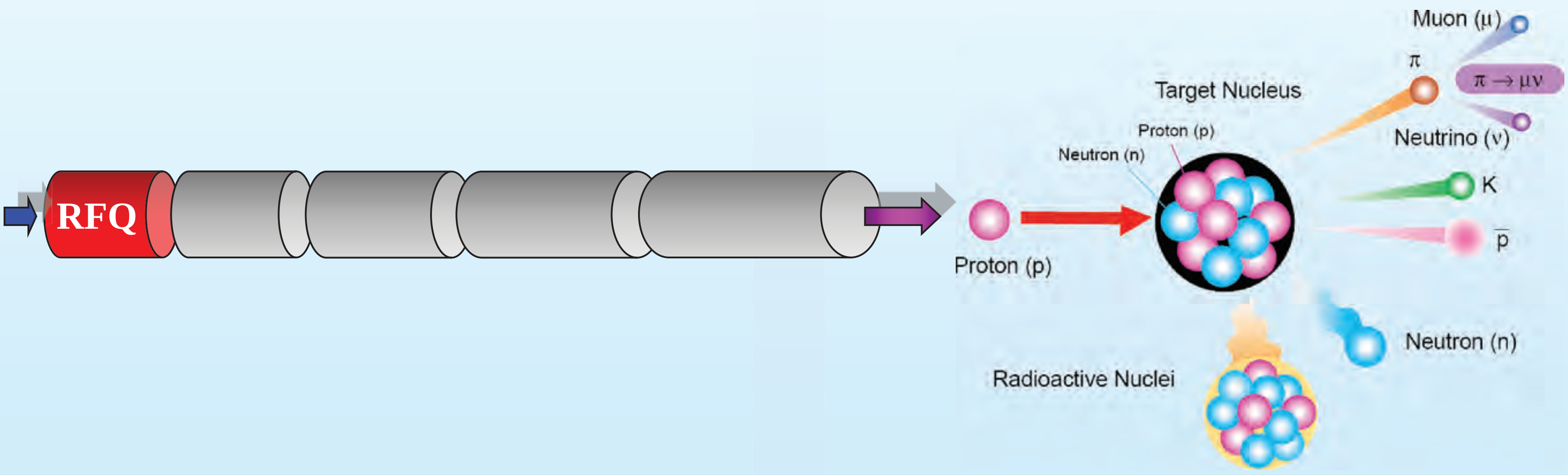
RFQ Beam Dynamics Design for Large Science Facilities and Accelerator Driven Systems

Chuan Zhang

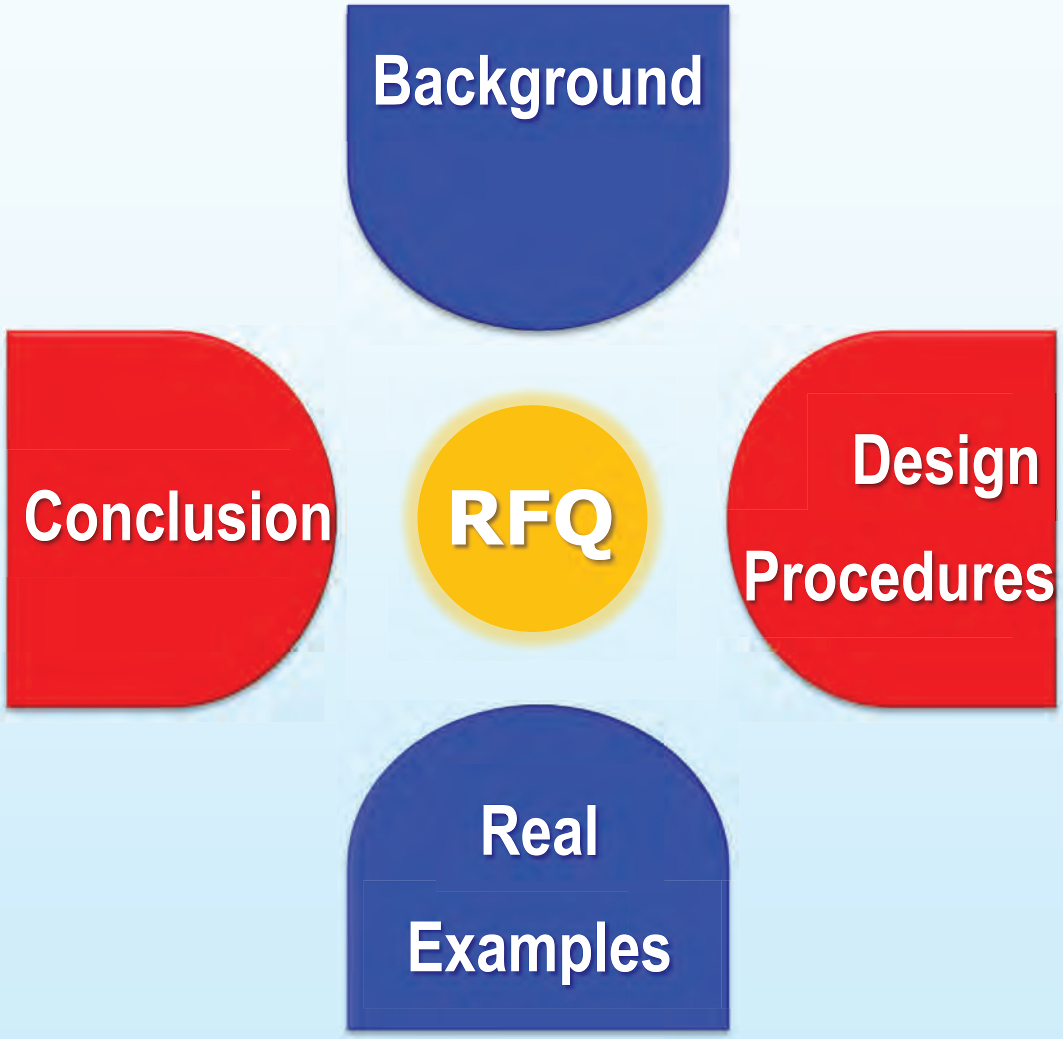
Institute for Applied Physics, Goethe-University

zhang@iap.uni-frankfurt.de

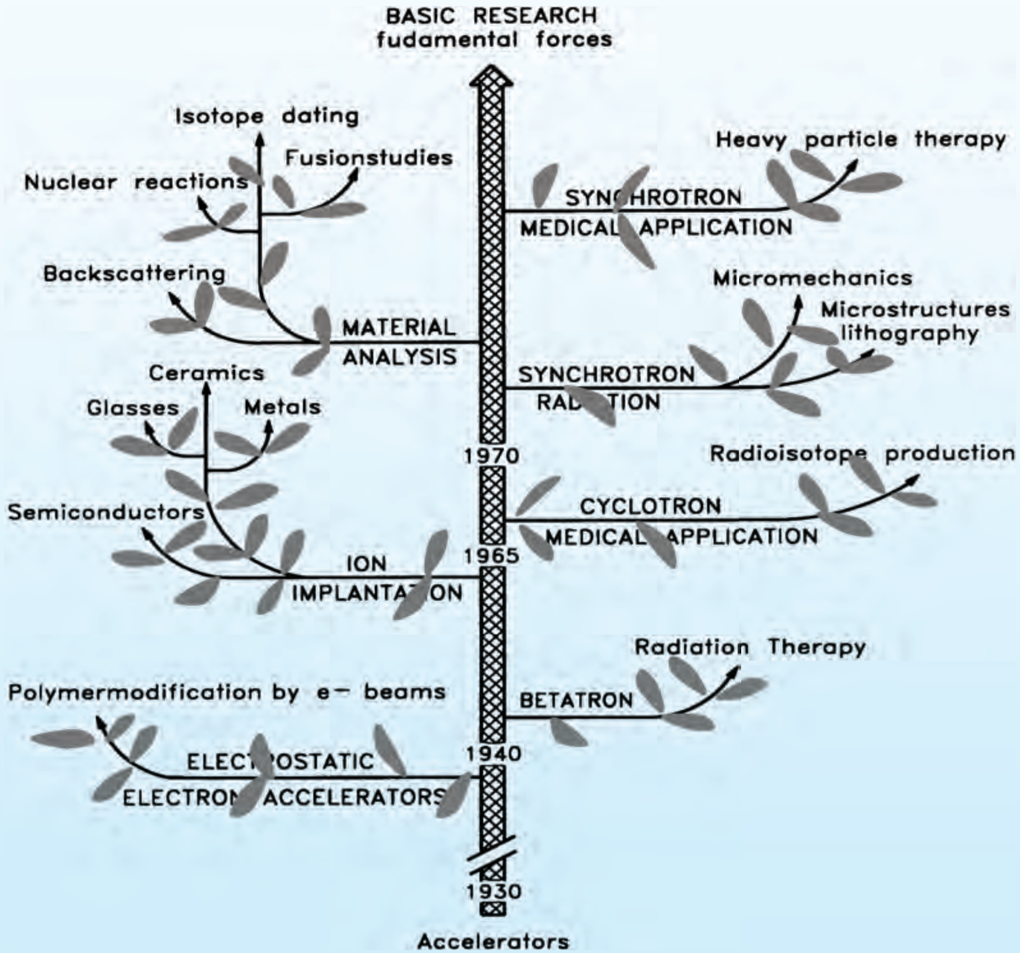


52nd ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams

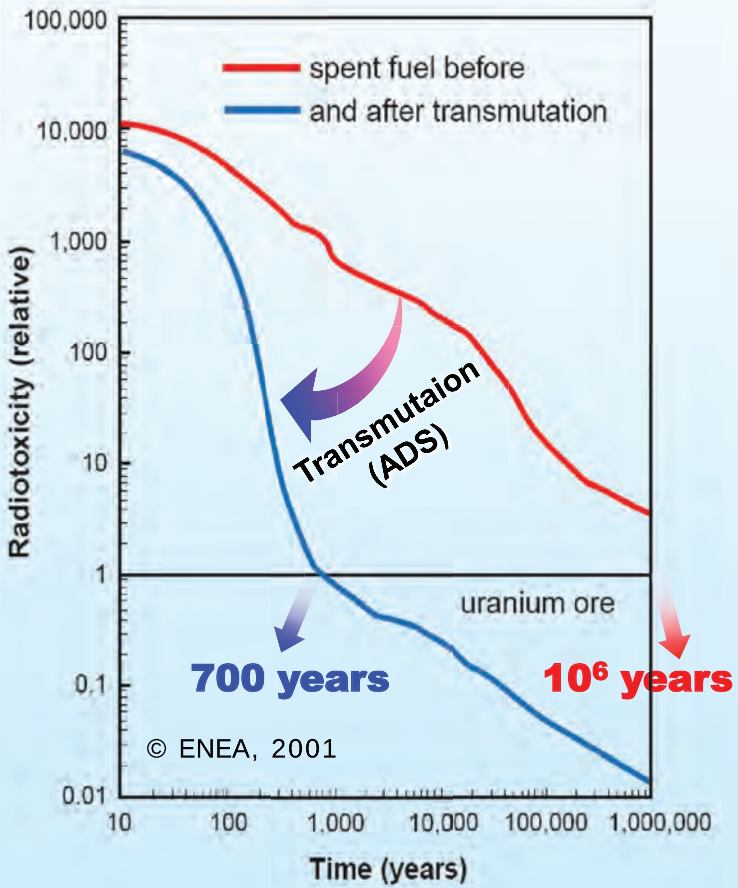
HB2012, Beijing, China, Sept. 17-21, 2012


Background
Conclusion
RFQ
Design
Procedures
Real
Examples

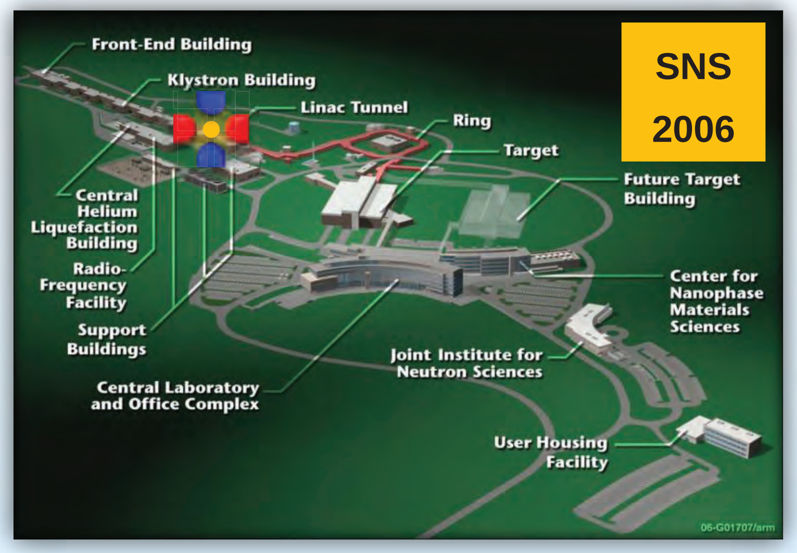
Accelerators for Science & Applications

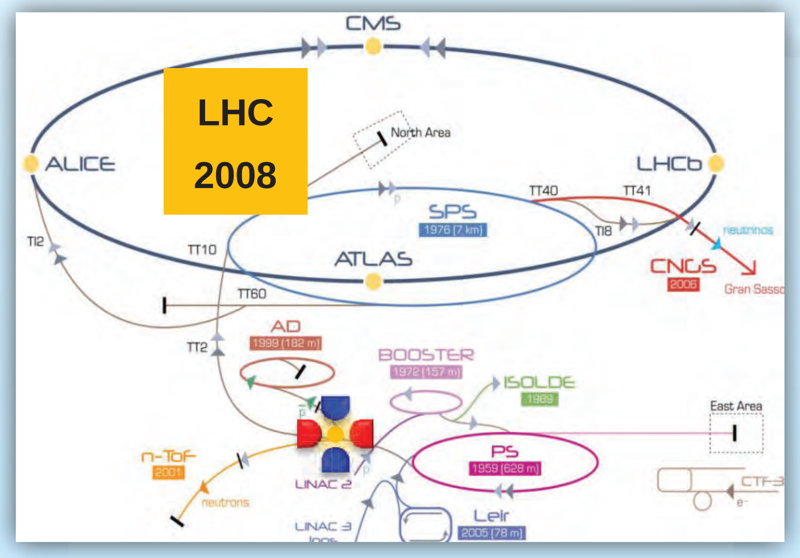


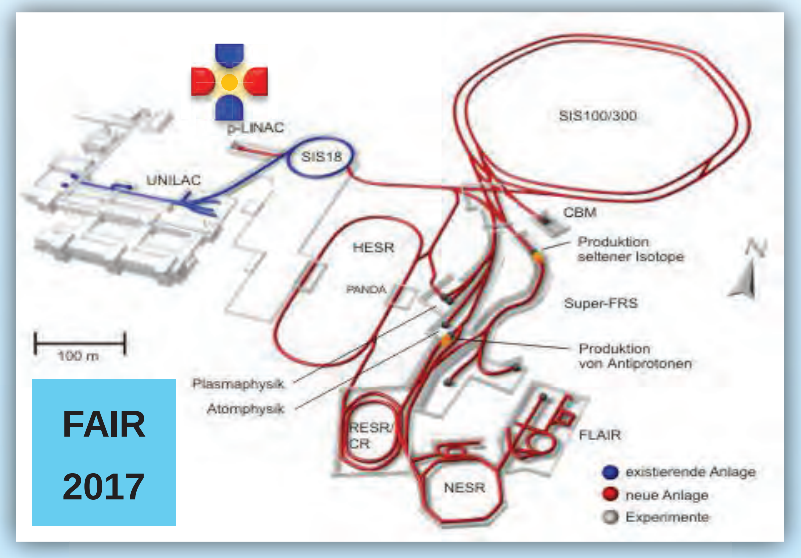
Plot: U. Amaldi & K. Bethge



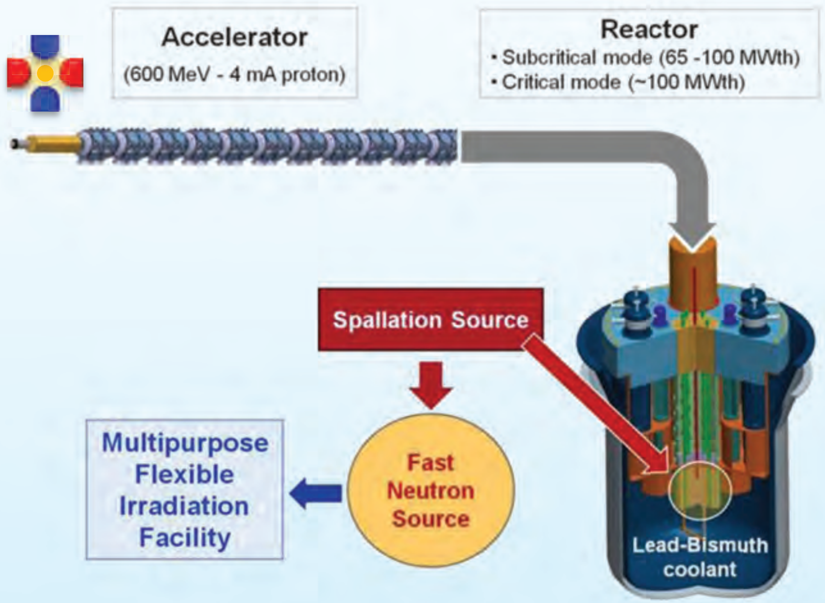
Accelerator-Based Science Centers







Accelerator-Driven Systems

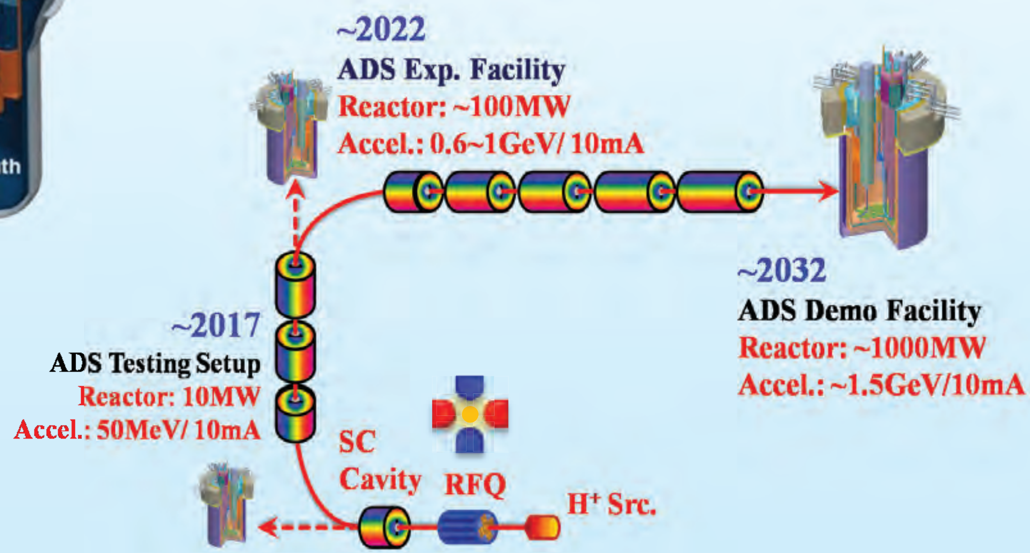


MYRRHA

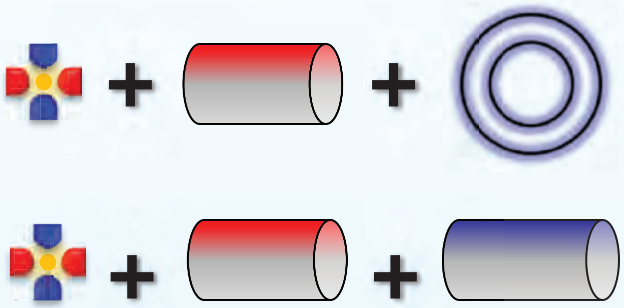
2023

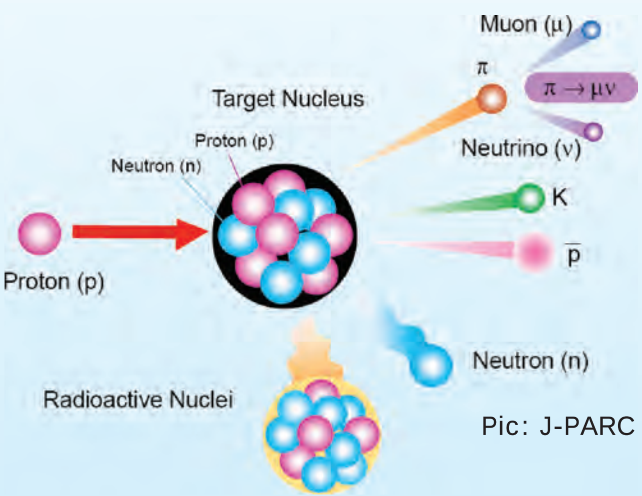
China ADS

2032



"Everything is Hard at the Beginning"





Pic: J-PARC

Peak Intensity × Duty Cycle

Space-Charge

Sparking / Cooling

High V

Low V

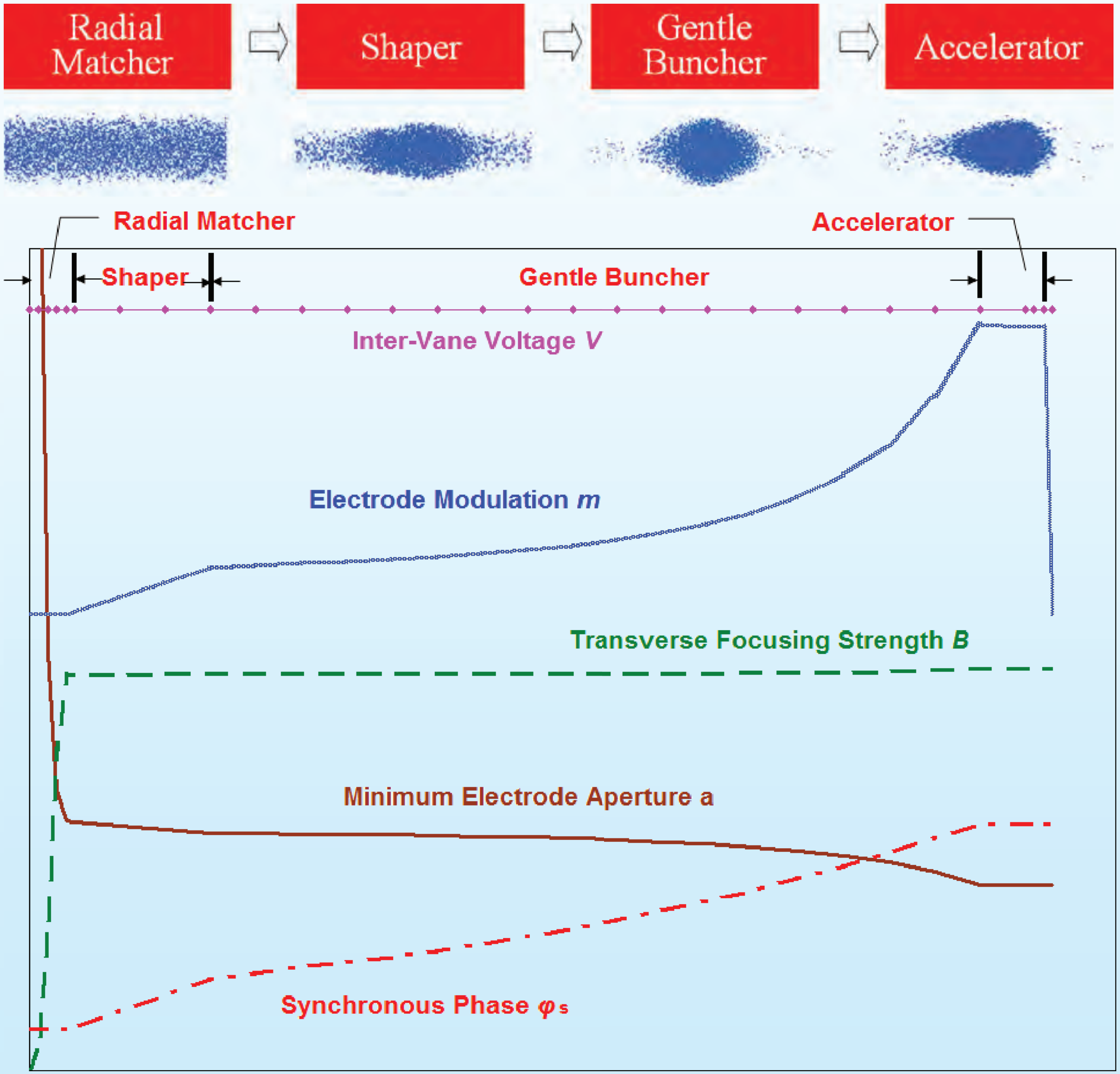
Modest V

Low Beam Losses (Hands-on Maintenance)

Good Beam Quality (Downstream HoM, Quenching)

Short Length (Costs)

LANL Four-Section Procedure



K-T Condition:

to maintain a constant beam density for an adiabatic bunching

- **Longitudinal small oscillation frequency**
- **Separatrix length in cm**

$$B \equiv \frac{qU\lambda^2}{Mc^2 r_0^{\ 2}}$$

The Shortcomings of the LANL Method

GB: beam bunching is not efficient (will lead to a long structure).

SH: could be an important source of unstable particles.

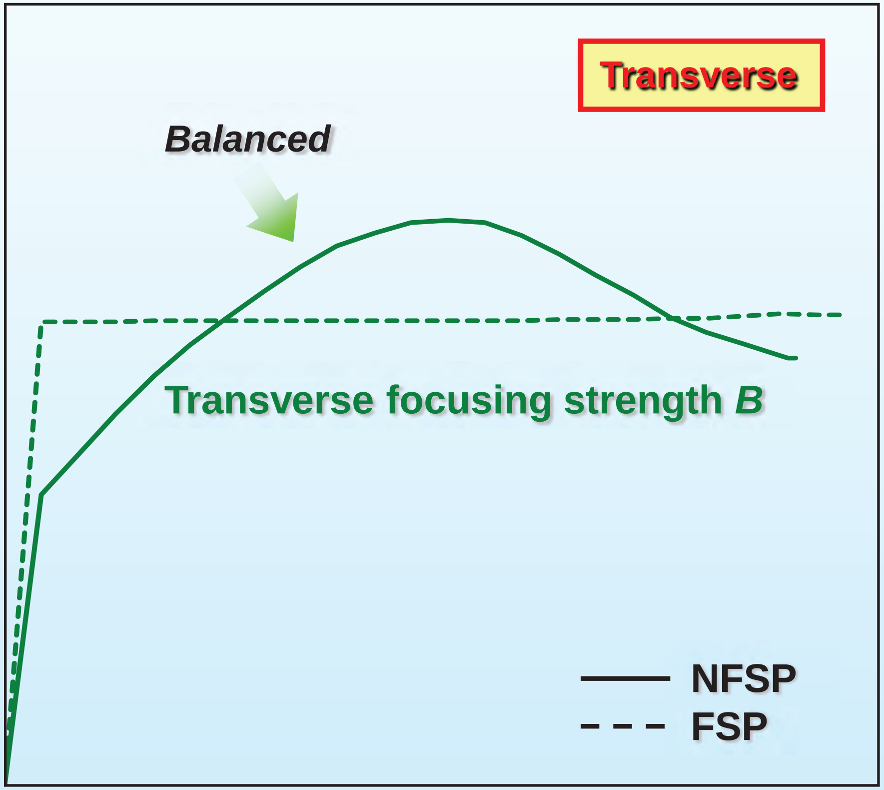
Constant *B*: deal with the longitudinal and tranverse planes separately;

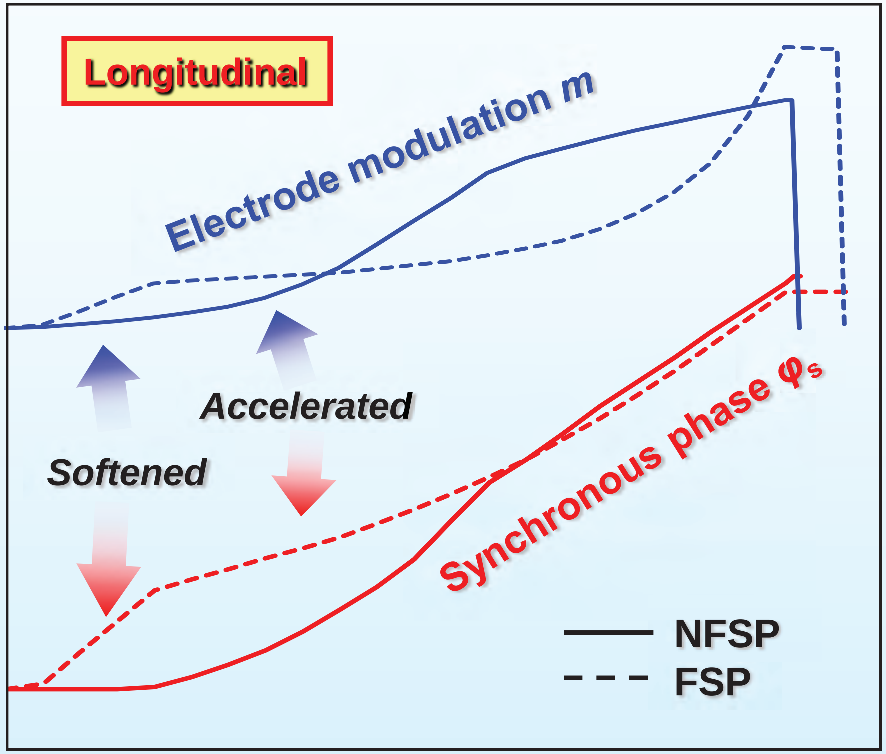
and MOST IMPORTANT, it ignores the space-charge effects.

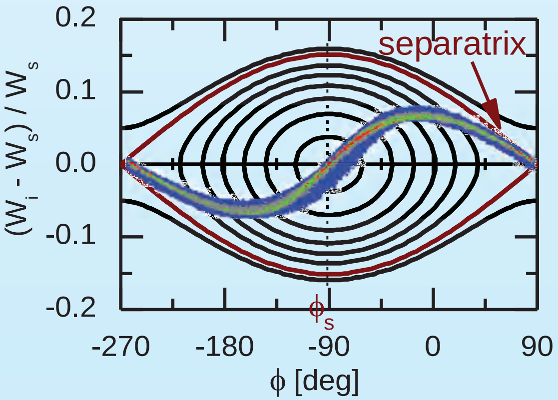
> The synchronous phase ϕ_s is controlled by controlling the center-to-center spacing of the unit cells. Combining Eqs. (8.39) and (8.40) gives a prescription for specifying both $A(\beta_s)$, and $\phi_s(\beta_s)$ to maintain a constant bunch length. This adiabatic bunching approach is the basis of the bunching section of the RFQ, known as the gentle buncher. Although the space-charge forces have been neglected in this discussion, numerical simulation studies that include space-charge forces have shown that this procedure leads to an approximately constant bunch density and provides excellent control of space-charge-induced emittance growth. In practice, all of the bunching of an initial dc beam cannot be done adiabatically without making the RFQ too long. The prebunching is usually started in a section called the shaper using a prescription that ramps the phase and the acceleration efficiency linearly with axial distance. A schematic drawing of the pole tips of an RFQ designed for adiabatic bunching is shown in

T.P. Wangler, Principles of RF Linear Accelerators (1998), pp.241

New Four Section Procedure

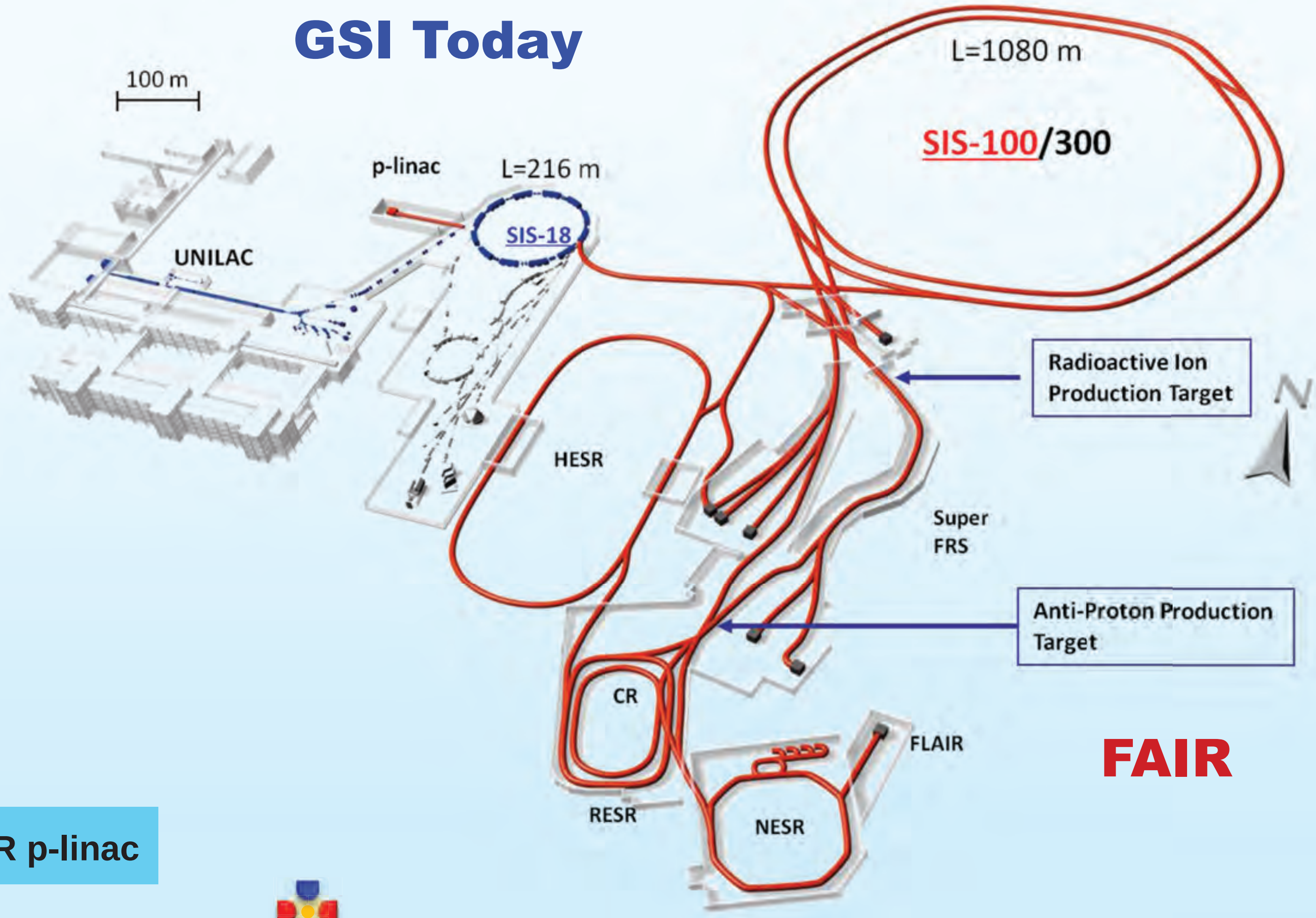




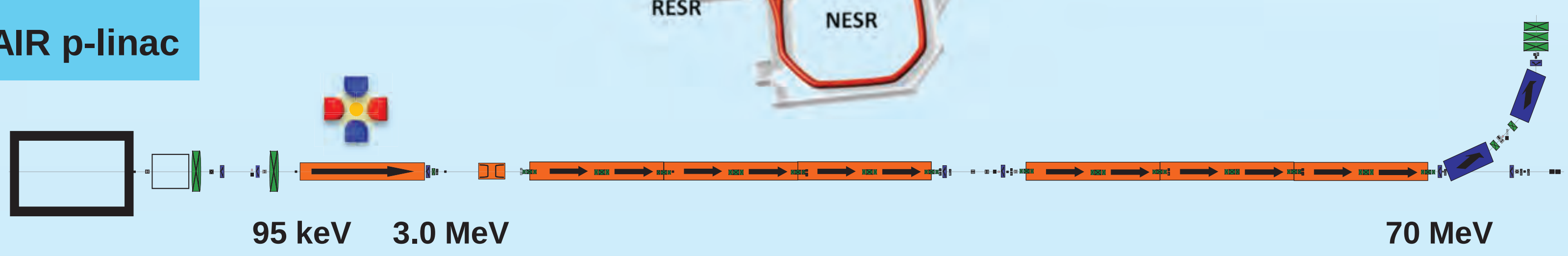


C. Zhang et al., NIM-A 2008 & PRST-AB 2004

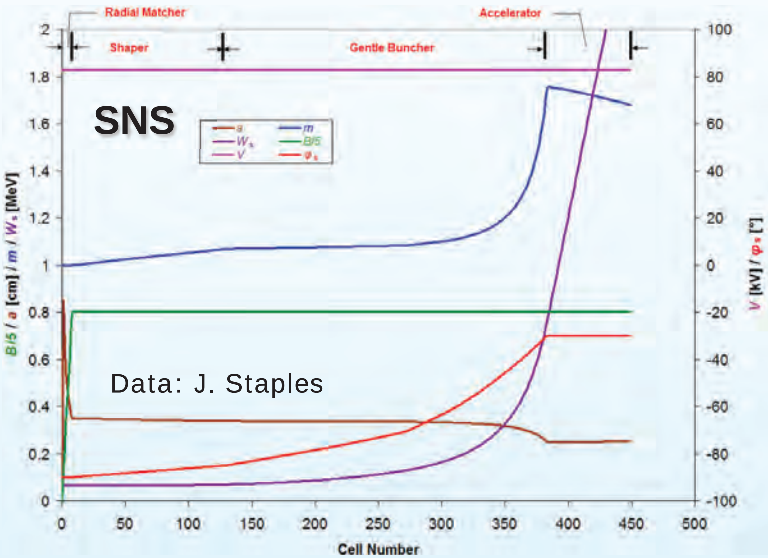
FAIR: Facility for Antiproton and Ion Research

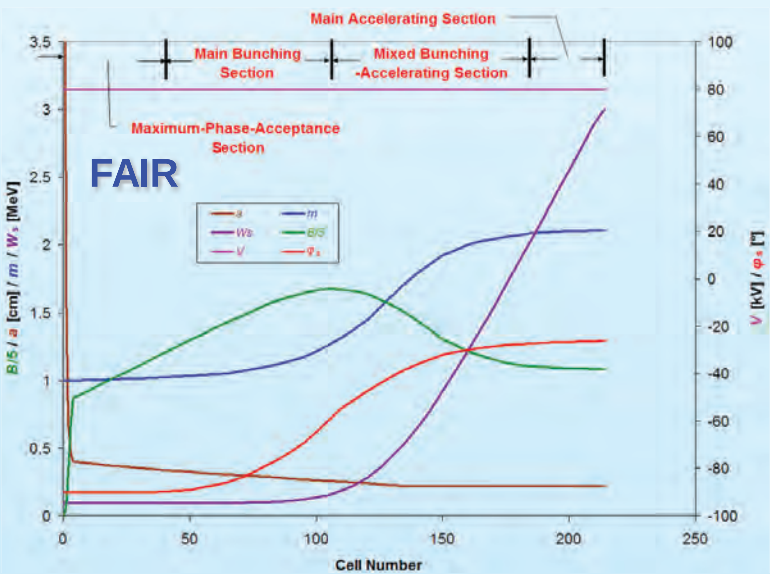


FAIR p-linac



FAIR Proton RFQ vs. SNS RFQ



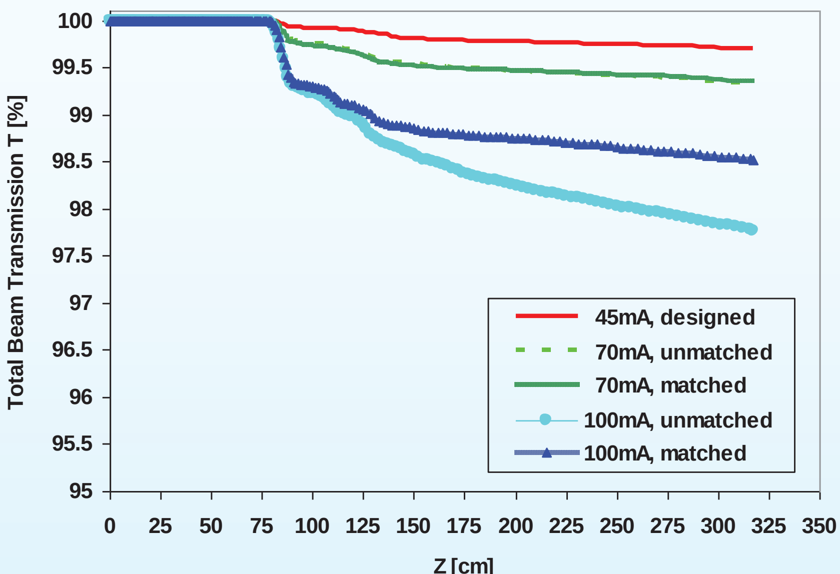


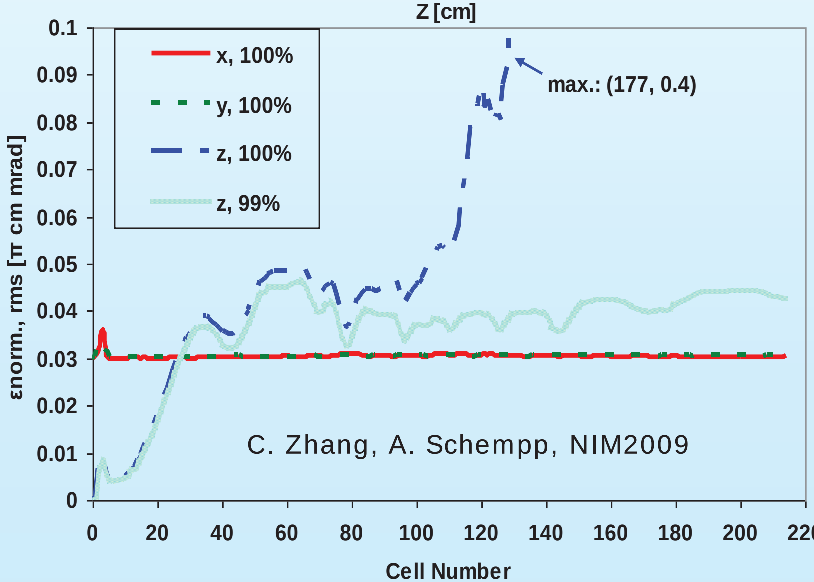
Parameters	SNS	FAIR		
Ion	H^-	H^+		
Duty cycle [%]	6.2	0.0144		
I_{peak} [mA] ✔	~60 (35)	45	70	100
f [MHz]	402.5	325.44		
W_{in} [MeV] ✔	0.065	0.095		
W_{out} [MeV] ✔	2.5	3		
U [kV]	83	80		
$\varepsilon_{in}^{trans.,norm.,\ rms}$ [π mm mrad] ✔	0.2	0.3		
$\varepsilon_{out}^{trans.,norm.,\ rms}$ [π mm mrad]	0.21 0.21	0.30 0.30	0.30 0.30	0.31 0.31
$\varepsilon_{out}^{longi.,\ rms}$ [π MeV deg]	0.103	0.163	0.153	0.152
L [m] ✔	3.7	3.2		
Transmission [%]	~90	98.7	97.2	95.3

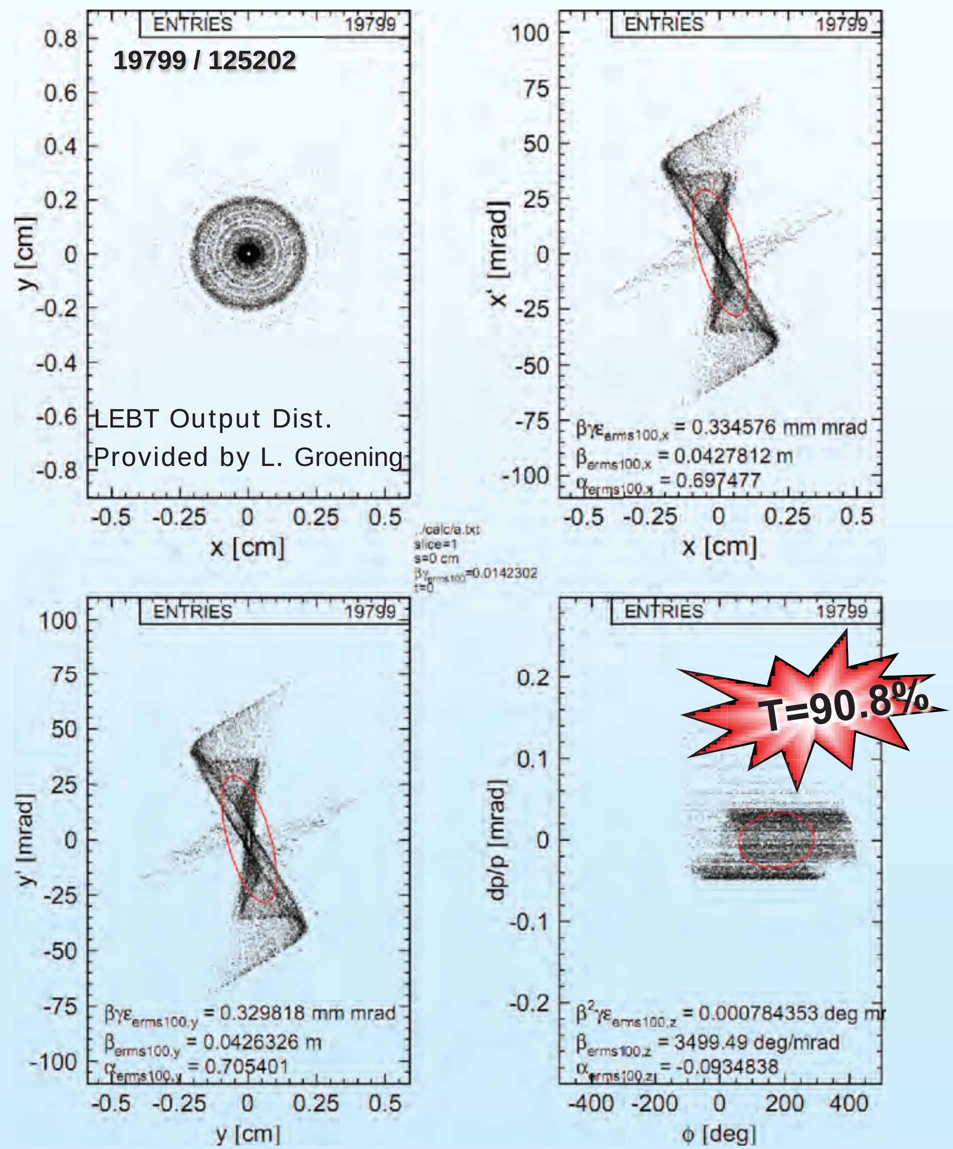
C. Zhang, A. Schempp, NIM-A 2009

For accelerated particles only

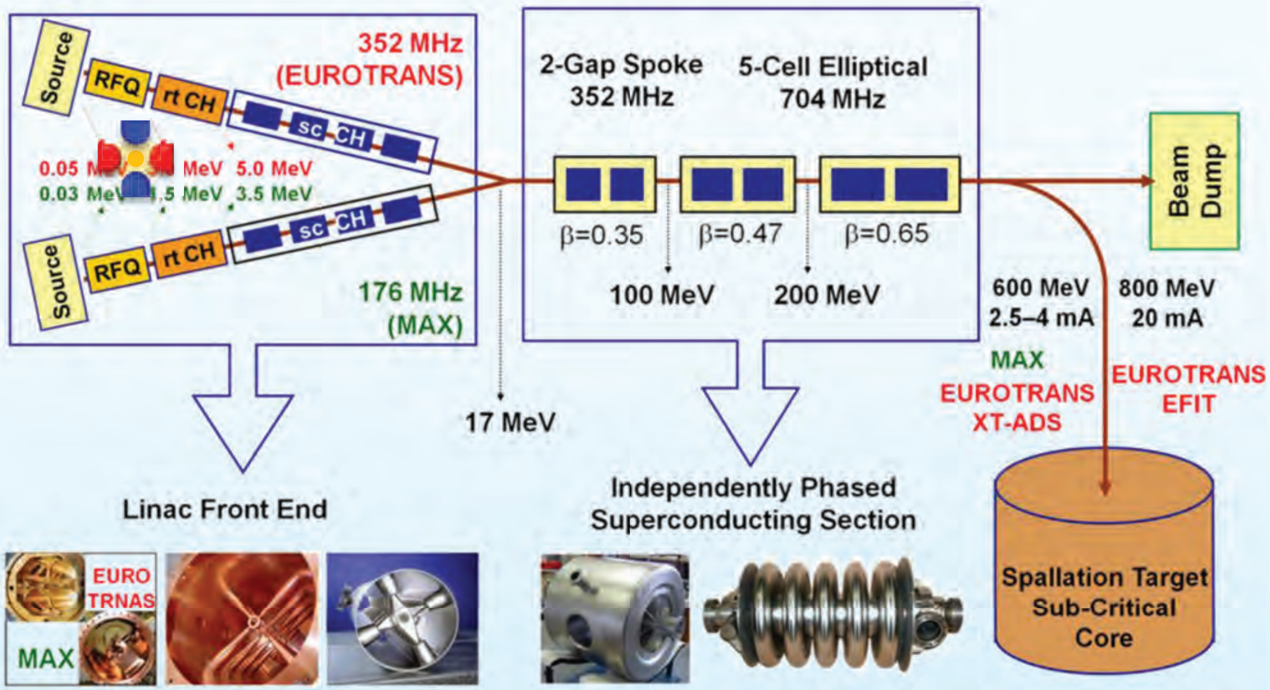
Design Results of the FAIR Proton RFQ







European ADS Projects



EUROTRANS – EUROPEAN RESEARCH PROGRAMME FOR THE TRANSMUTATION OF HIGH LEVEL NUCLEAR WASTE IN AN ACCELERATOR DRIVEN SYSTEM

(2005 – 2010)

MAX – MYRRHA Accelerator eXperiment, research & development programme – SEVENTH FRAMEWORK PROGRAMME

(2011 – 2014)

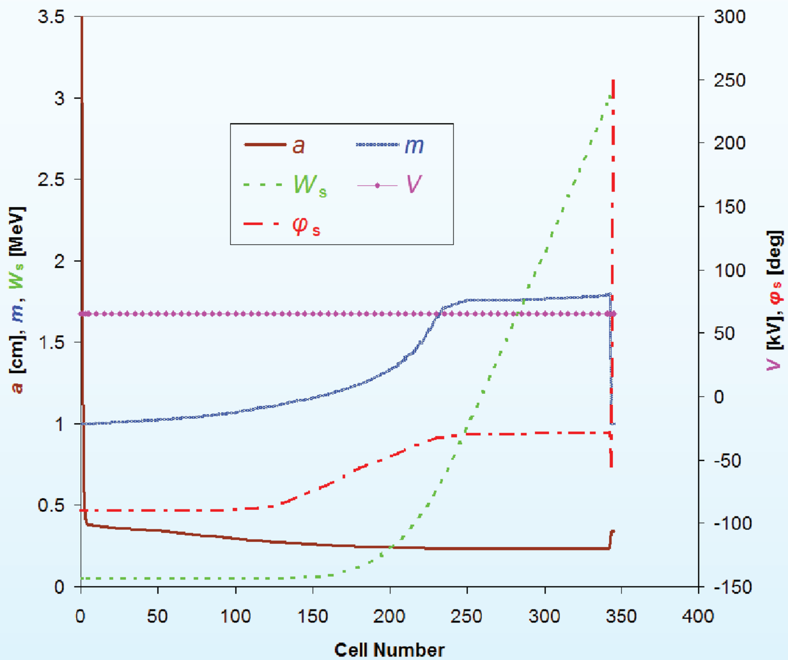
Specifications	XT-ADS	EFIT	MAX
Design current	5 mA	30 mA	5 mA
Beam trips	>1s: < 5 per three-month	>1s: < 3 per year	>3s: < 10 per three-month
Time structure	CW, with 200µs zero-current holes		

trips. The above requirement is still very aggressive. The number of beam trips on actual machines is at least two orders of magnitude higher (a couple per hour).

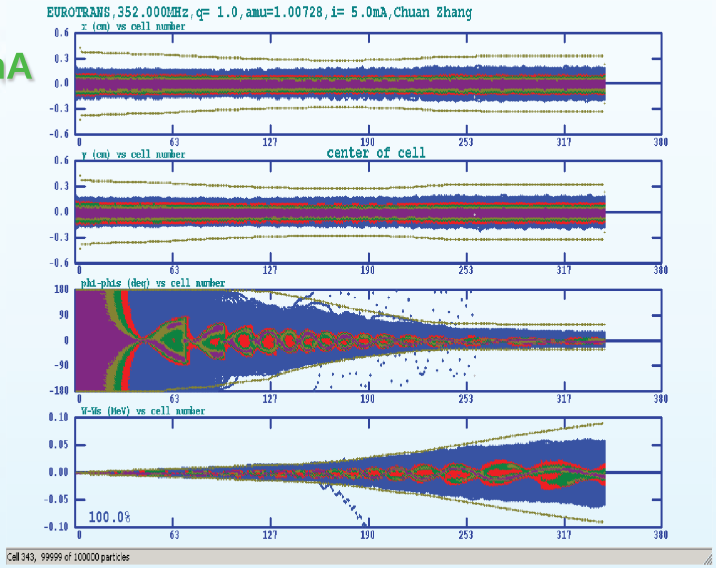
However, a distinction should be made between the availability, which ... the relevant parameter for ...

N. Pichoff, EPAC 2001

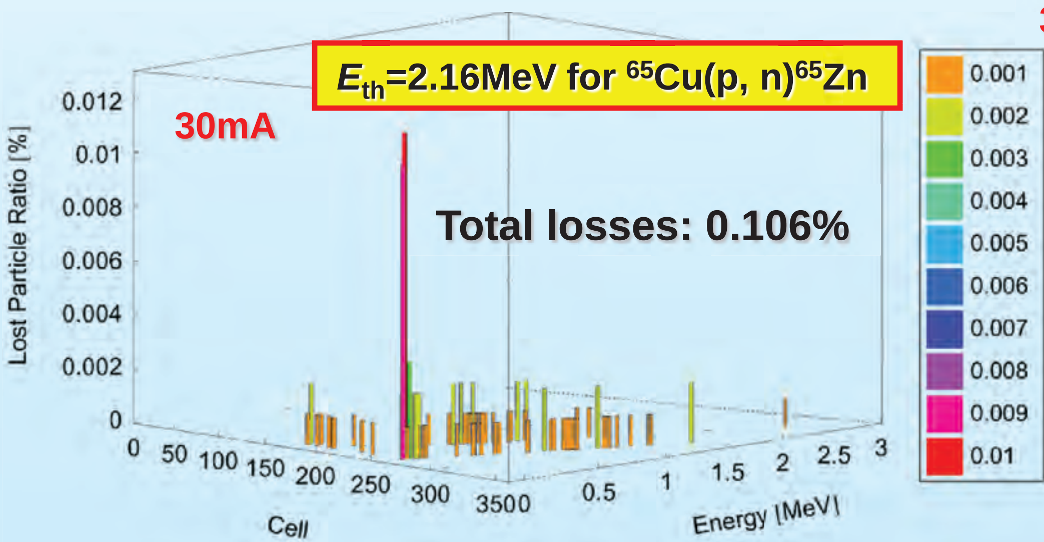
Design of the EUROTRANS RFQ

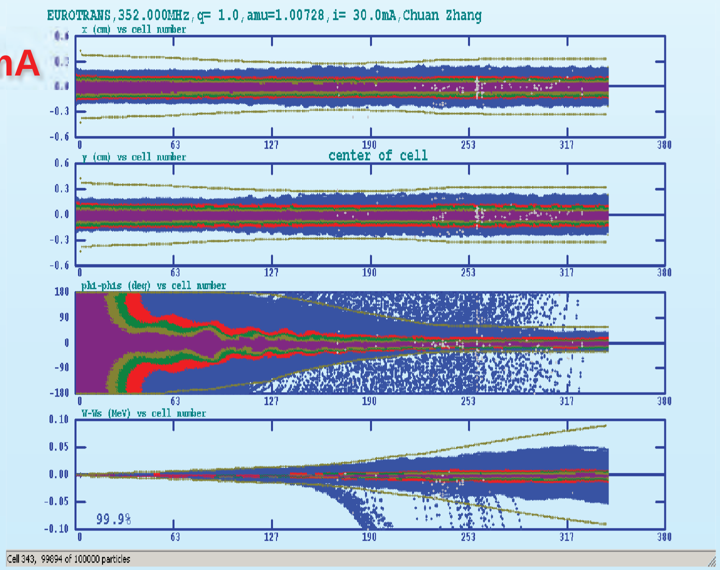


5mA

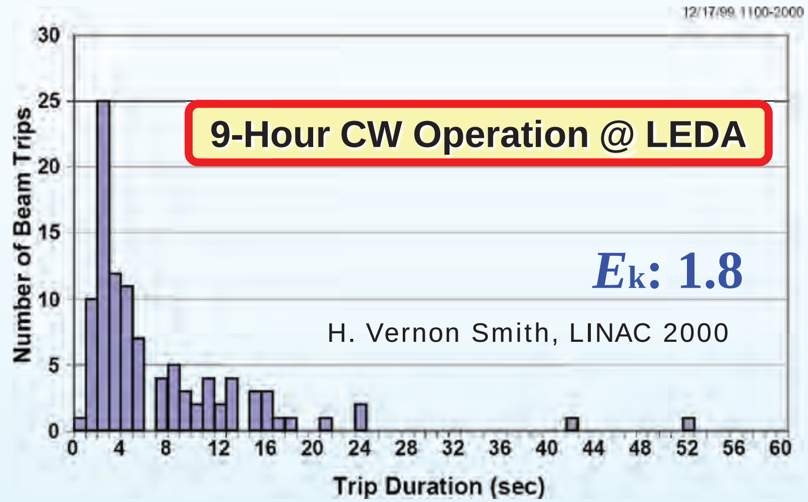


30mA

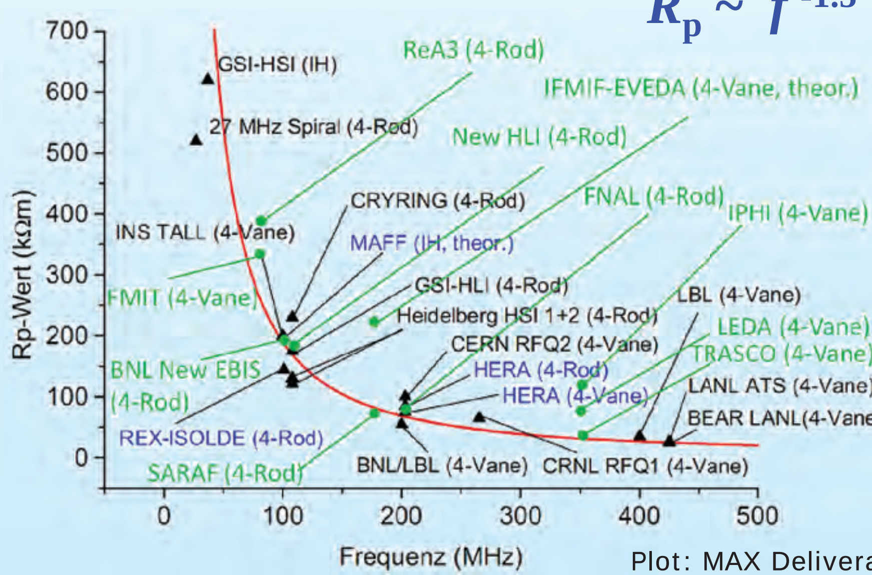




EUROTRANS: a Toy! MAX: a Real Boy !

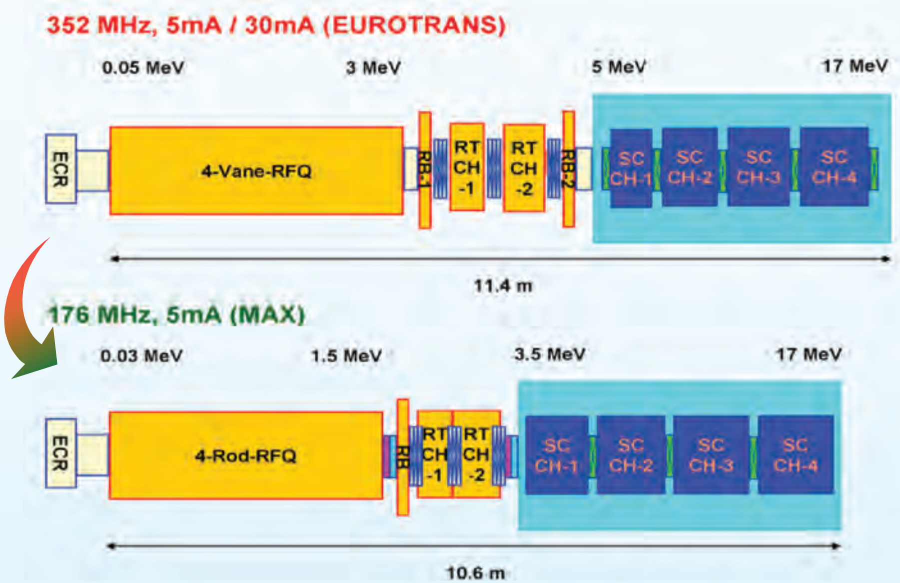


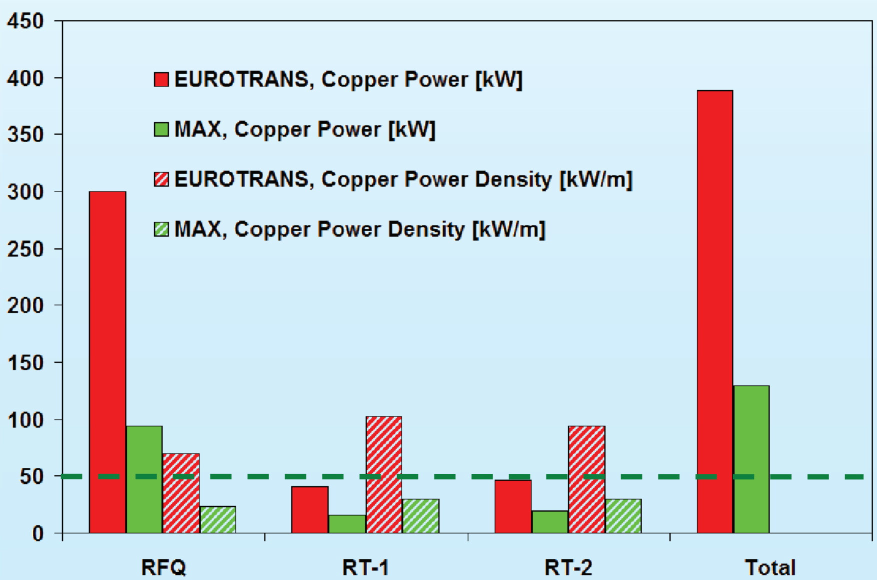
$R_p \sim f^{-1.5}$



Plot: MAX Deliverable 2.1

EUROTRANS RFQ vs. MAX RFQ

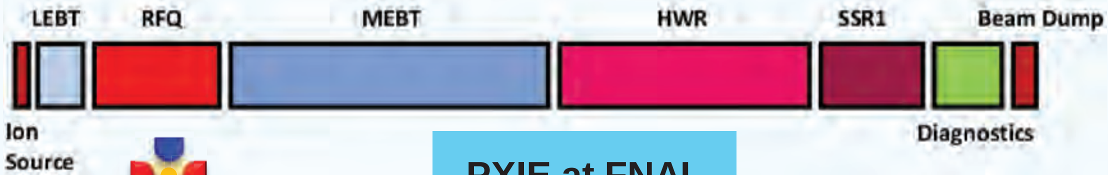




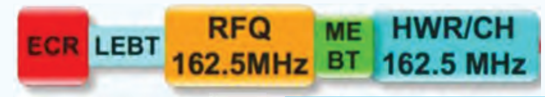
Parameter	EUROTRANS @5mA	MAX
RF Structure	4-Vane	4-Rod
f [MHz]	352	176
W_{in} / W_{out} [MeV]	0.05 / 3	0.03 / 1.5
U [kV]	65	40
E_k	1.7	1
g_{min} [mm]	2.6	3.6
$\varepsilon_{in}^{t., n., rms}$ [π mm-mrad]	0.2	0.2
$\varepsilon_{out}^{t., n., rms}$ [π mm-mrad]	0.21 / 0.20	0.22 / 0.22
$\varepsilon_{out}^{l., rms}$ [keV-deg]	109	64.6
L [m]	4.3	4.0
T [%]	~100	~100

C. Zhang, H. Klein, H. Podlech et al., IPAC 2011, WEPS043

Project X Injector Experiment & China ADS Injector II



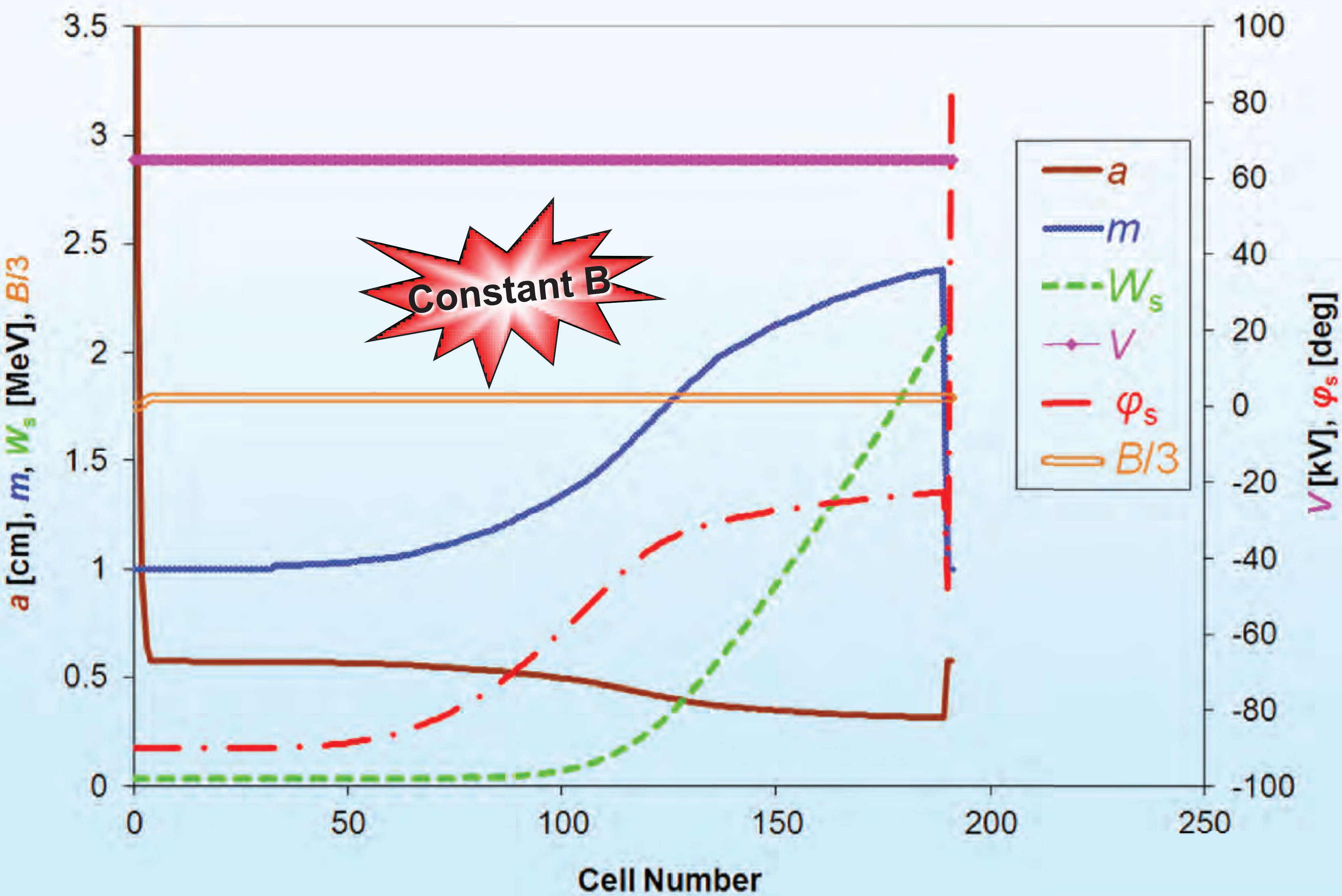
PXIE at FNAL



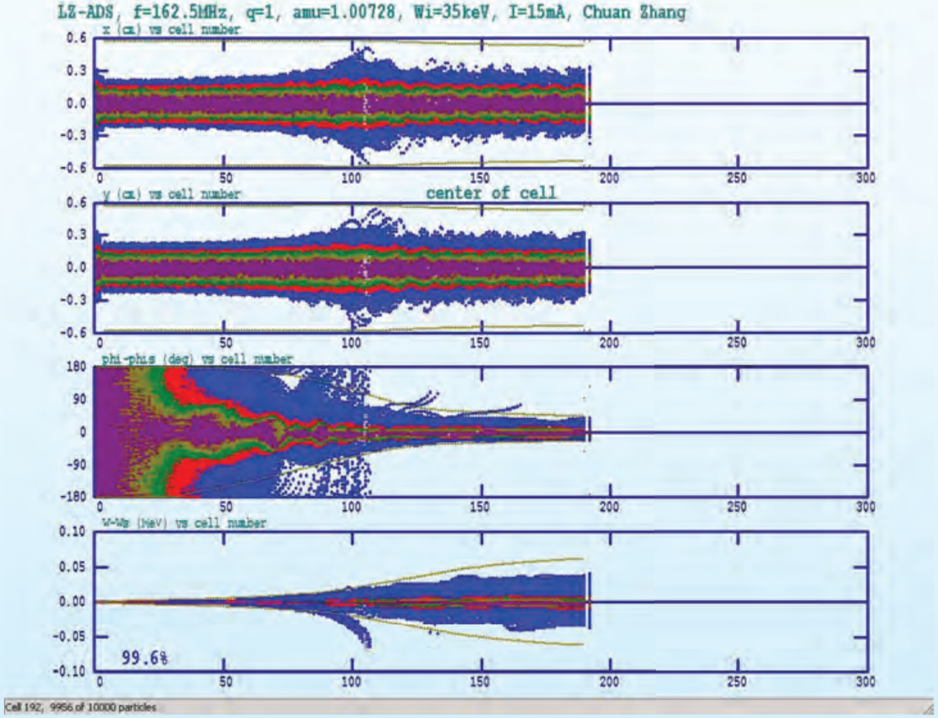
China ADS Project

Parameters	PXIE	China ADS
Ion type	H-	H+
Input energy [keV]	30	35
Output energy [MeV]	2.1	2.1
Duty factor [%]	100	100
Frequency [MHz]	162.5	162.5
Beam current [mA]	5 (nominal); 1-10	15 (nominal); 1-20
Input transverse emittance [πmm-mrad]	0.25 (norm. rms)	0.3 (norm. rms)
Transverse emittance growth [%]	≤10	≤10
Output longitudinal emittance [keV-nsec]	≤0.8	≤1.0
Transmission [%]	95	95
TWISS Parameter α [%]	≤1.5	≤1.5

Evolutions of Main RFQ Parameters

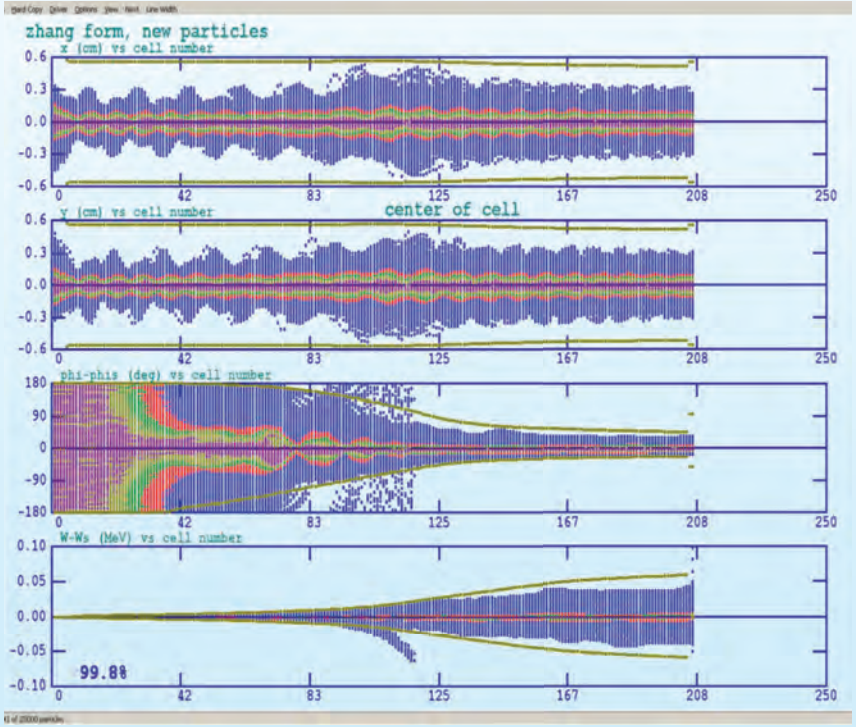


Beam Transport Simulations



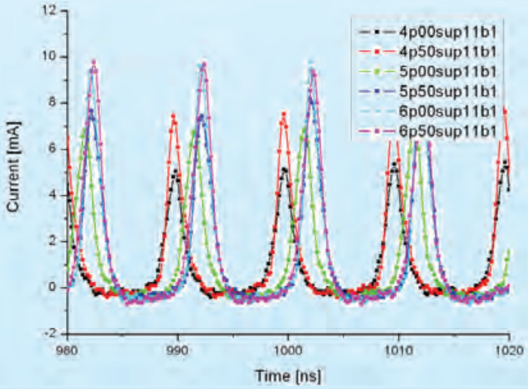
China ADS

PXIE



Conclusions

- The RFQ accelerator is the standard injector.
- Challenges to modern RFQs:
  - High beam intensity
  - High duty factor even CW
- An efficient design method for modern RFQs, "New Four Section Procedure", has been developed:
  - Applied for the designs of more than 20 RFQs:
    - Ion species: proton – uranium (*A*/*q*: 1 – 59.5)
    - Frequency [MHz]: 36.136 – 352
    - Peak beam intensity [mA]: 0 – 200 (300)
    - Duty factor [%]: 0.0144 – 100
  - Proven experimentally:
    - New EBIS RFQ for BNL
    - New HLI RFQ for GSI



M. Okamura et. al., PAC 2009

Vielen Dank

謝謝

Thank You