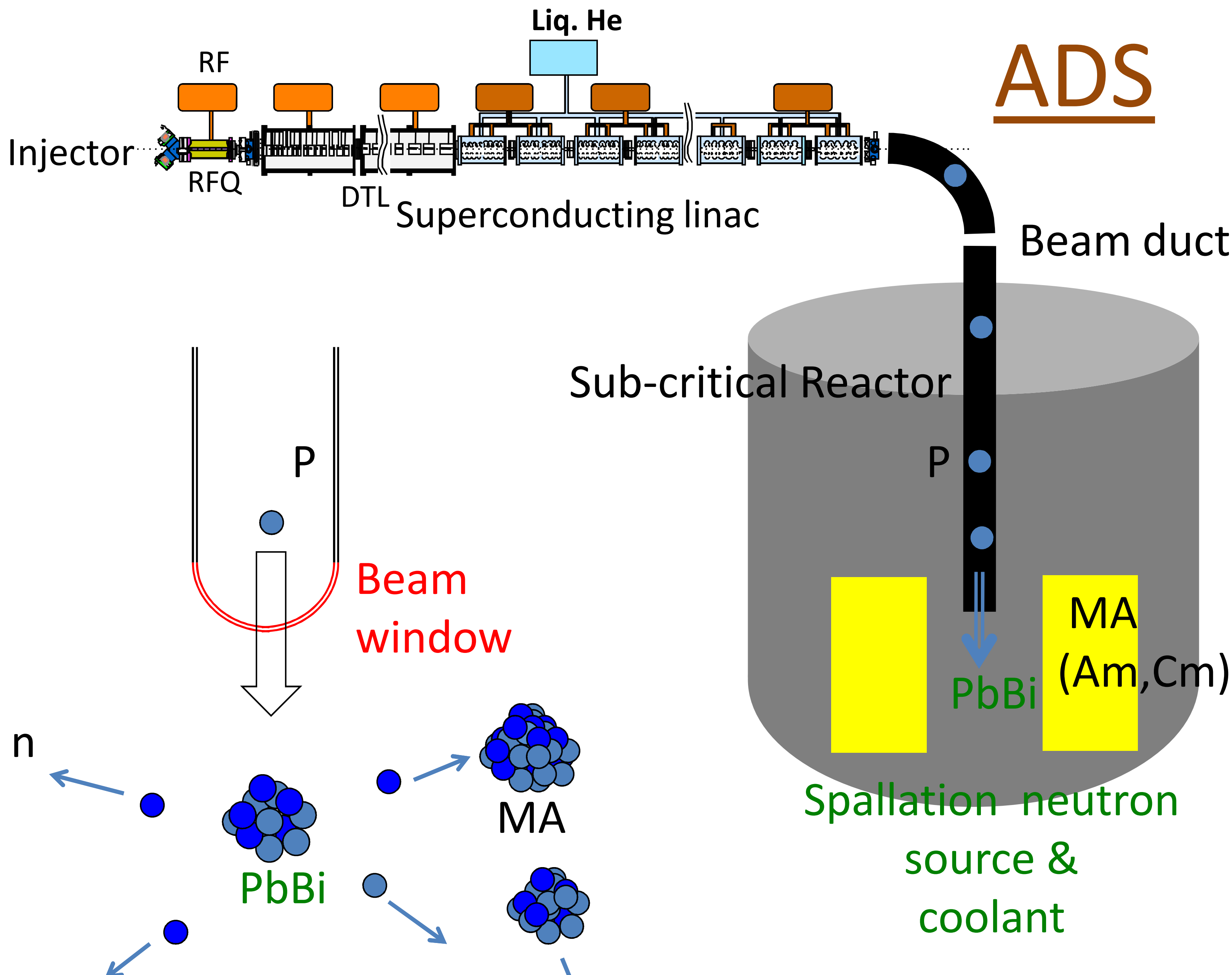
FFAG Pros and Cons

Advantages (compared to a Synchrotron)

- DC magnets: cheap and reliable
- Fast acceleration. Not limited by magnet iron. Acceleration to 1 GeV in ~1000 turns envisaged (say 50 m radius ring: take ~ 1 ms)

Disadvantages

- Complicated Magnet shape
- May require varying RF frequency
- Limited gain in energy (momentum change factor 2-5 depending on design)
- nsFFAG principle not yet proven


ADS
Liq. He
RF
Injector
RFQ
DTL
Superconducting linac
Beam duct
Sub-critical Reactor
P
MA
(Am,Cm)
PbBi
Spallation neutron
source &
coolant
P
Beam
window
n
PbBi
MA

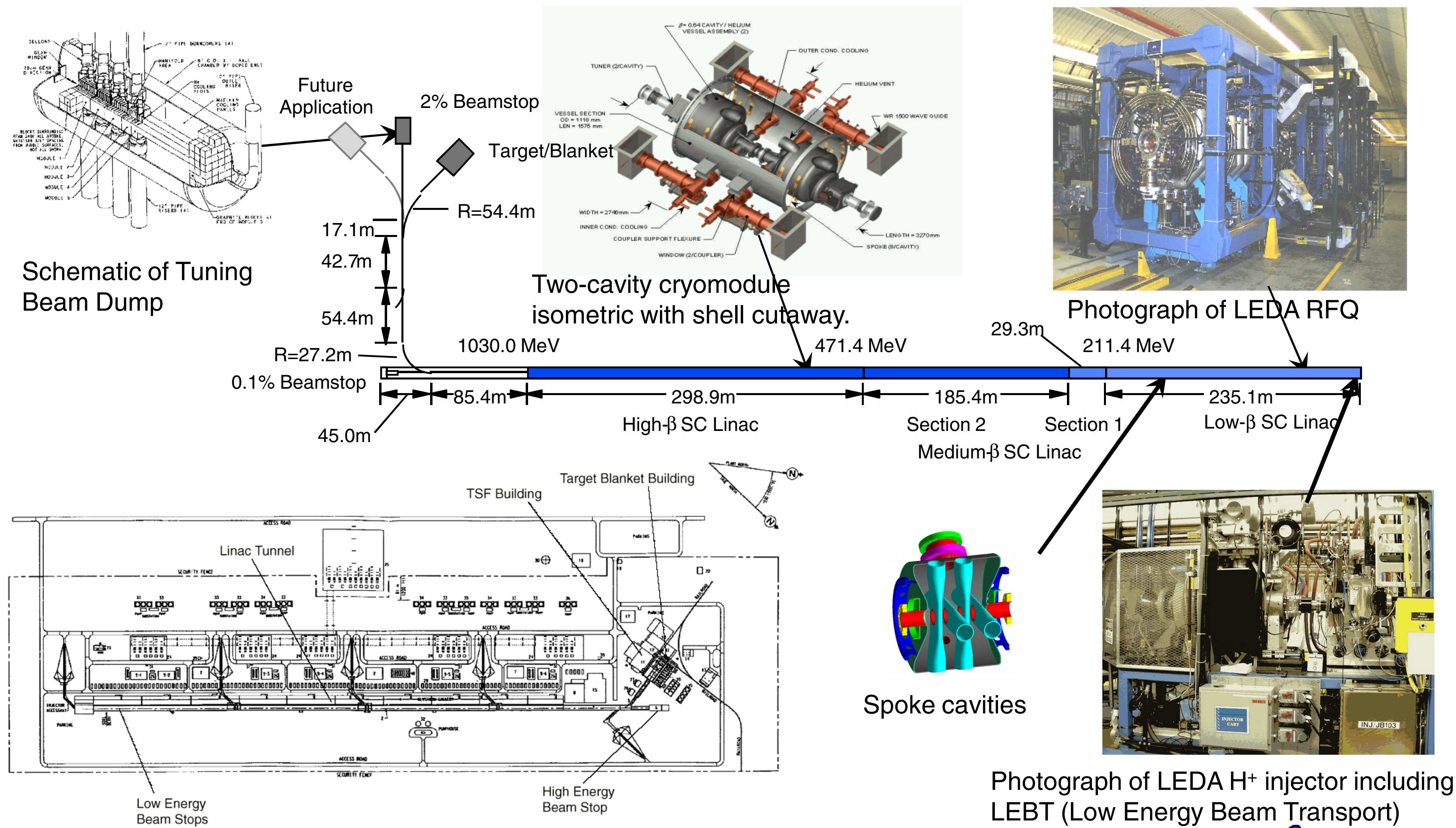
Design parameters

- Accelerator power: 20MW (1.3mA, 1.5GeV)
- Reactor power: 800MW
- SC-LINAC (0.1-1.5GeV): 472m
- Reactor size: 10m ϕ x 8m height
- LBE 5 ktons
- Earthquake resistant building

Summary and conclusions

- n_TOF @ CERN is a first class neutron Time Of Flight facility
- It is specially well suited for radioactive materials, samples of rare materials or low cross section.
- Excellent facility for measuring neutron capture and fission cross sections and the most needed cross sections identified for nuclear applications (nuclear waste minimization). Sustained support from the EU framework programs.
- The measurements provide very relevant parameters to improve the understanding and physics models of nuclides and reactions.
- Combined with high performance detectors and DAQ allows to perform high accuracy cross section measurements.
- The n_TOF potentiality was proved by successful operation from 2000 to 2004
- The current campaign, with improved setup, will allow to fully exploit its possibilities to fulfill the request of the highest priority nuclear data needs
- There are plans to enhance the performance with an additional short flight path and EAR2 that will allow to open a new frontier of sample masses, short lived isotopes and accurate measurements

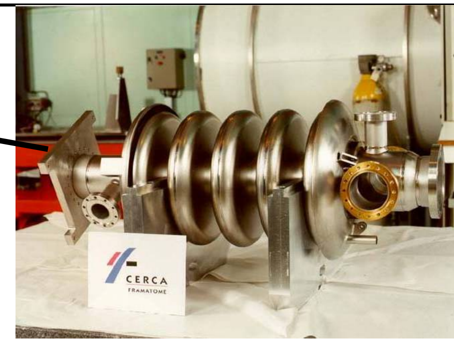
Work on the 1 GeV, 100 mA (100 MW) APT Accelerator and Target Provides the Design Basis for an ADS System



Baseline and Advanced SC Accelerator Design Concepts for Proton Linac for ADS

350 MHz spoke cavities | 700 MHz 5-cell ellip β=0.50 | 700 MHz 5-cell ellip β=0.64 | 700 MHz 5-cell ellip β=0.84

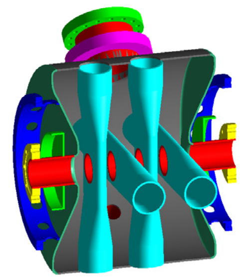
6.7 MeV β=0.12 | 130 MeV β=0.49 | 250 MeV β=0.61 | 1500 MeV β=0.79



β=0.64
5-cell
cavity

350 MHz spoke cavities | 350 MHz 5-cell spoke cavities

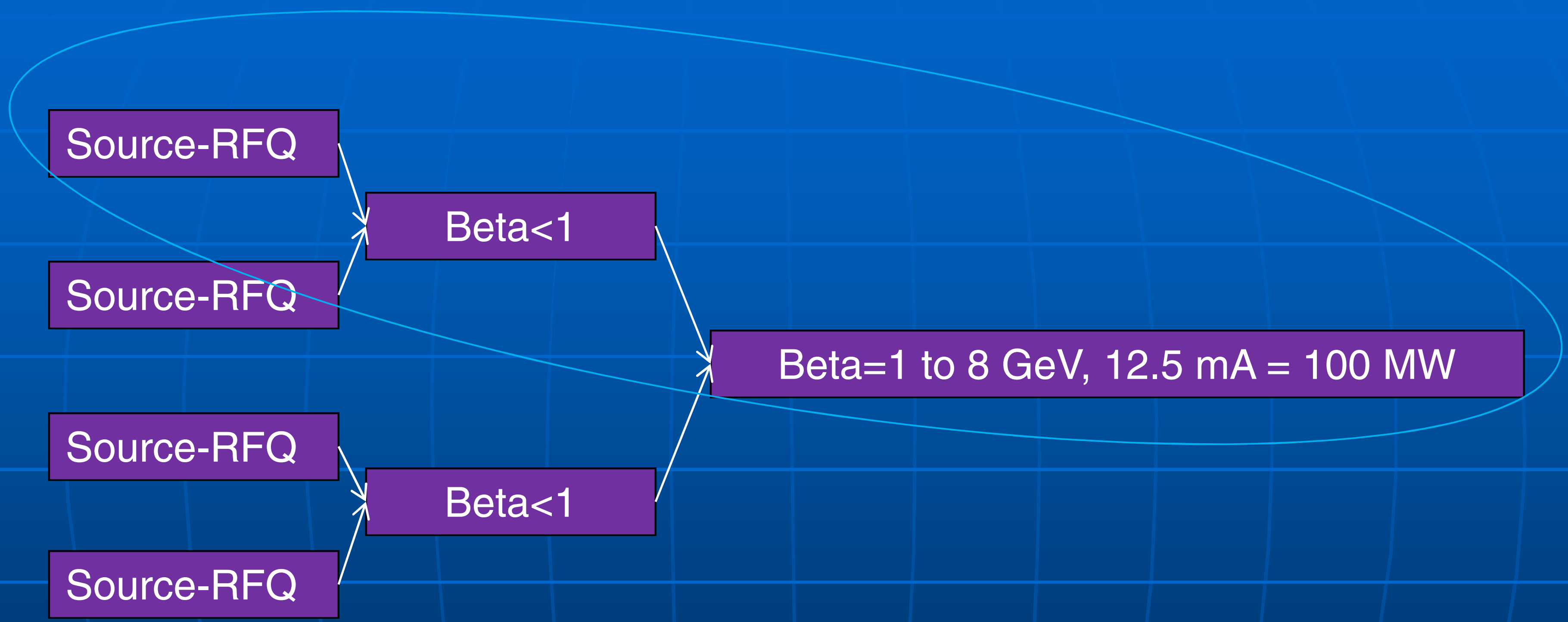
6.7 MeV | 130 MeV | 1500 MeV



As Part of the AAA Program, a β = 0.125, 5-Gap, 350 MHz Cavity was Developed

- Replaces APT-like baseline with all-superconducting linac that could reduce cost and improve performance and reliability (i.e. beam continuity).
- 4K Spoke cavities provide a higher temperature superconducting alternative to the 2K elliptical cavities.

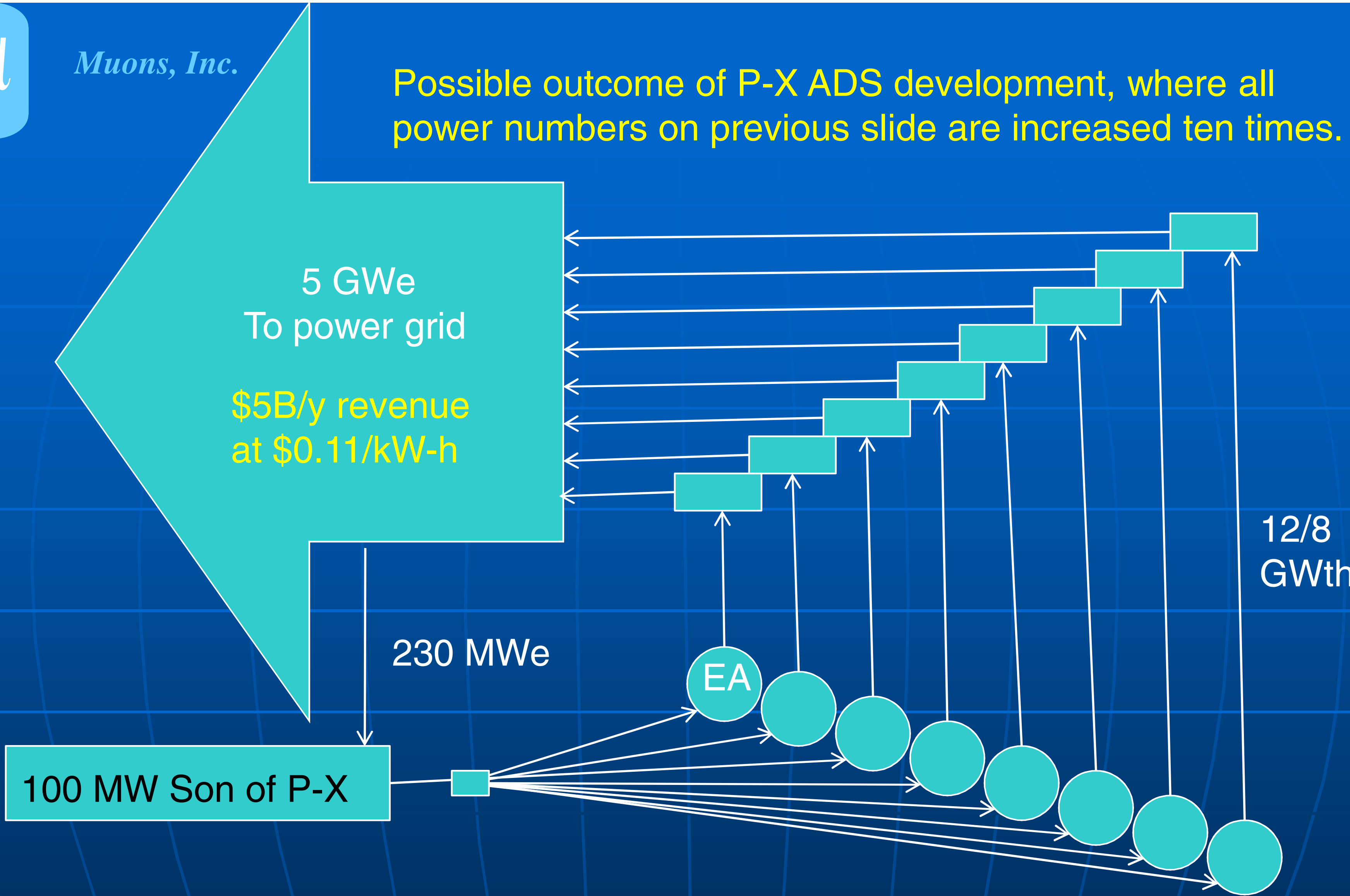
Son of P-X Conceptual Picture



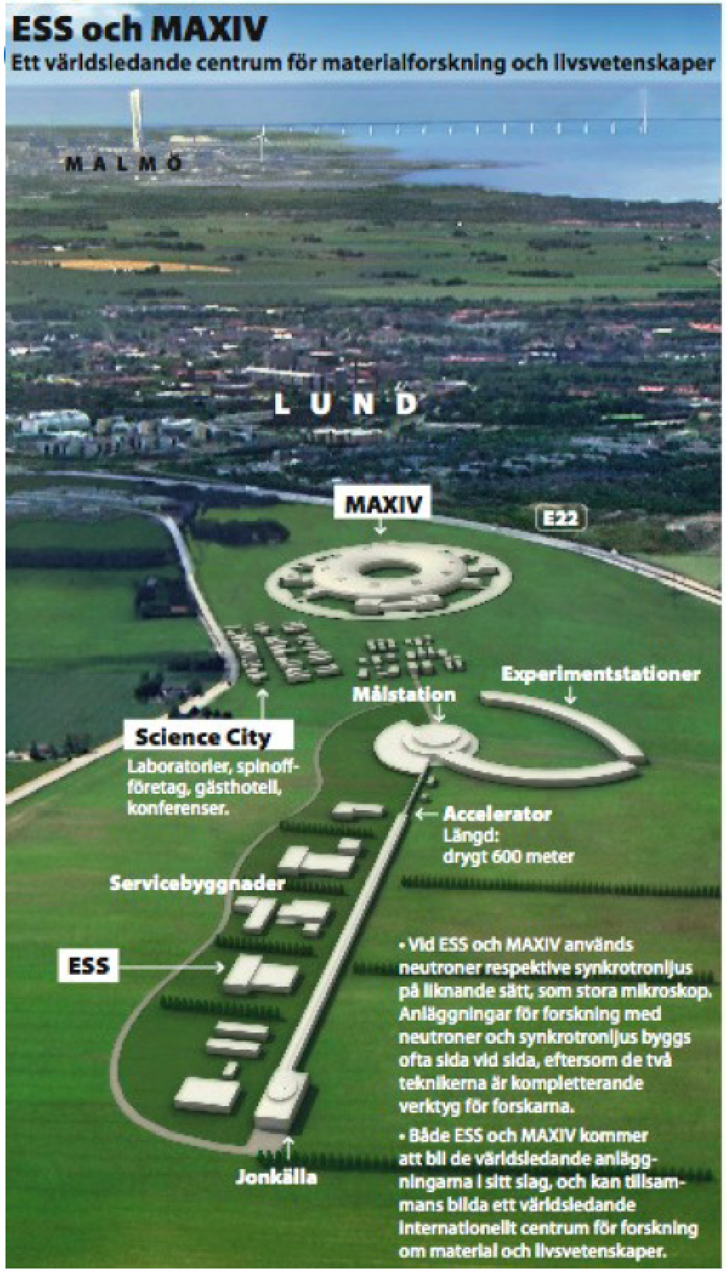
Less reliable components are duplicated. Maybe even the beta=1 part, too.

Muons, Inc.

Possible outcome of P-X ADS development, where all power numbers on previous slide are increased ten times.



In a few years the grid should be lossless and this power station can be placed anywhere, e.g. in a geologically, environmentally, etc. acceptable location.



Primary parameters

5 MW long pulse source
(upgrade to 7.5 MW?)

≤ 2 ms pulses

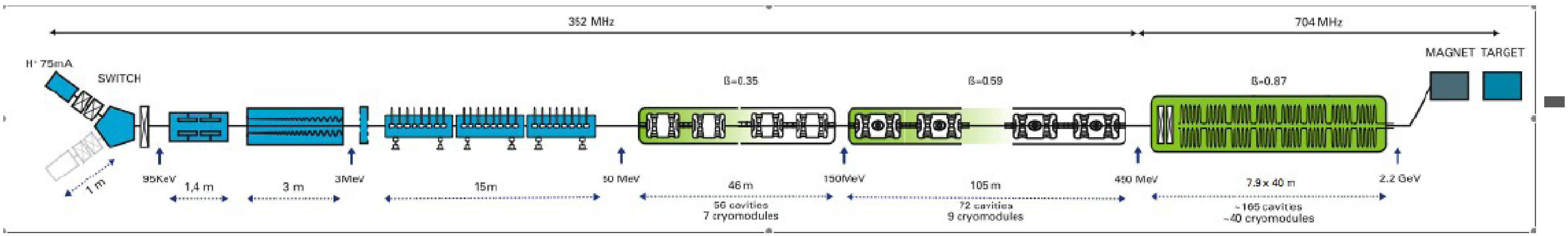
≤ 20 Hz

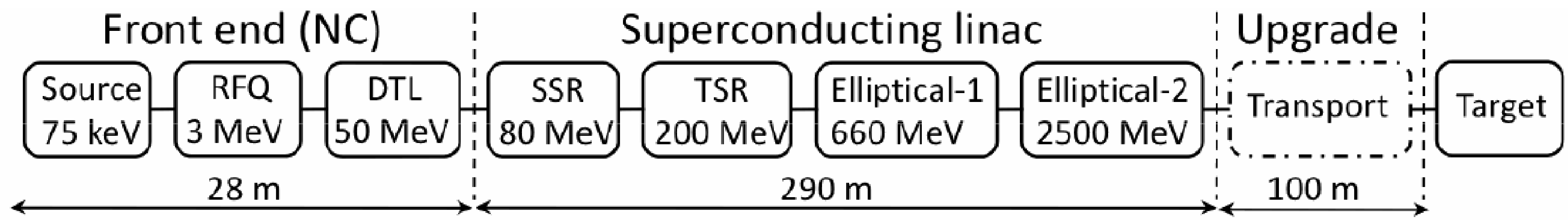
Protons (H+)

Low losses ! 1 W/m

High reliability, >95%

S. Peggs 5





INPUT		**B**		**S**
Average beam power	[MW]		5.0	
No. of instruments			22	
Macro-pulse length	[ms]	1.5		2.0
Pulse repetition rate	[Hz]		20	
Proton kinetic energy	[GeV]	2.2		2.5
Peak coupler power	[MW]	1.2		1.0
Beam loss rate	[W/m]		<1.0	
OUTPUT				
Duty factor		0.03		0.04
Ave. current on target	[mA]	2.3		2.0
Ave. pulse current	[mA]	75		50
Ion source current	[mA]	~ 90		60
Total linac length	[m]		~ 420	

System	**T** [K]	**Energy** [MeV]	**Freq.** [MHz]	β v/c	**Length** [m]
Source	300	0.075	–	–	2.5
LEBT	300	–	–	–	1.1
RFQ	300	3	352.2	–	4.0
MEBT	300	–	352.2	–	1.1
DTL	300	50	352.2	–	19.2
SSR	4	80	352.2	0.35	23.3
TSR	4	200	352.2	0.50	48.8
Ellipt-1	2	660	704.4	0.65	61.7
Ellipt-2	2	2500	704.4	0.92	154.0

Integrate multiple perspectives

"Single particle interacts with core" dominates the dynamics?

- Fast simulations can aid design ....

Integrate:

- Front end halo generation
- Warm-to-cold transition (& design opportunities)
- SC linac halo losses (longitudinal → transverse)

Can LLRF be incorporated?

- Feed-forward is crucial in lowering SNS losses
- Connect ESS, L4, and SPL activities?
- Does warm-to-cold allow separable design problems?

Parting Thoughts

- If we had a clean beam of a few tens of mA at a few tens of MeV, we have the technology and the hardware to accelerate it to any energy
  - Experimental demonstration still needed
    - Front end demonstrator and test bed is crucial
  - Many options, optimal design still an open question
    - For a linac, ~350 and 700 MHz
  - Substantial design and development work done one decade ago,
    - APT: 100 mA
    - ATW: 30 mA
    - IFMIF (prototype under construction): 125 mA, 40 MeV, D
    - SNS, ESS

Parting Thoughts

- What are the critical questions/issues?
  - Accelerator (reliable operation at high cw power, a few MW)
    - Origin of trips, fast recovery
    - Are the trip rates realistic?
  - How can Px contribute to ADS
    - CW front end/HINS at ADS-relevant current
    - MW-scale cw low-loss demonstrator
    - 650 MHz intermediate section (β~0.9)
- From the proton linear accelerator physics aspect
  - The beam physics up to several 10s of mA is well understood
  - The critical accelerator physics is at ~<50 MeV
  - We do not yet have the simulation tools to accurately predict halo formation and evolution when we include all the accelerator errors (static and dynamic)
  - Benchmark codes against existing machines and test them on a MW-class demonstrator