Development of RFQ Accelerators for Modern Scientific and Applied Research

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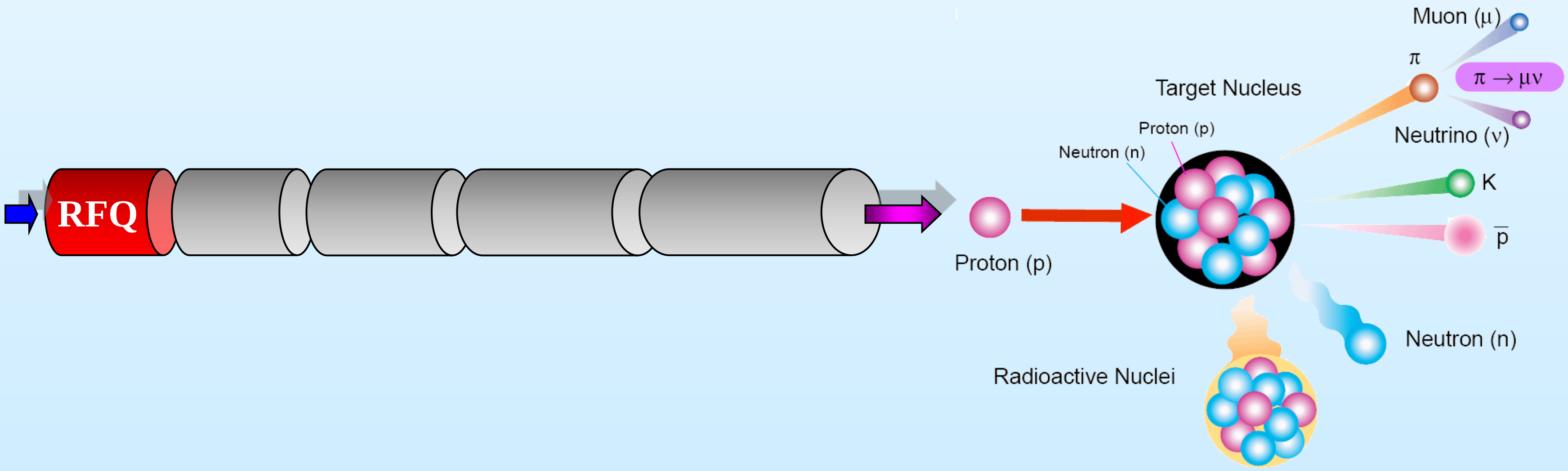


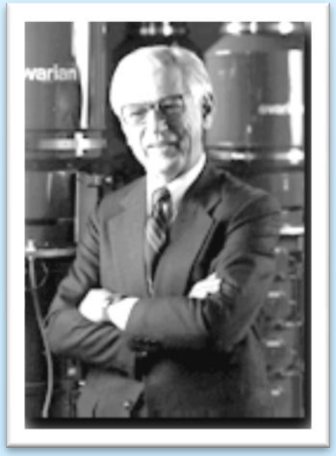
Seminar at Lawrence Berkeley National Laboratory, United States, May 31, 2012

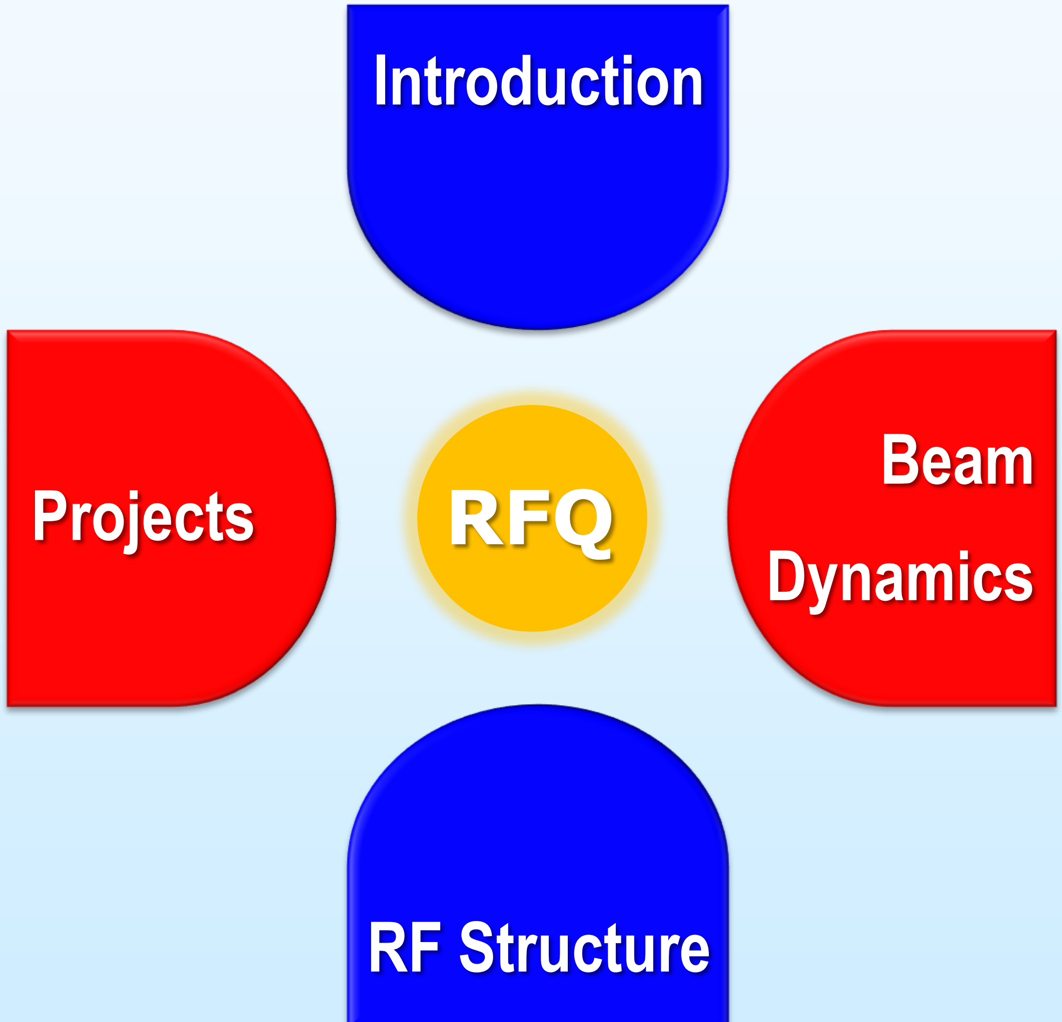
San Francisco Bay:
A Cradle for Modern Accelerators

1930: Ernest O. Lawrence invented the cyclotron at University of California, Berkeley.

1947: Luis W. Alvarez built the first Drift Tube Linac for protons at University of California, Berkeley.

1949: Edward L. Ginzton developed the first disc-loaded linac for electrons at Stanford University.

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Beam
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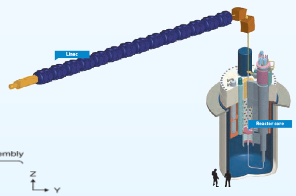
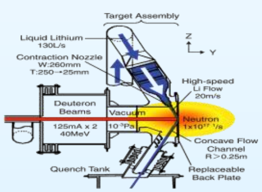
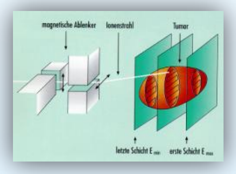
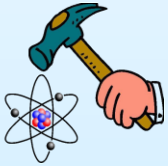
RF Structure

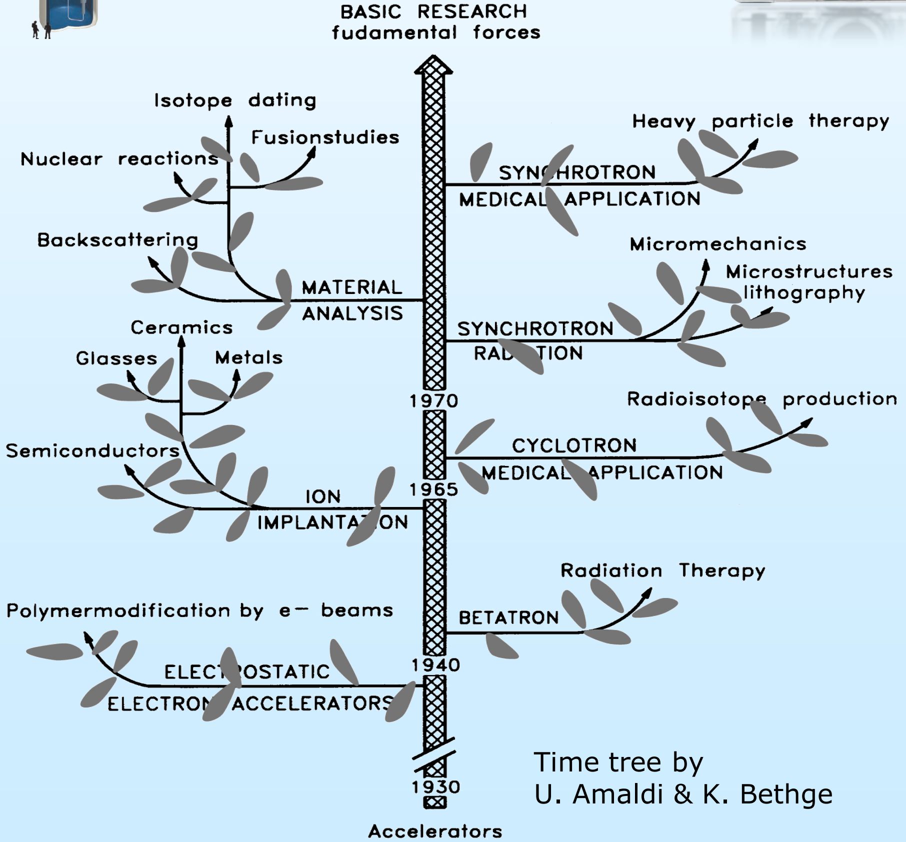
Scientific and Applied Research Driven by Accelerators









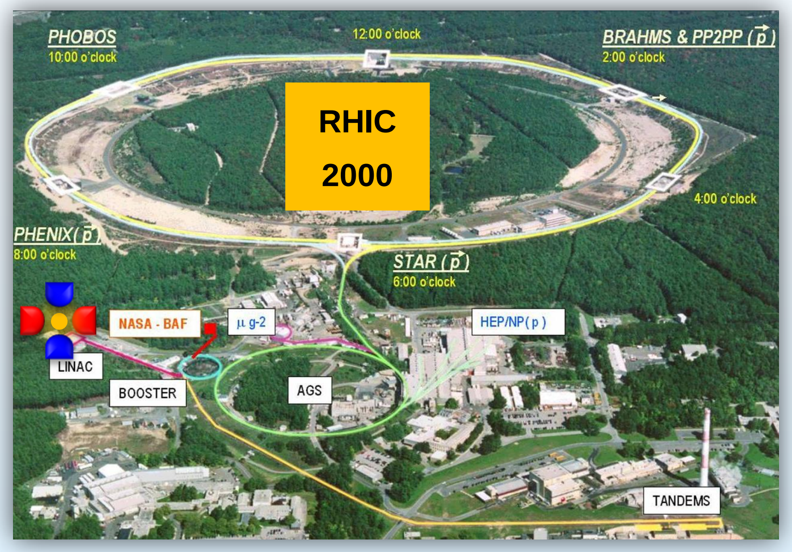


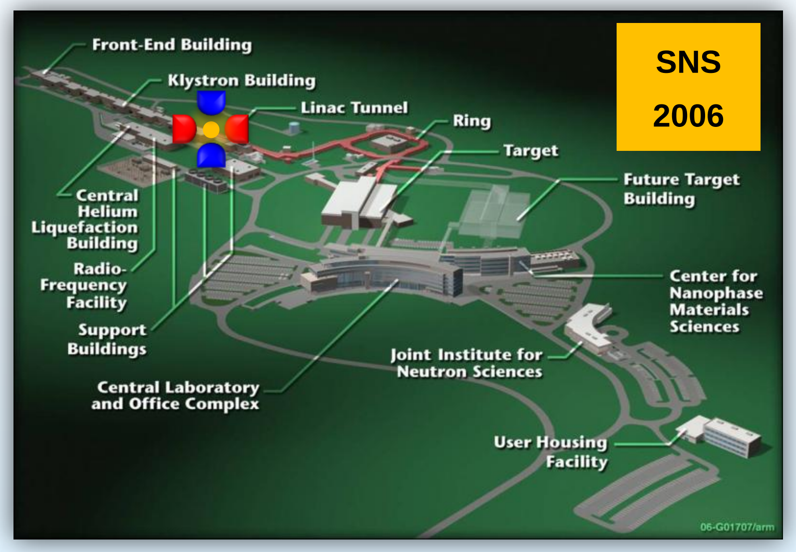
Time tree by
U. Amaldi & K. Bethge

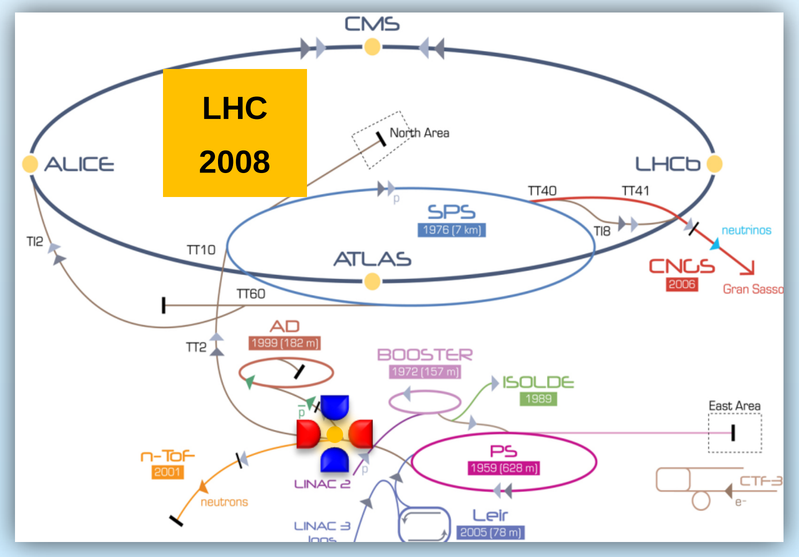

Pic: lbl.gov

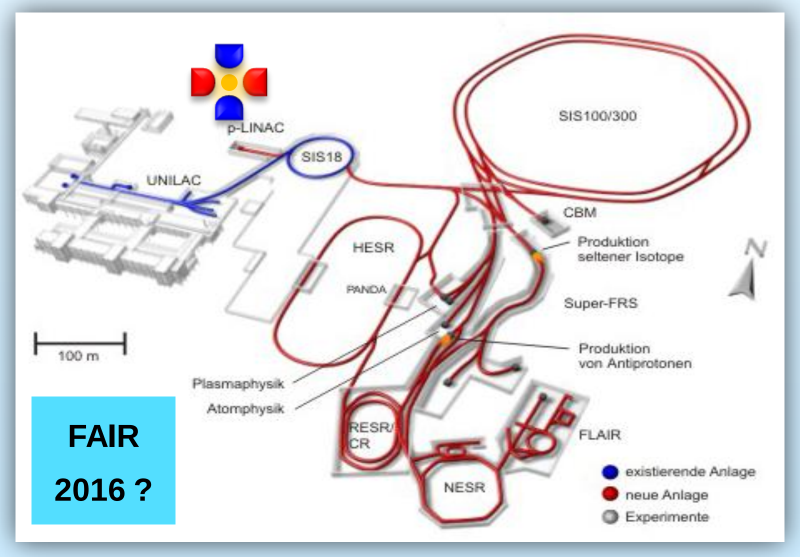

Pic: lbl.gov

Modern Accelerator-Based Science Centers





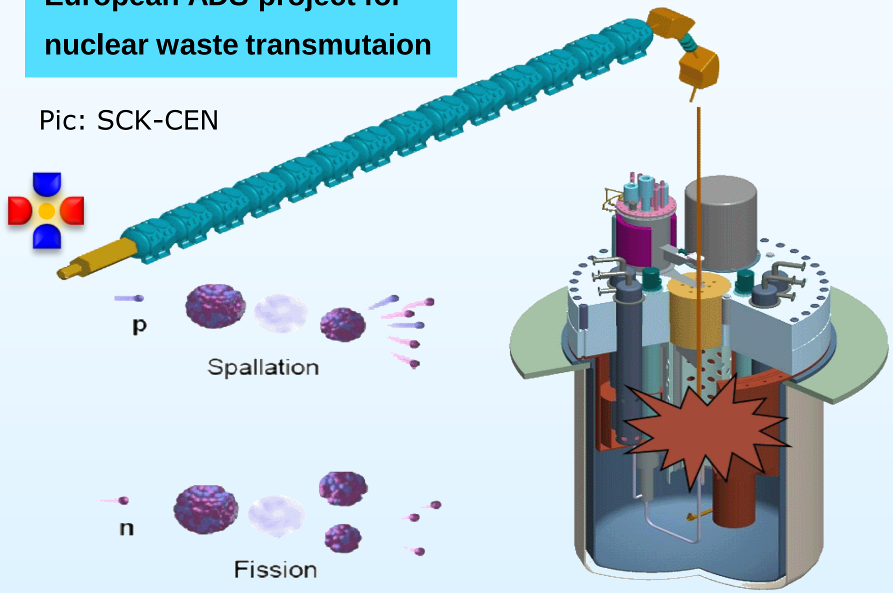


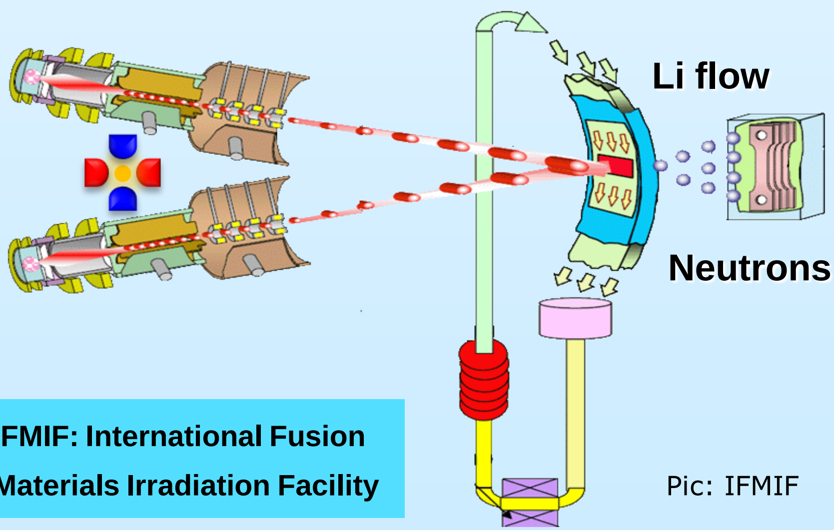


Modern Accelerators for Energy Development

European ADS project for nuclear waste transmutaion

Pic: SCK-CEN



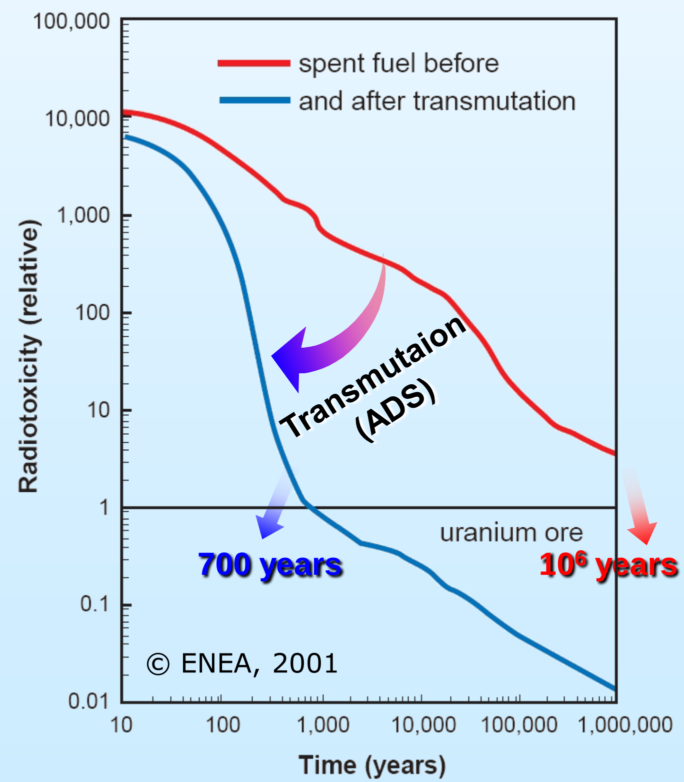


IFMIF: International Fusion Materials Irradiation Facility

Pic: IFMIF

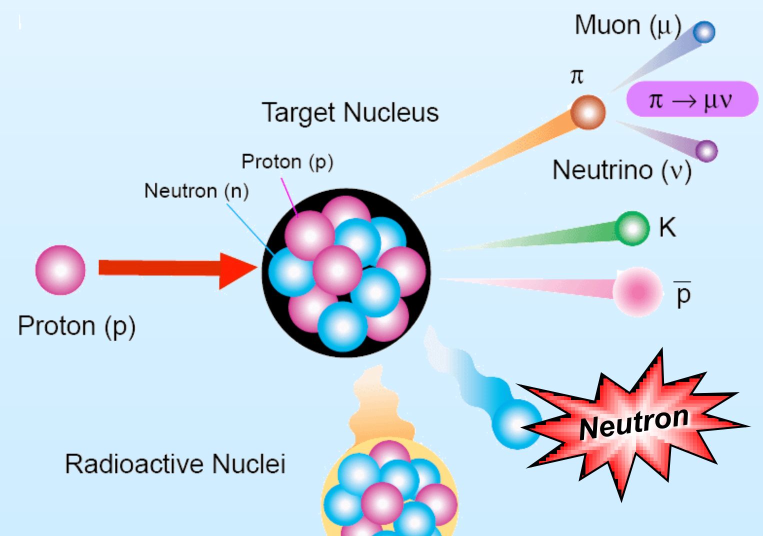
© ENEA, 2001

- ***EU: 145 reactors***
- ***35% of electricity***
- ***2500 tons of waste/year (Pu: 1%, minor actinides…)***



"Everything is Hard at the Beginning"

0.01	0.1	0.5	1
Low-β	Medium-β	High-β	
RFQ	H-type DTL Alvarez-type DTL Coupled-Cavity DTL CH-DTL $\lambda/4$ Resonator $\lambda/2$ Resonator Spoke Resonator	Elliptical Resonator Reentrant Resonator	
RT	RT-SC Transition	SC	



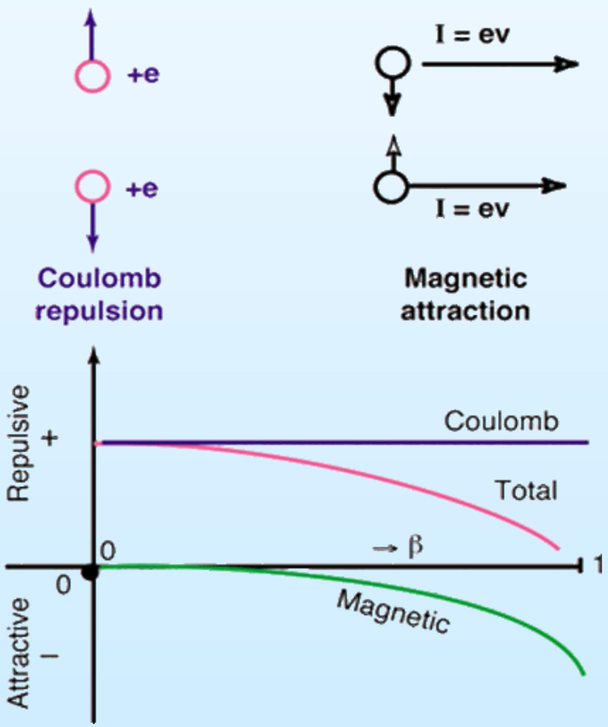
Pic: J-PARC

Challenges for Realizing Modern RFQs

$$\text{Beam Intensity} = \text{Peak Intensity} \times \text{Duty Cycle}$$

Space-Charge

Sparking / Cooling



Plot by K. Schindl

High V

Low V

Modest V

Low Beam Losses
(Hands-on Maintenance)

Good Beam Quality
(Downstream HoM, SC Quenching)

Short Length (Costs)

Introduction

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RFQ

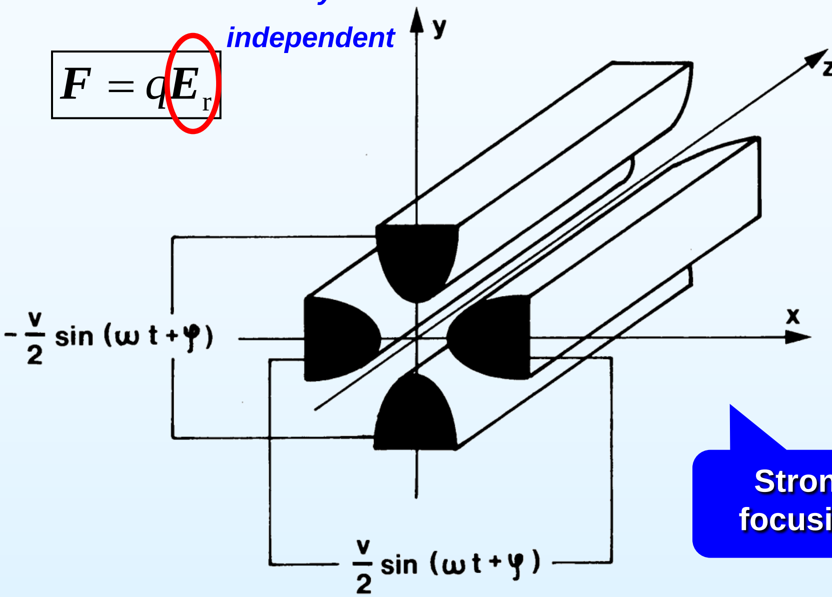
Beam Dynamics

RF Structure

How does an RFQ Accelerator Work

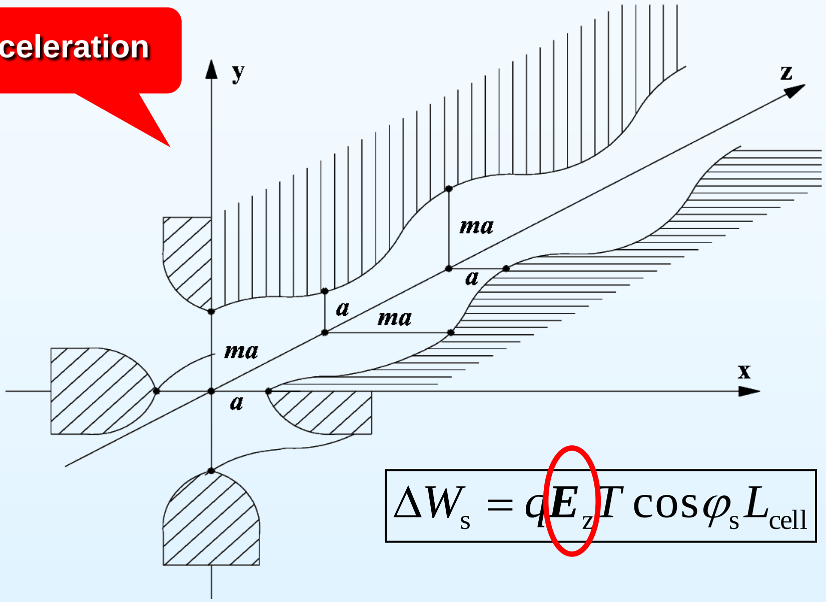
Velocity independent

$F = qE_r$

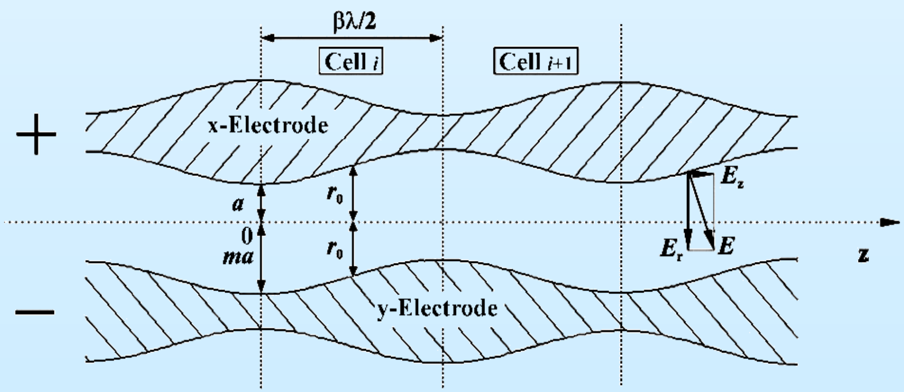


Strong focusing

Acceleration

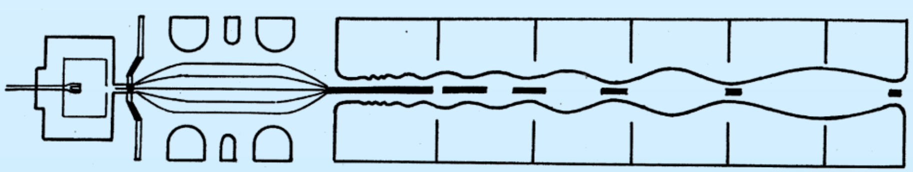


$\Delta W_s = qE_z T \cos\varphi_s L_{cell}$



$f, A/q, W, V, a\ (r_0, B), m, \varphi_s \ldots$

$\varphi_s = -90$ … $\varphi_s = -30$



Progressive bunching

$m = 1$ … $m = 1.8 - 2.5$

LANL Four-Section Procedure

Radial Matcher → Shaper → Gentle Buncher → Accelerator

Kapchinsky-Teplyakov Condition:
to maintain a constant beam density for an adiabatic bunching

Acceleration efficiency; Inter-vane voltage; Synchronous phase

$$\omega_l^2 = \frac{\pi^2 qAV \sin(-\varphi_s)}{M\beta_s^2\lambda^2}$$

Longitudinal small oscillation frequency; Synchronous velocity

Separatrix length in degree; Synchronous velocity

$$Z_b = \frac{\psi_b \beta_s \lambda}{2\pi}$$

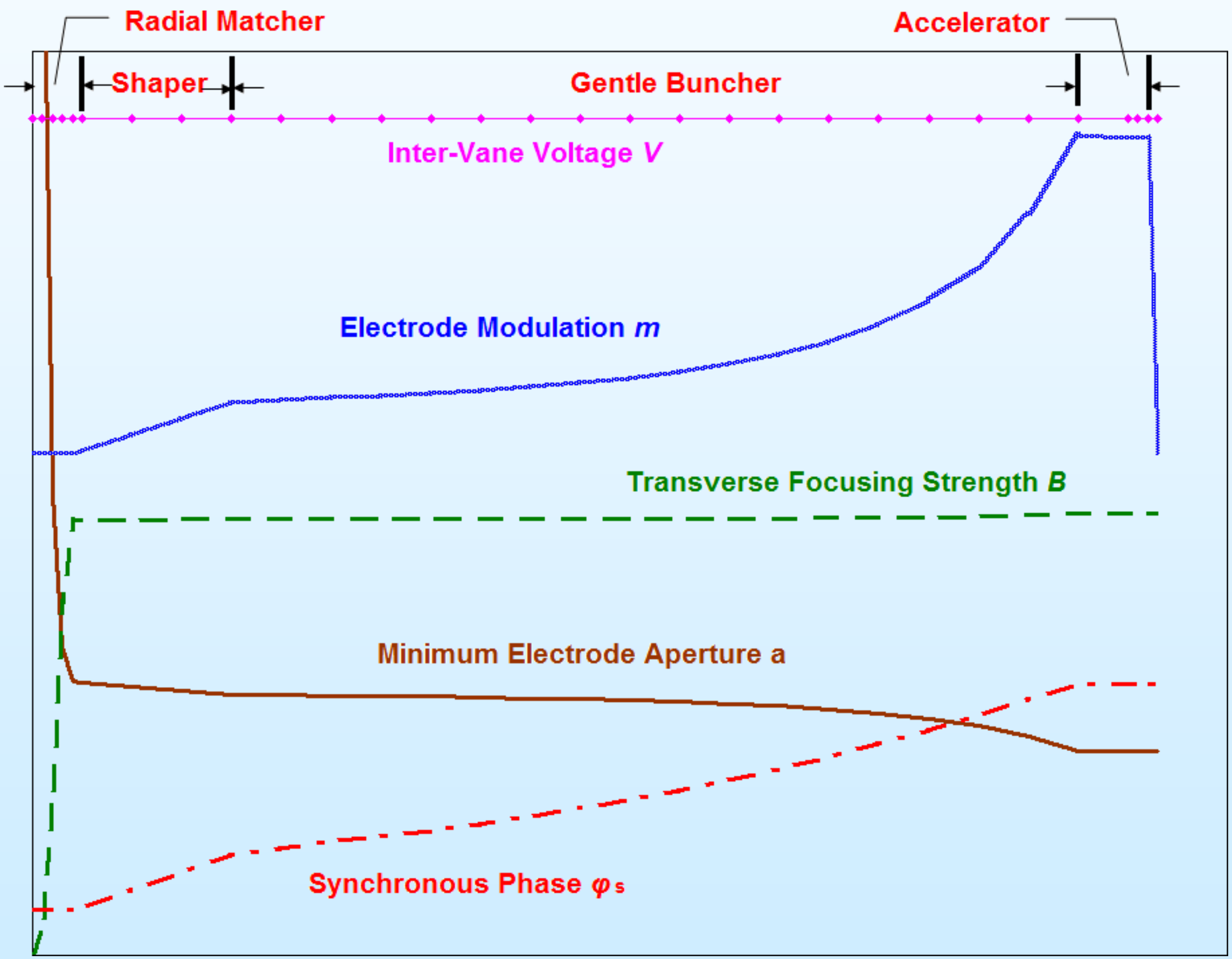
Separatrix length in cm

Separatrix length in degree

$$\tan\varphi_s = \frac{\sin\psi_b - \psi_b}{1-\cos\psi_b}$$

Synchronous phase

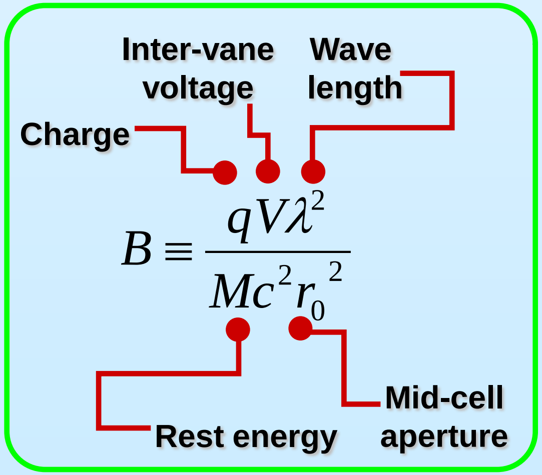
An Example of the LANL Method



Transverse focusing strength
B = constant

Mid-cell aperture
r_0 = constant

Capacitance:
position
independent



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

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.

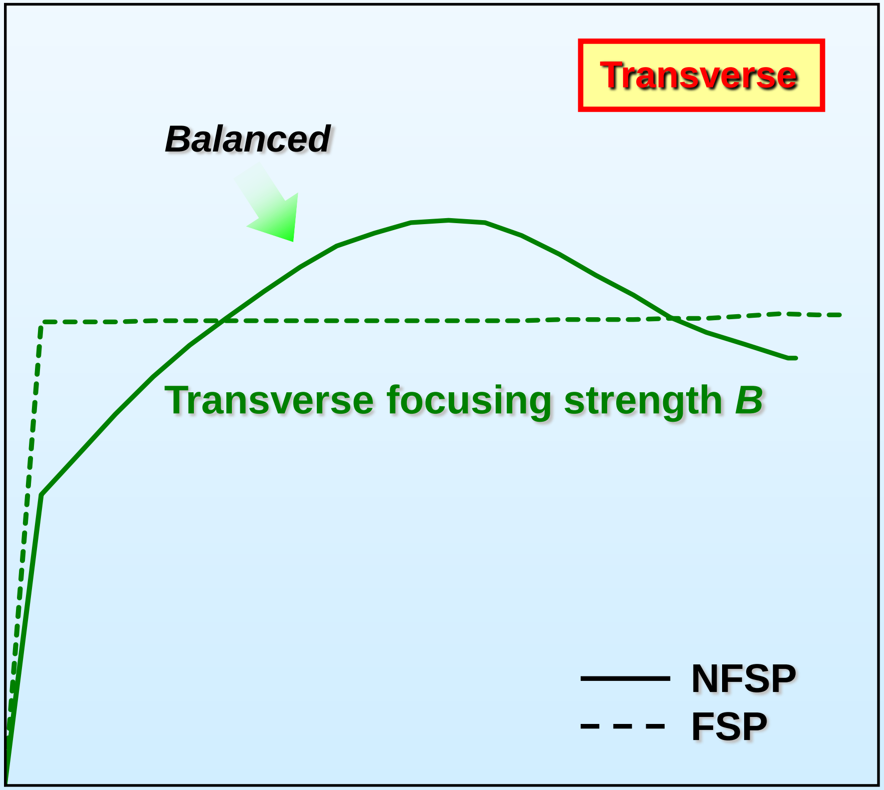
Constant *B*: deal with the longitudinal and tranverse planes separately;

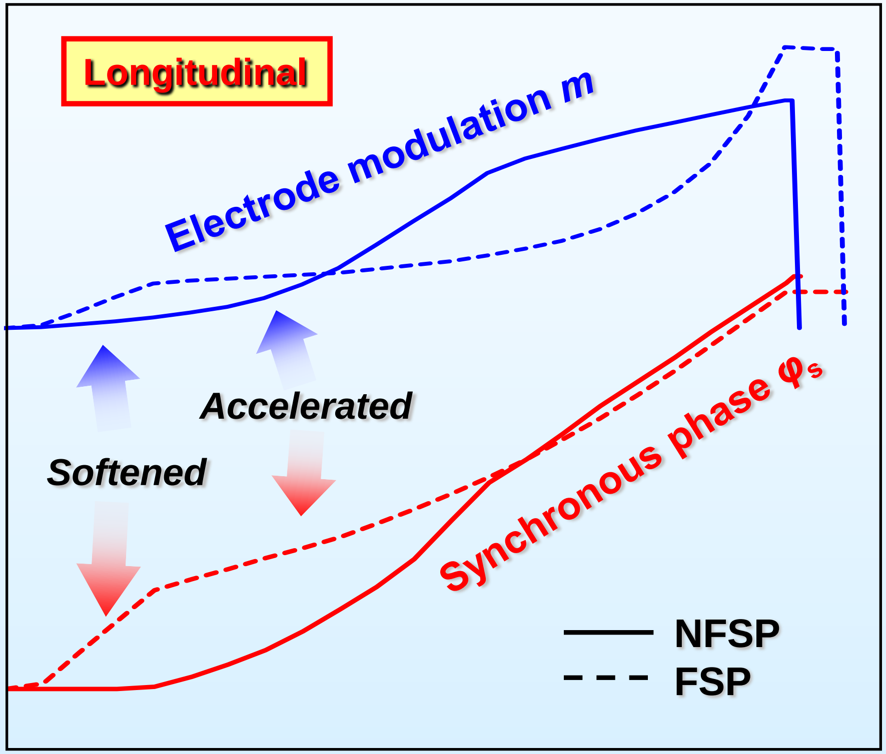
and MOST IMPORTANT, it ignores the space-charge effects.

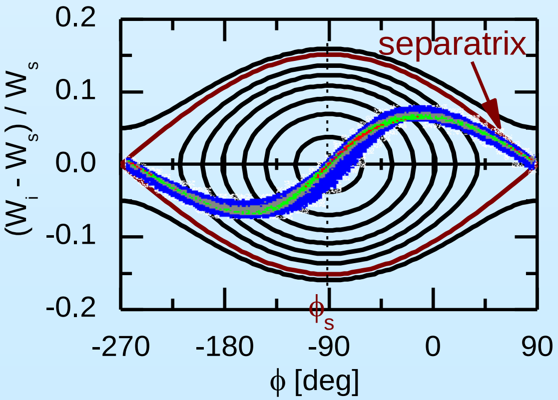
The synchronous phase ϕ_s is controlled by controlling the center-to-center spacing of the unit cells. Combining Eqs. (8.39) and (8.40) gives a prescription for specifying both $A(\beta_s)$, and $\phi_s(\beta_s)$ to maintain a constant bunch length. This adiabatic bunching approach is the basis of the 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

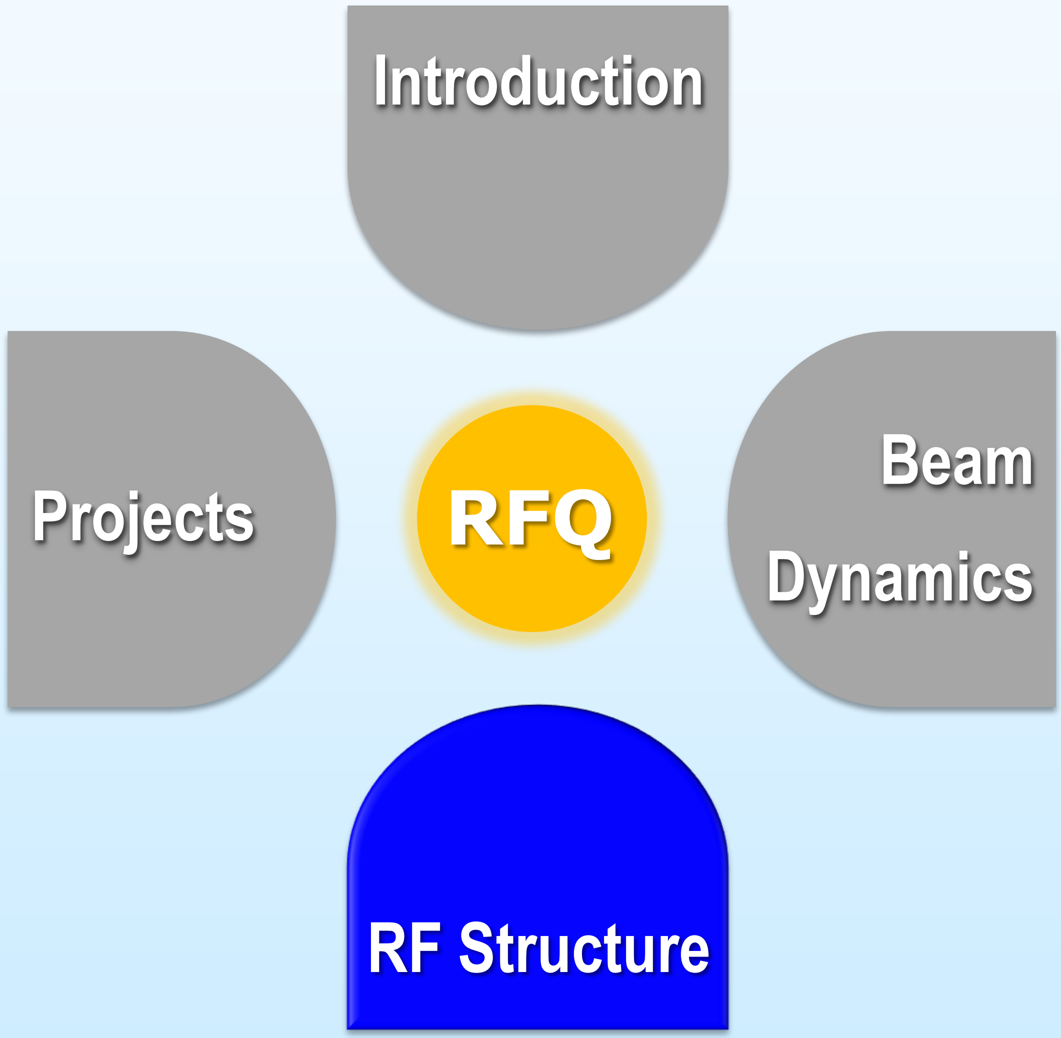
New Four Section Procedure







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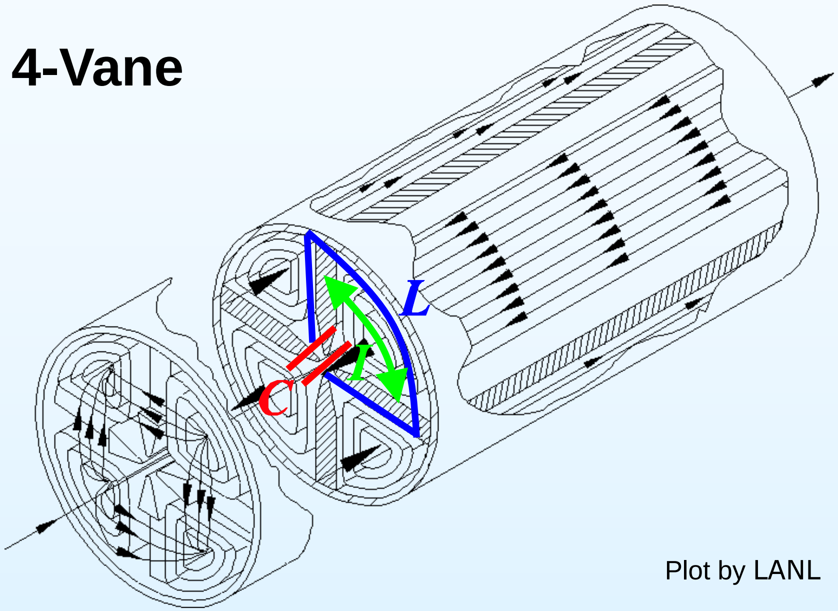
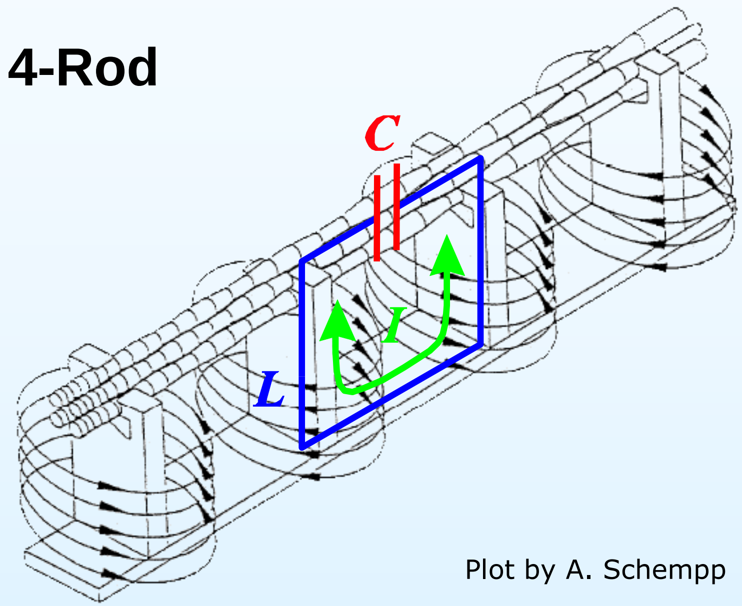
Main RFQ Structures

4-Vane



Plot by LANL

4-Rod



Plot by A. Schempp

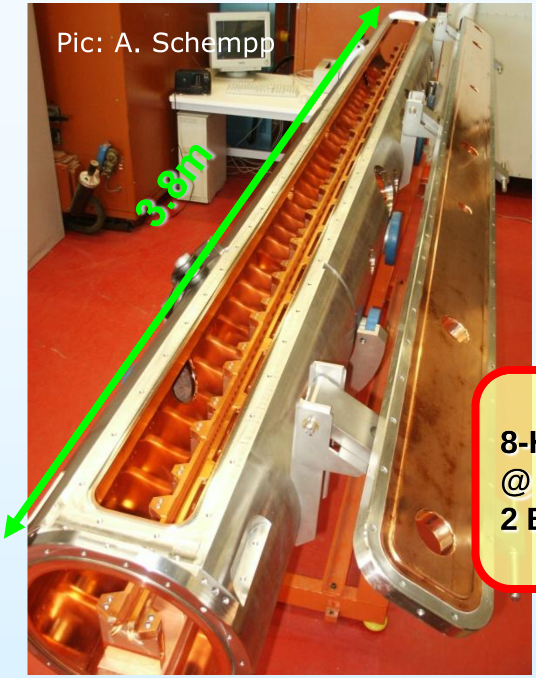
4-Vane

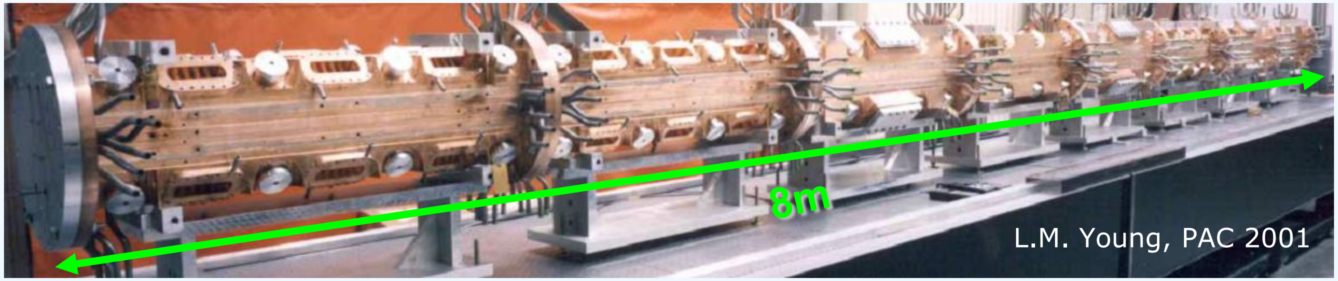
- TE-mode resonator
- Vanes + cavity wall => RF properties
- Even RF power density
- Easy cooling
- Large radial size at low frequencies (<200MHz)
- Error sensitive and tight tolerances
- Relatively complicated & expansive construction

4-Rod

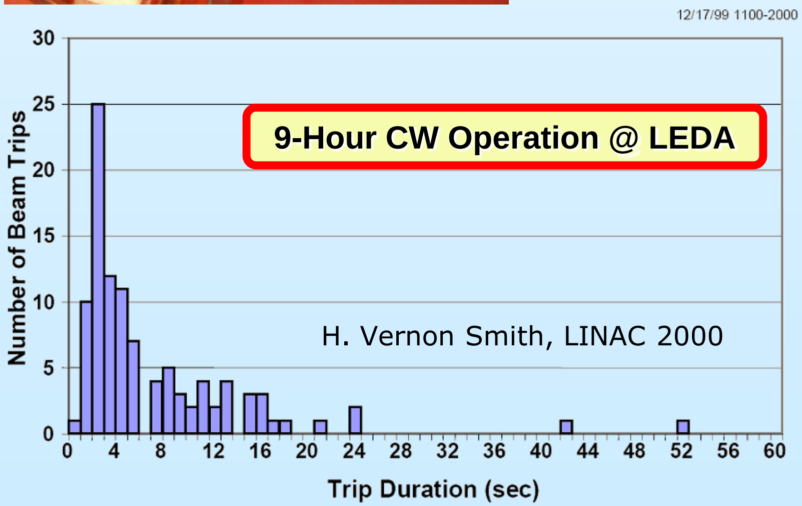
- A chain of $\lambda/4$ resonators
- Inner structure => RF properties
- Always compact radial size
- Easy construction, tuning & repair
- RF power density is locally 2 times higher
- Dipole problem at high frequencies (>200MHz)
- CW operation is challenging at $P_c \geq 50$kW/m

LEDA vs. SARAF





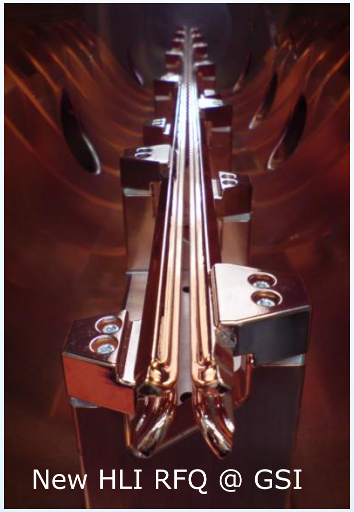
8-Hour CW (150kW) @ SARAF * :
2 Beam Trips (ms)

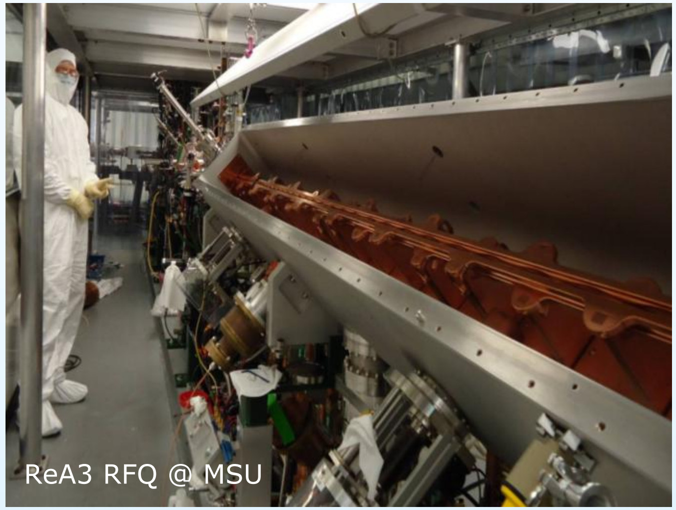


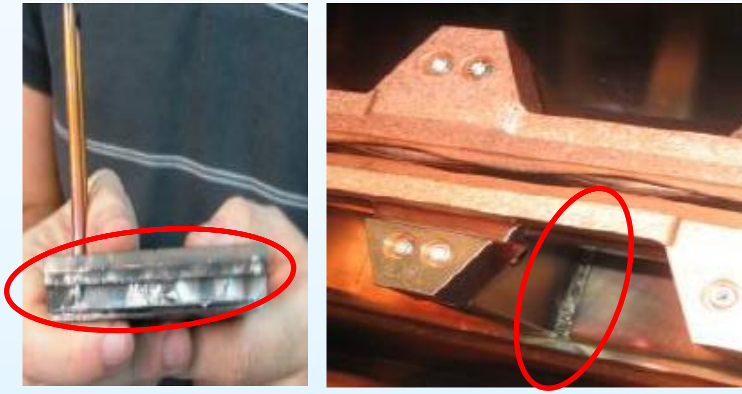
Parameter \ Project	LEDA (4-Vane)	SARAF (4-Rod)
Ion species	H^+	D^+ (H^+)
f [MHz]	350	176
W_{in} / W_{out} [MeV]	0.075 / 6.7	0.040 (0.020) / 3.0 (1.5)
U [kV]	66-120	65 (32.5)
L [m]	8	3.8
$\#_{tank}$	8	1
$\#_{coupler}$	12	1
$\#_{tuner}$	128	2 plungers
E_k	1.8	1.6 (0.8)
P_c [kW/m]	150 In oper.: 182	62.5 (15.6) Reached in CW: 50 *

* Provided by A. Bechtold

CW 4-Rod RFQs Made at IAP

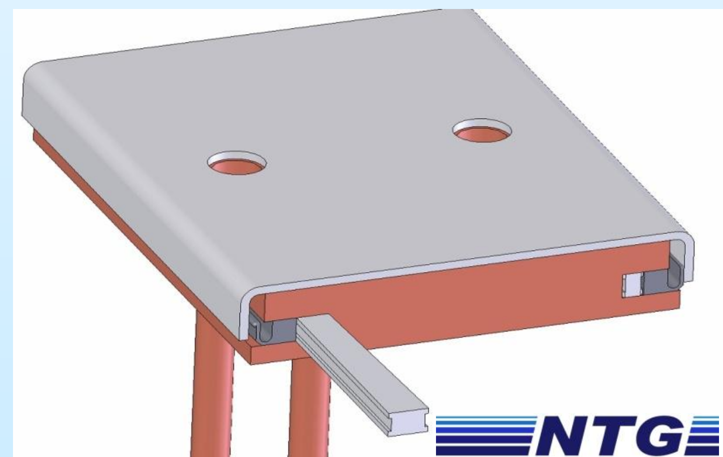


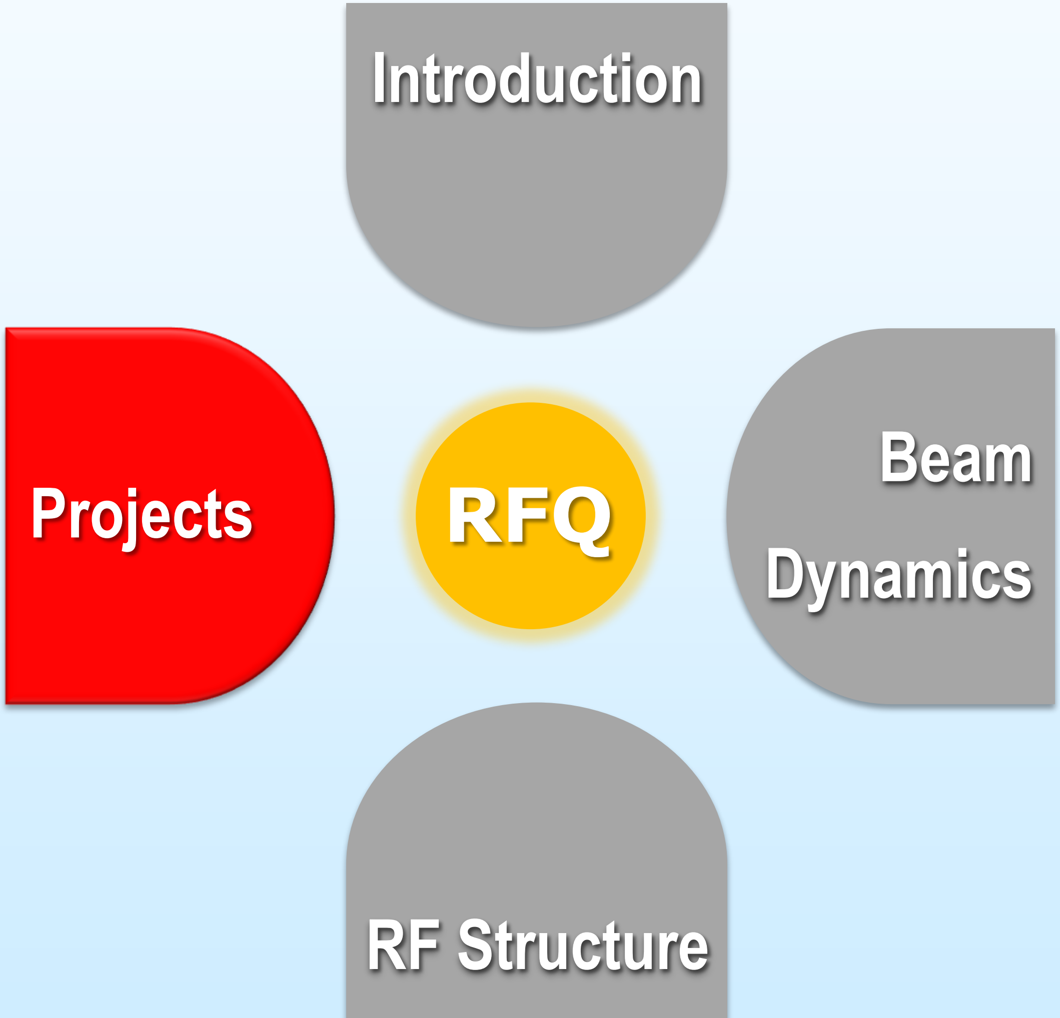




Mardoron, SARAF Workshop 2009

Parameter \ Project	New HLI @ GSI	ReA3 @ MSU	FRANZ @ IAP
A/q	6	≤5	1
f [MHz]	108.48	80	175
W_{in} / W_{out} [MeV/u]	0.004 / 0.3	0.012 / 0.6	0.120 / 0.7
U [kV]	55	87	75
L [m]	2.0	3.4	1.8
E_k	2.0	1.6	1.5
P_c [kW/m]	28	35	65

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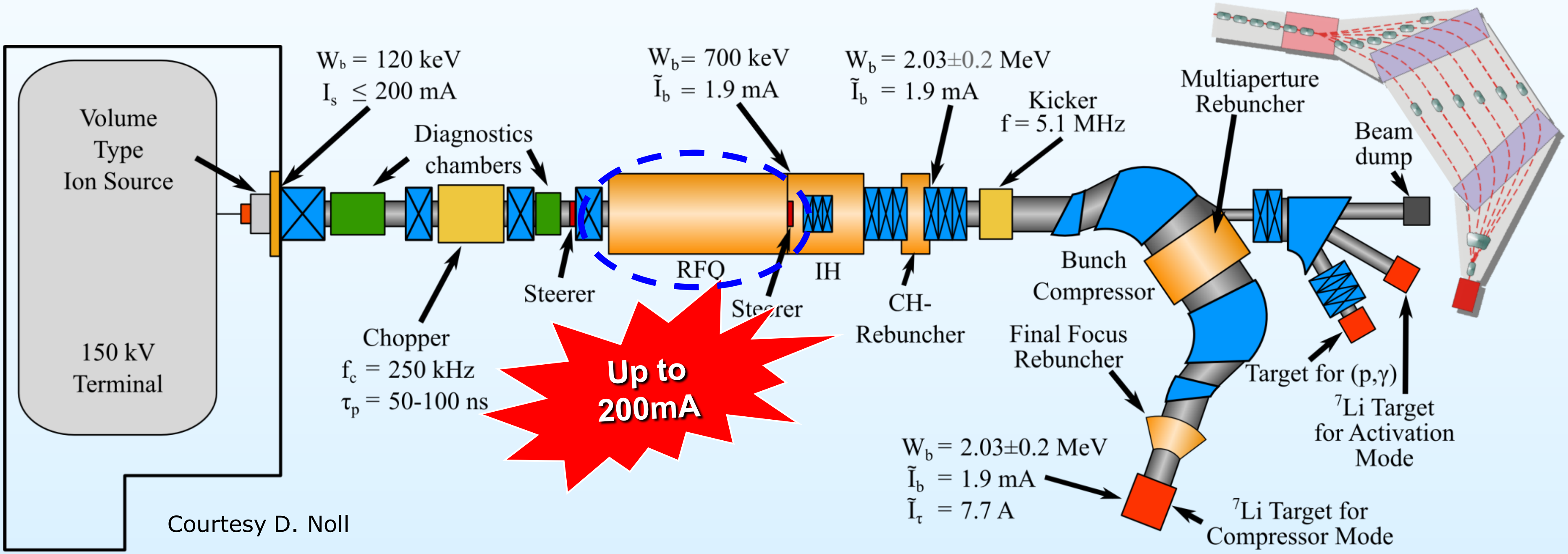
FRANZ: Frankfurt Neutron Source at the Stern-Gerlach-Zentrum



Courtesy D. Noll

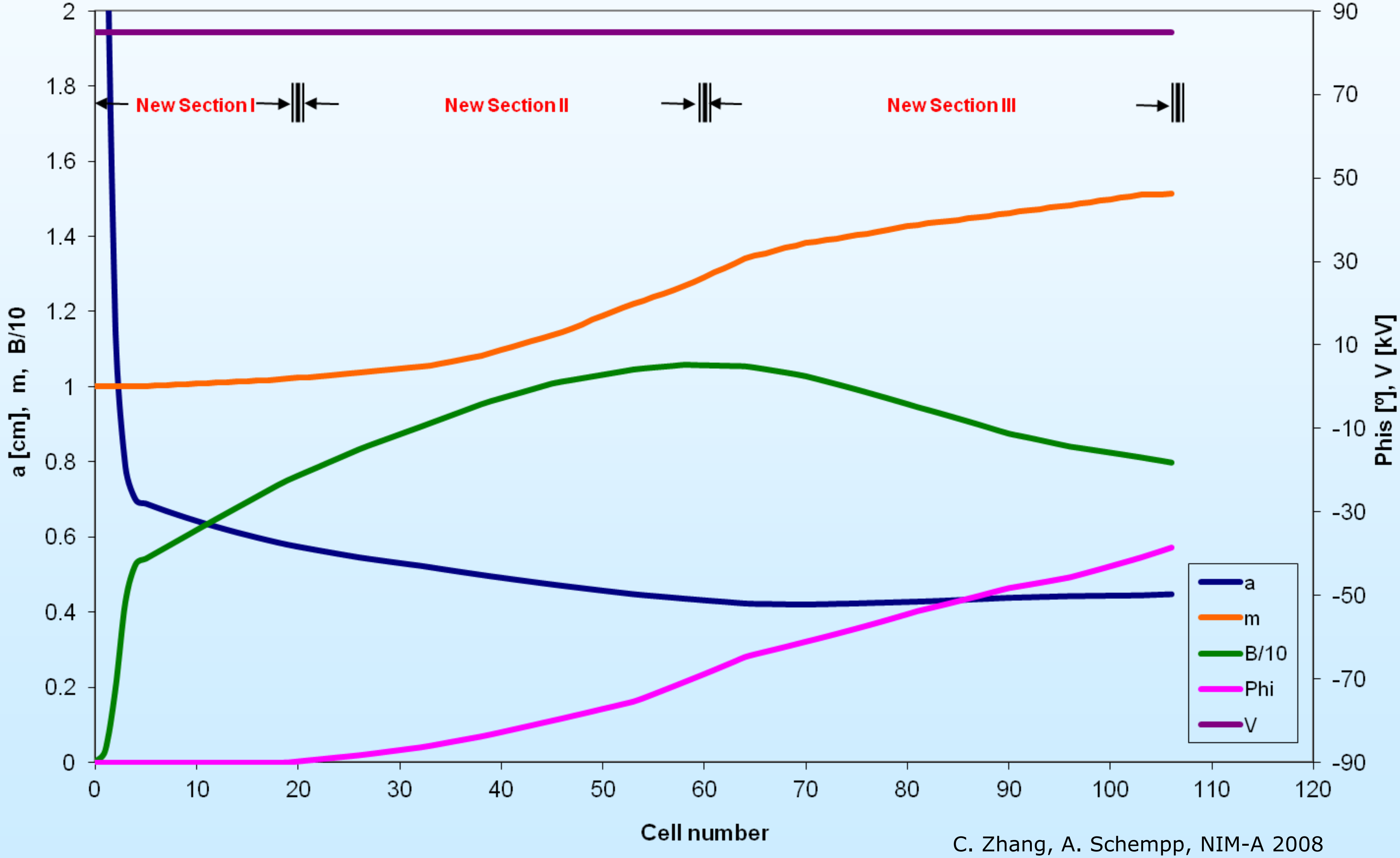
	I_{peak} [mA]	Ion	f [MHz]	W_{in} / W_{out} [MeV]	L [m]	U [kV]	$E_{s,max}$	Duty cycle	Transmission [%]
CERN RFQ2	200	H^+	202.56	0.090/0.750	1.8	178	$2.5E_k$	<1%	~90
FRANZ	200	H^+	175	0.120/0.700	2.0	85	$1.6E_k$	CW	98.3

LHC FSP NFSP

~1/2 of inter-vane voltage

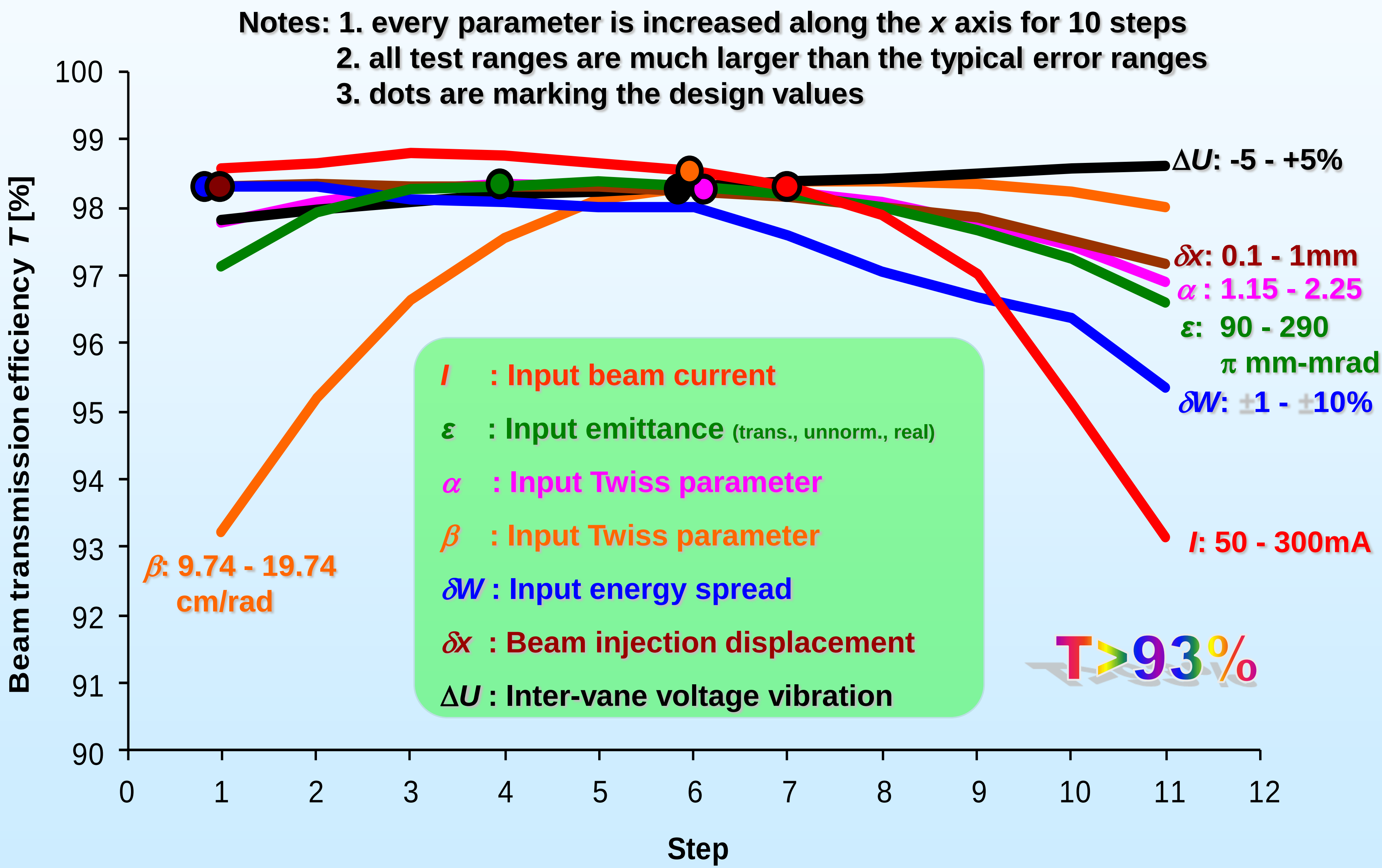
C. Zhang, A. Schempp, NIM-A 2008

Design Parameters of the FRANZ RFQ

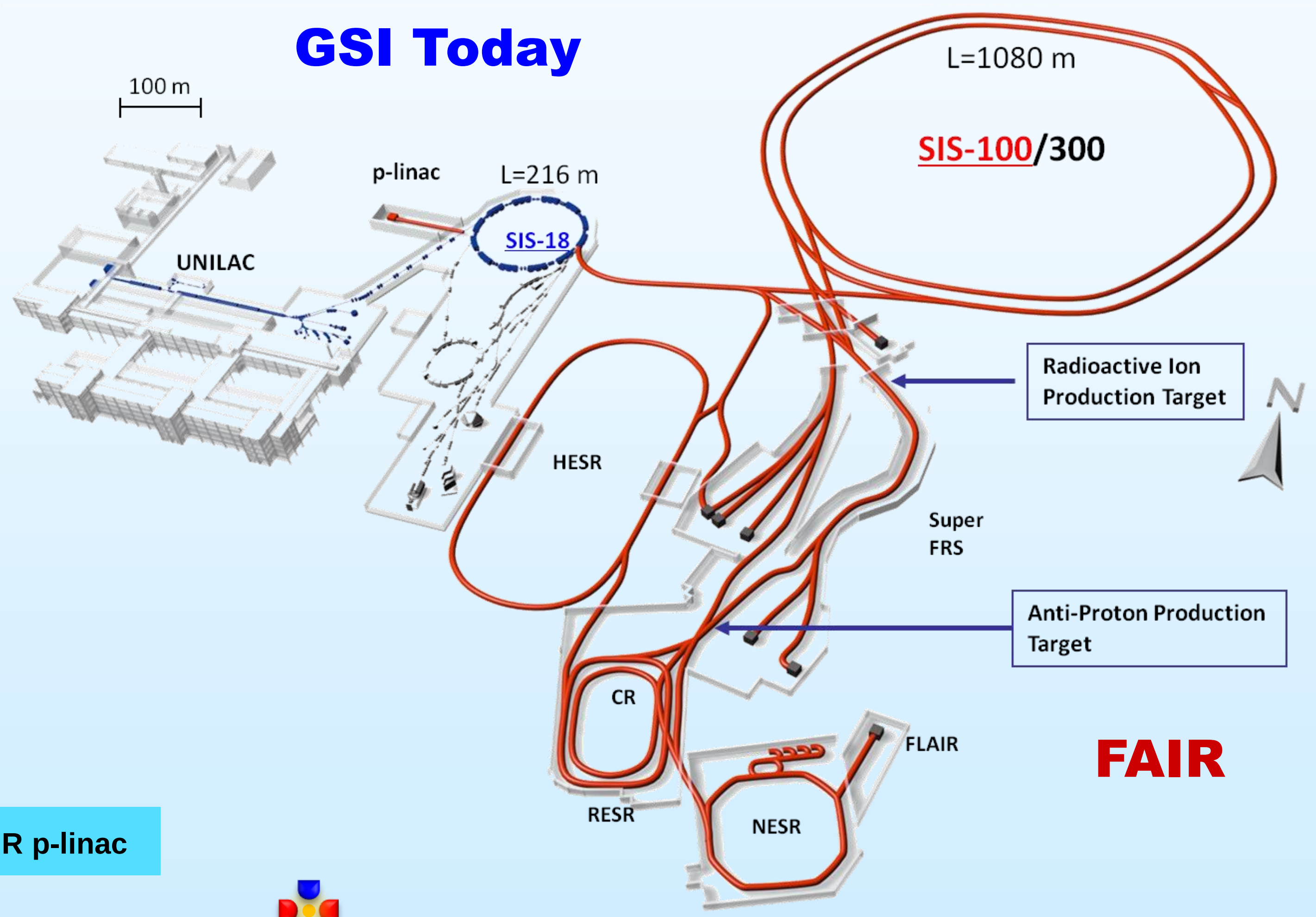


C. Zhang, A. Schempp, NIM-A 2008

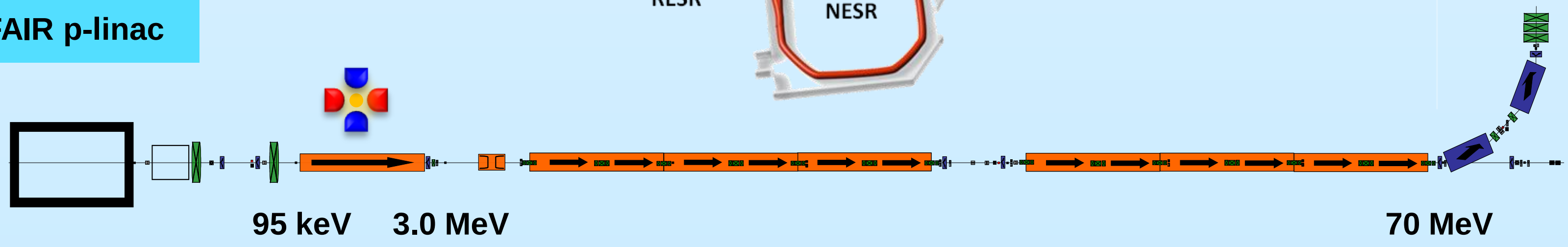
Stability Tests of the FRANZ RFQ Design



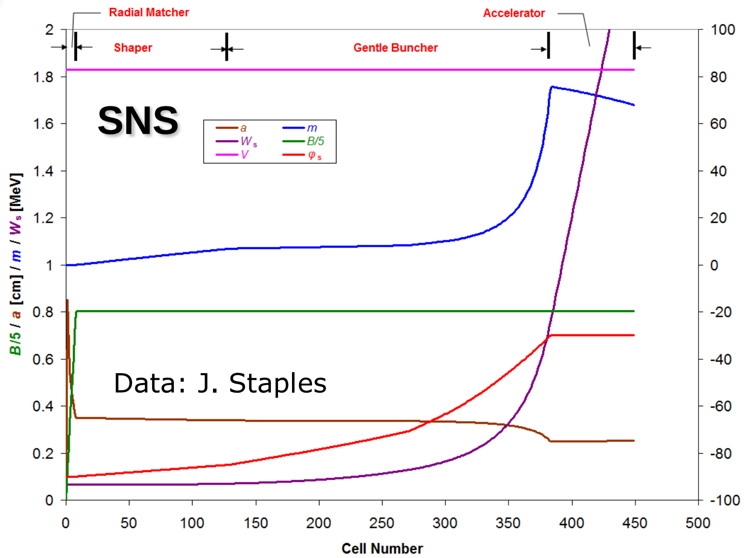
FAIR: Facility for Antiproton and Ion Research

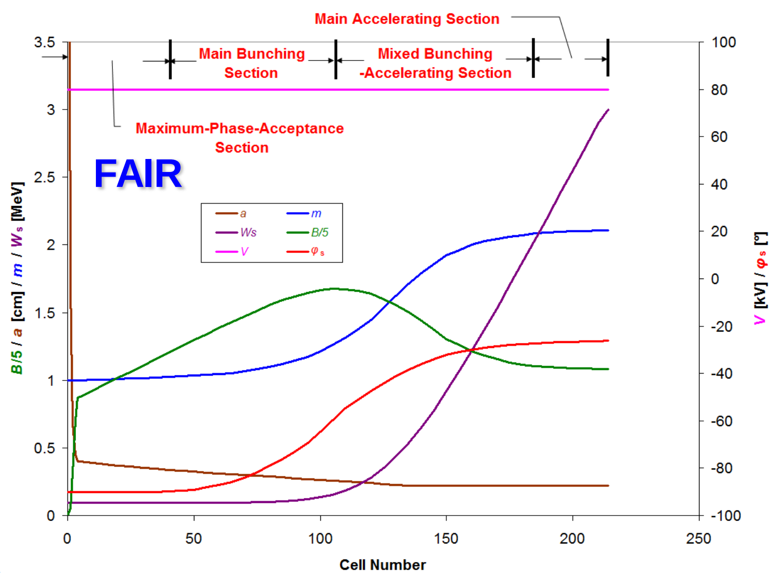


FAIR p-linac



SNS RFQ vs. FAIR Proton RFQ



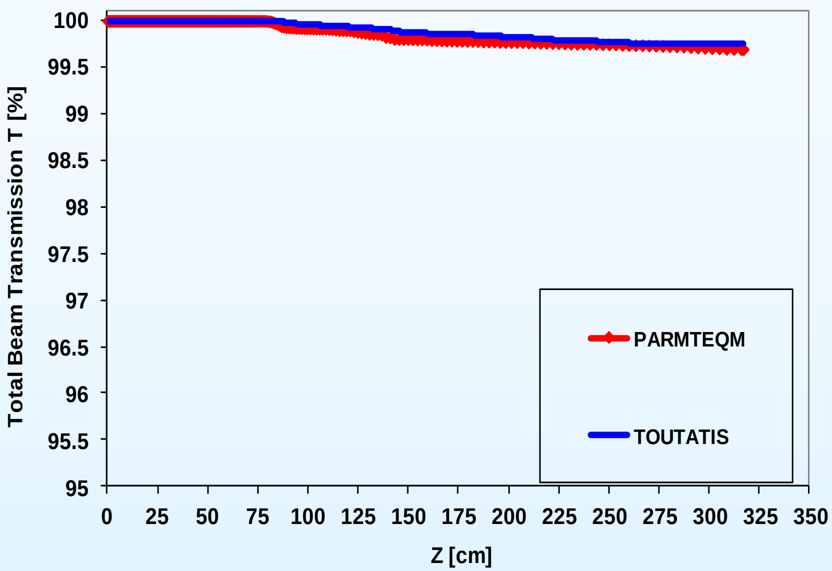


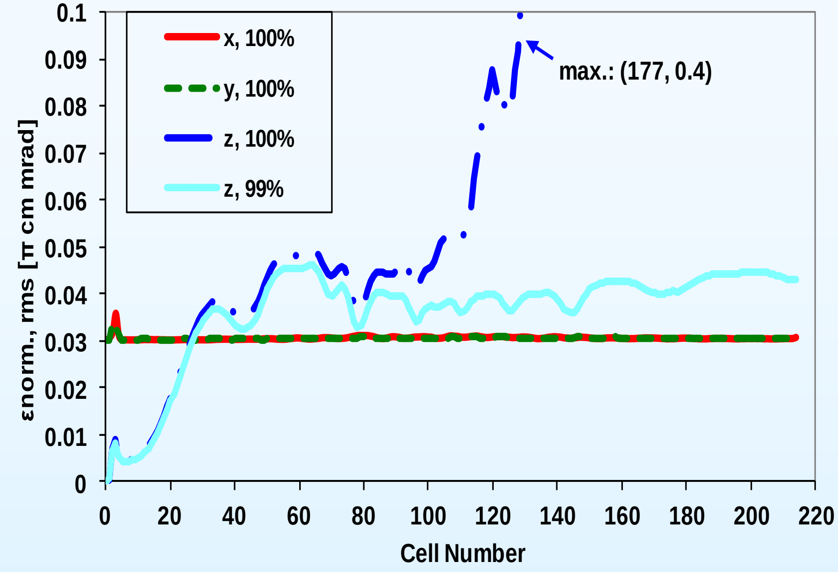
Parameters	SNS	FAIR		
Ion	H^-	H^+		
Duty cycle [%]	6.2	0.0144		
I_{peak} [mA] ✓	~60 (35)	45	70	100
f [MHz]	402.5	325.44		
W_{in} [MeV] ✓	0.065	0.095		
W_{out} [MeV] ✓	2.5	3		
U [kV]	83	80		
$\varepsilon_{in}^{trans.,norm., rms}$ [π mm mrad] ✓	0.2	0.3		
$\varepsilon_{out}^{trans.,norm., rms}$ [π mm mrad]	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

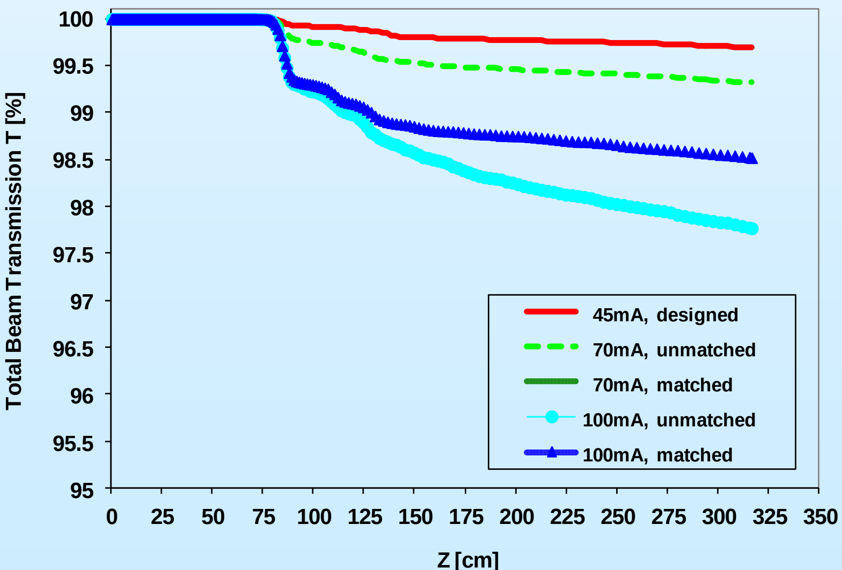
For accelerated particles only

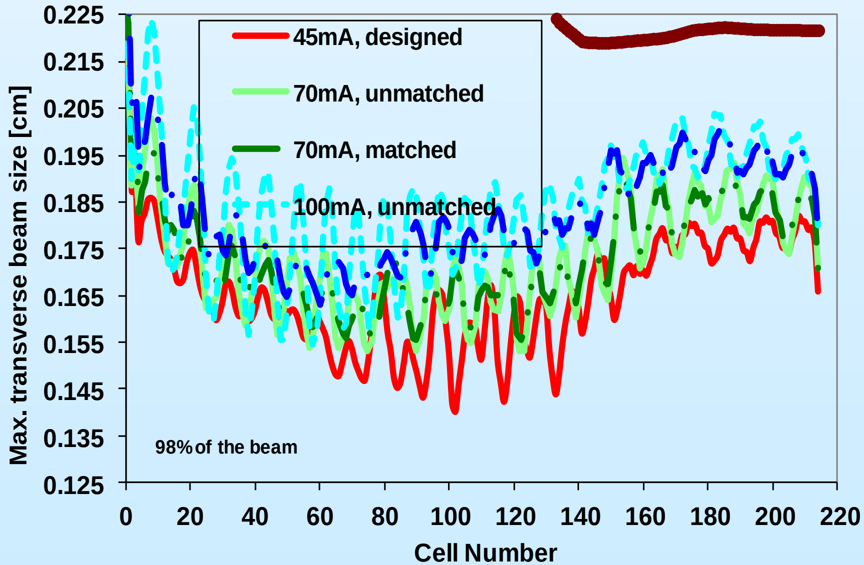
C. Zhang, A. Schempp, NIM-A 2009

Design Results of the FAIR Proton RFQ



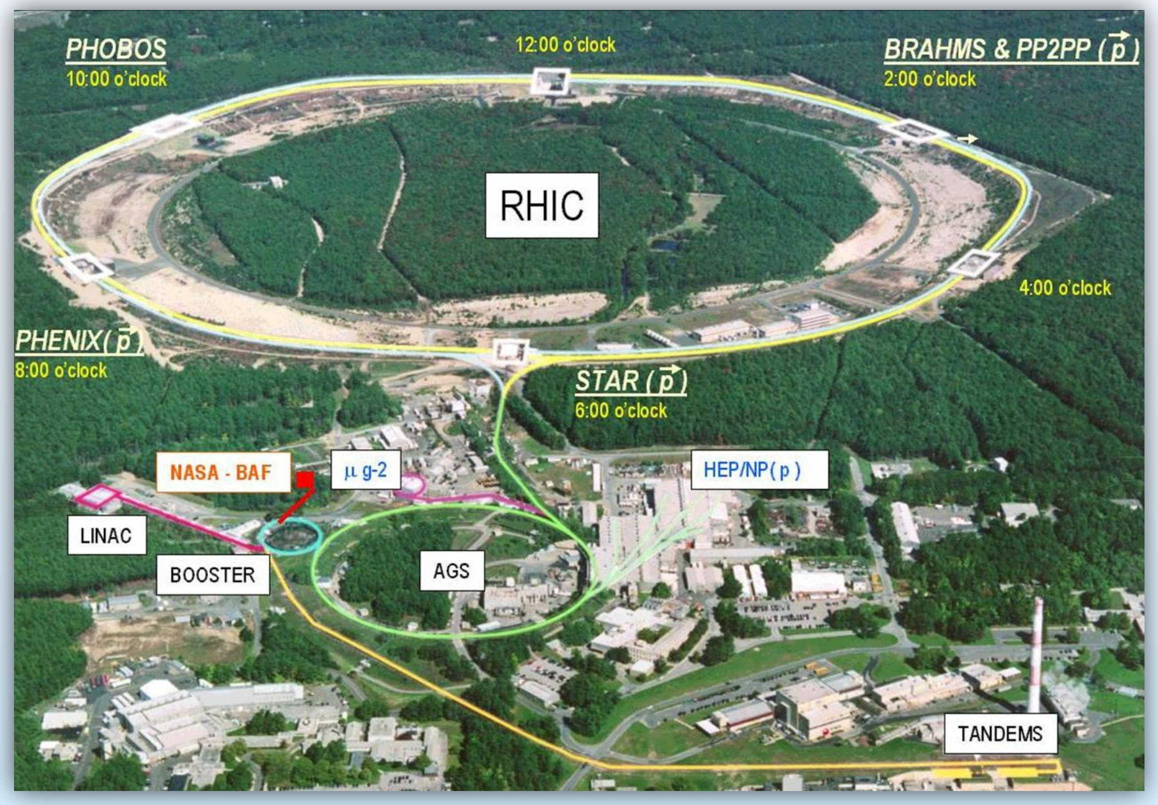




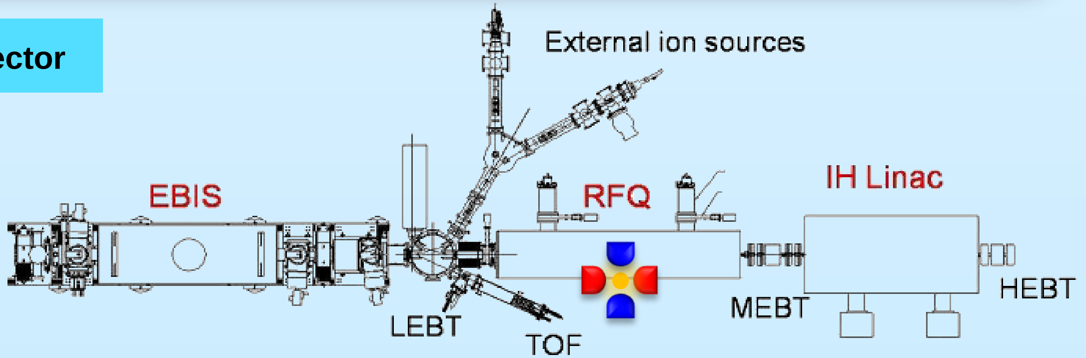


C. Zhang, A. Schempp, NIM-A 2009

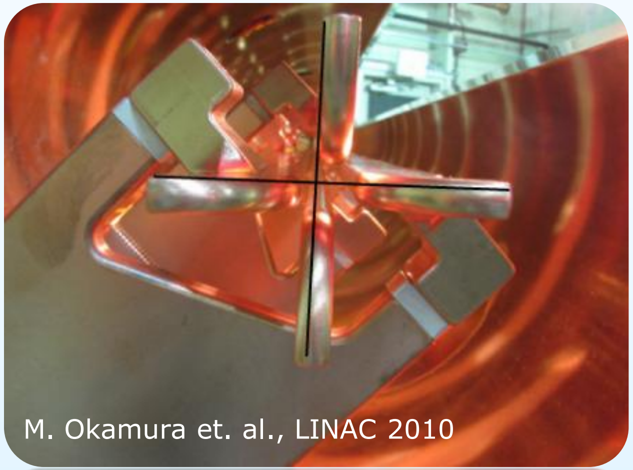
RHIC: Relativistic Heavy Ion Collider



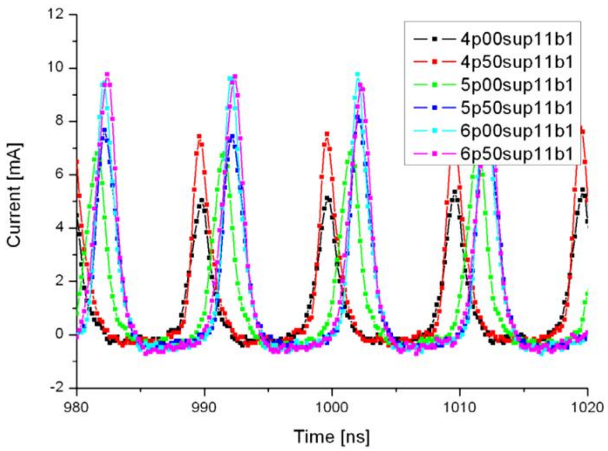
New EBIS Preinjector



Design of the New EBIS RFQ for RHIC, BNL



M. Okamura et. al., LINAC 2010

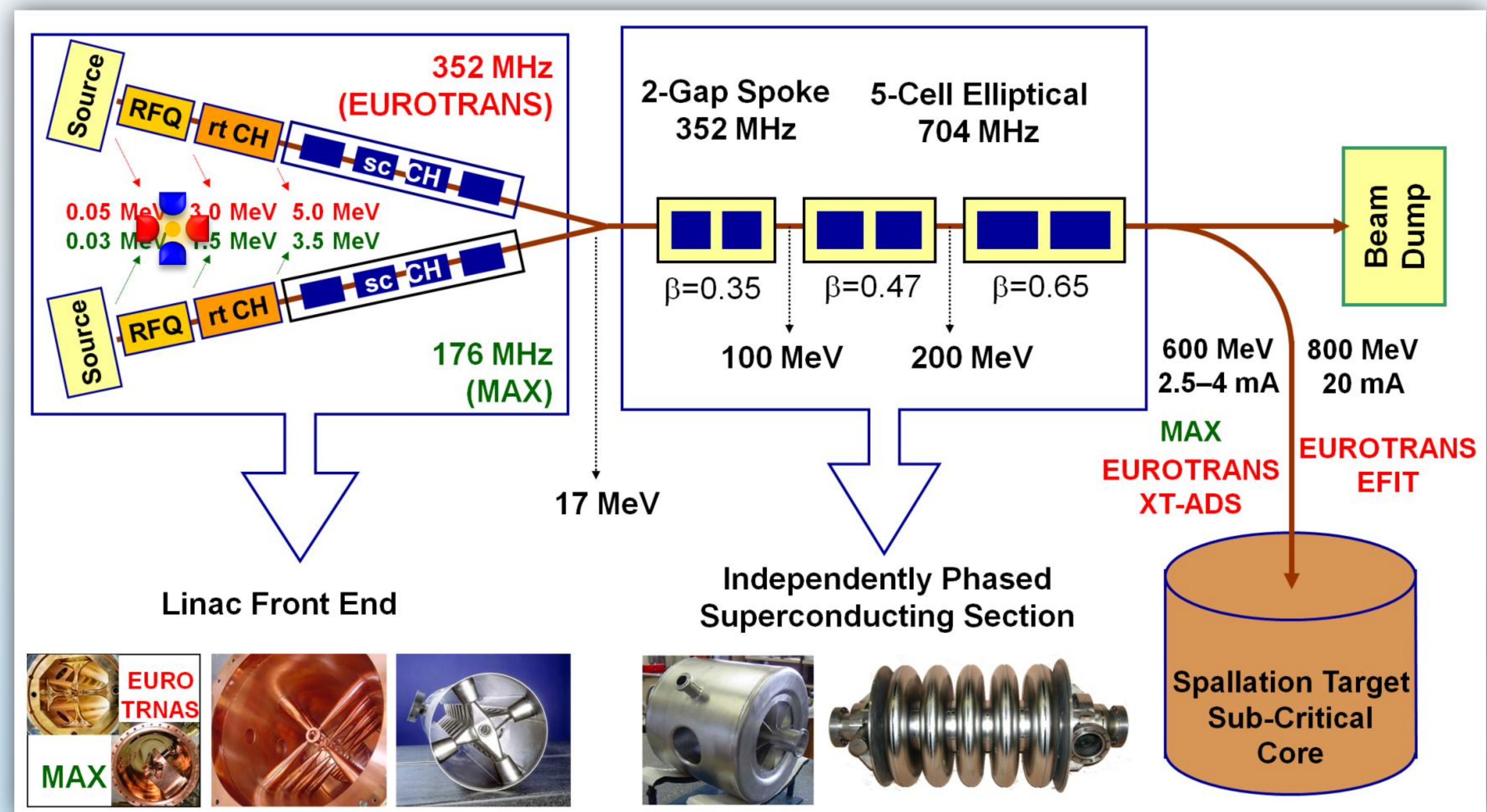


M. Okamura et. al., PAC 2009

Parameters	CZ Design 6	
A/q	6.25 / 1	2 / 1
Input Energy [MeV/u]	0.017	
Output Energy [MeV/u]	0.300	
Frequency [MHz]	100.625	
Inter-Electrode Voltage [kV]	70	22.4
Design Beam Current [mA]	**10**	
Max. Beam Current [mA]	20	
$\varepsilon_{in}^{trans.,norm., rms}$ [π mm mrad]	0.058	
Kilpatrick Factor	**1.8**	**0.6**
Electrode Length [m]	**3.1**	
T [%]	> **98**	

Cu^{10+}, He^{2+}, He^{+}, Ne^{5+}, Au^{32+} and Fe^{20+} have been successfully tested …

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)

Proton Beam Specifications

High power (radiation, cooling, sparking …)

Easy upgradeability

Phase / Parameter	XT-ADS {MAX}	EFIT
Operation (Design) intensity [mA]	2.5 – 4 (5)	20 (30)
Output energy [MeV]	600	800
Beam trip number (>1s) {>3s}	< 5 {<10} per 3-month operation cycle	< 3 per year
Beam stability (on target)	Energy: 1 %, Intensity: 2 %, Beam Size: 10 %	
Beam time structure	CW with 200μs zero-current holes	

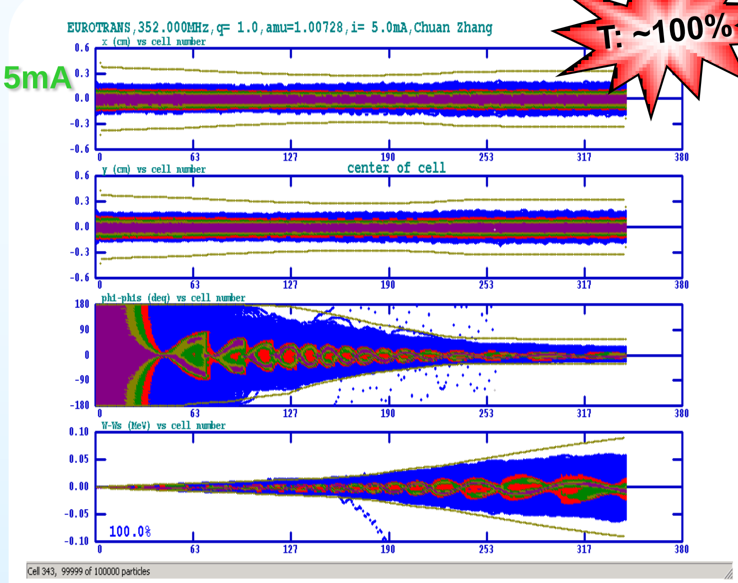
extremely high reliability

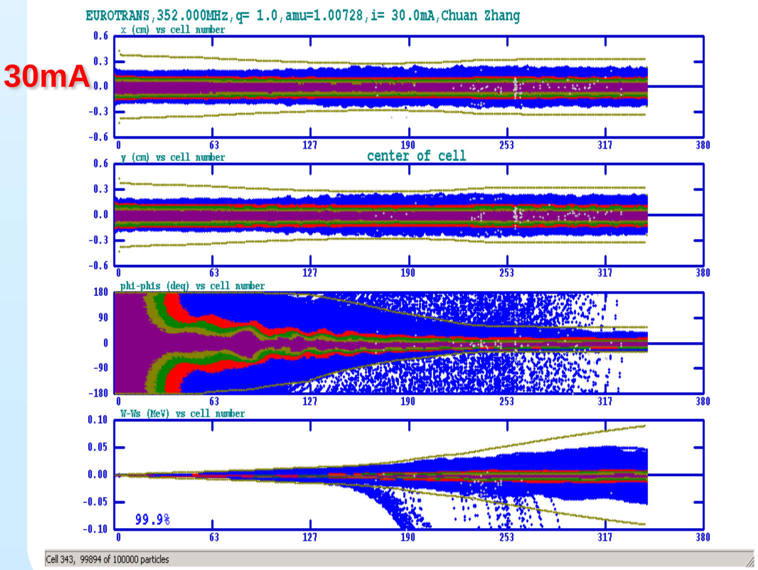
trips. The above requirement is still very aggressive. The number of beam trips on actual machines is at least two orders of magnitude higher (a couple per hour).

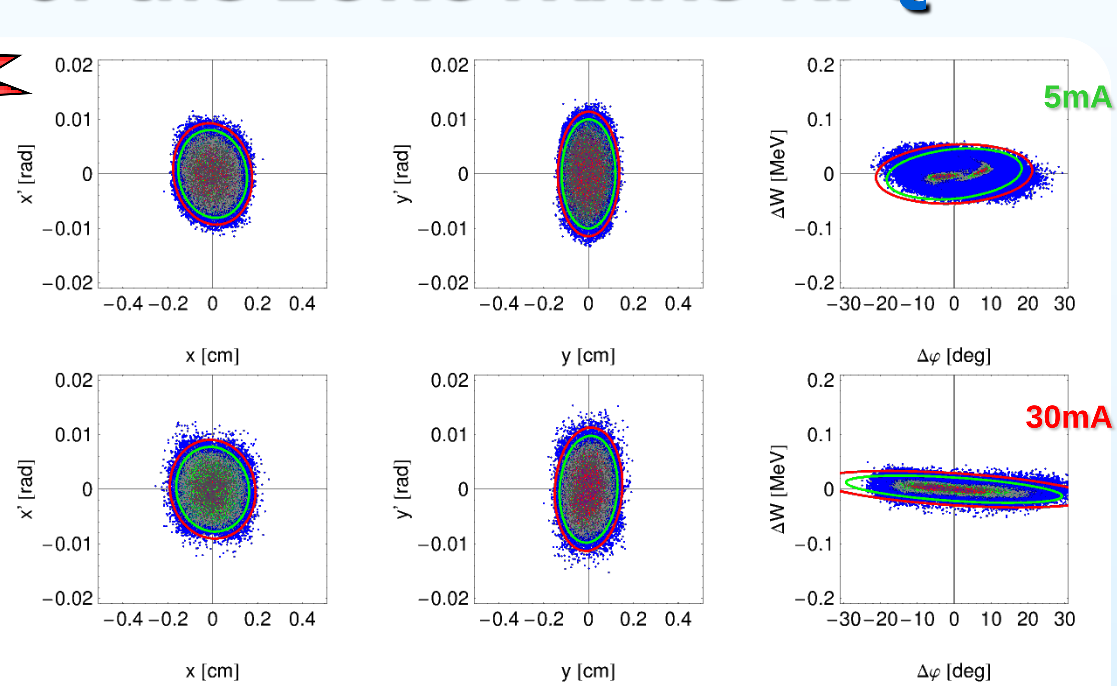
However, a distinction should be made between the availability, which ... the relevant parameter for ...

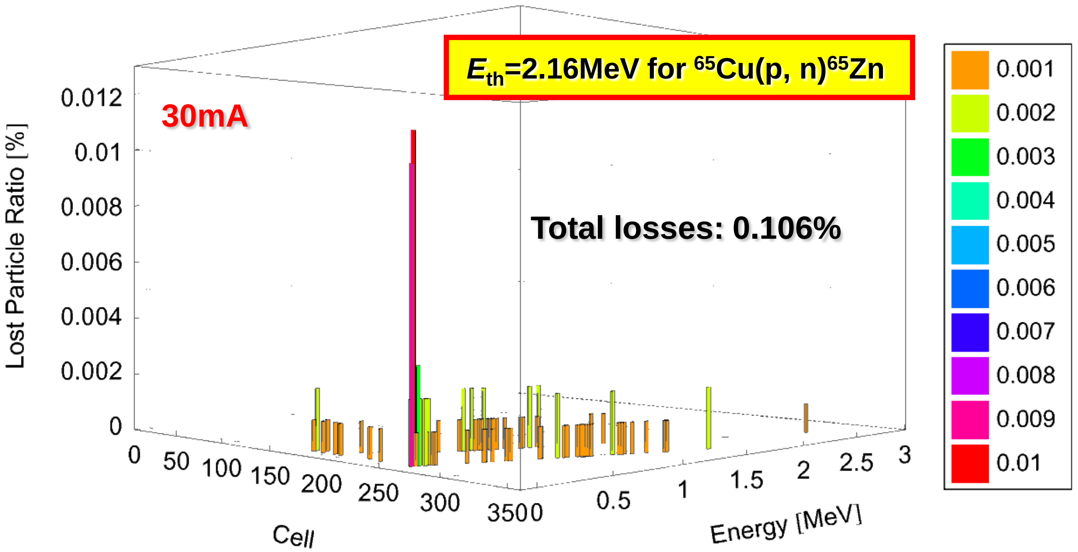
N. Pichoff, EPAC 2001

Design Results of the EUROTRANS RFQ

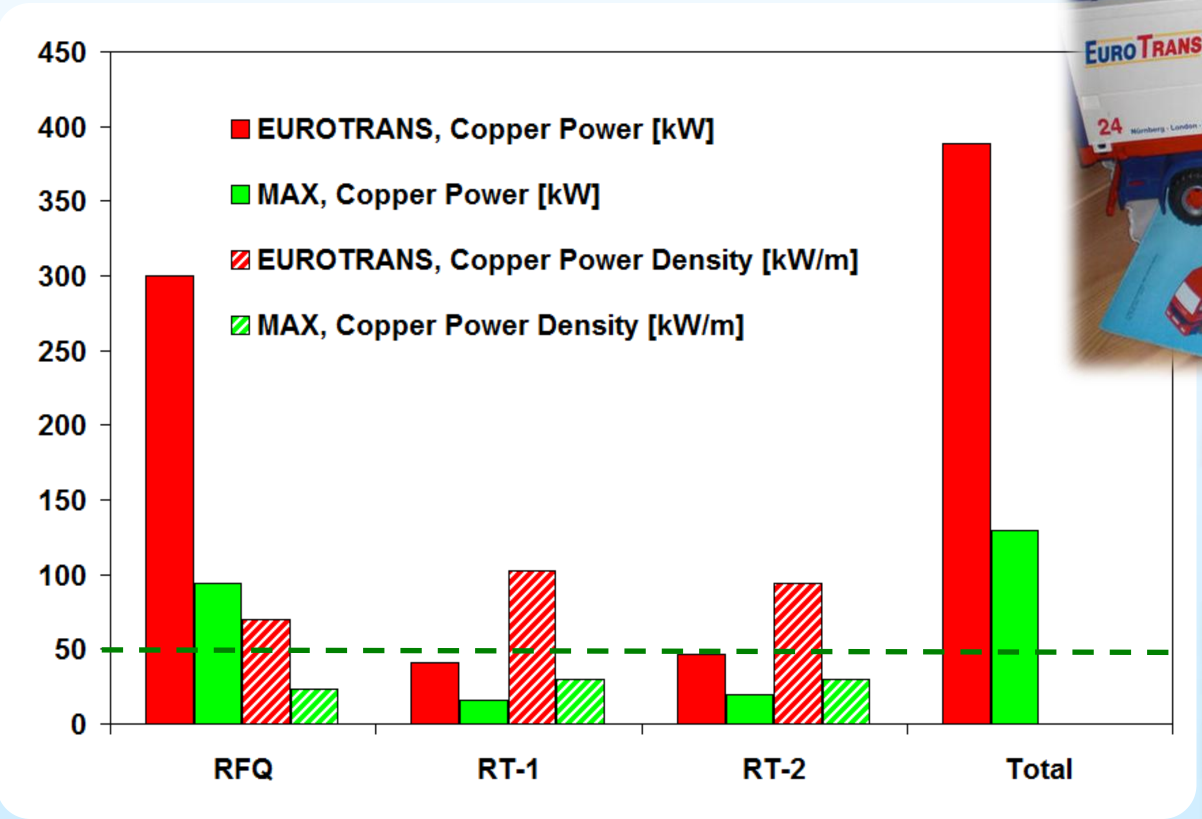


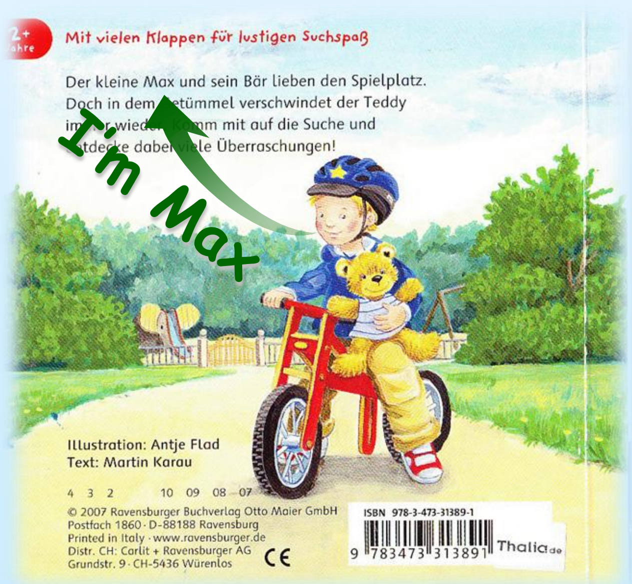




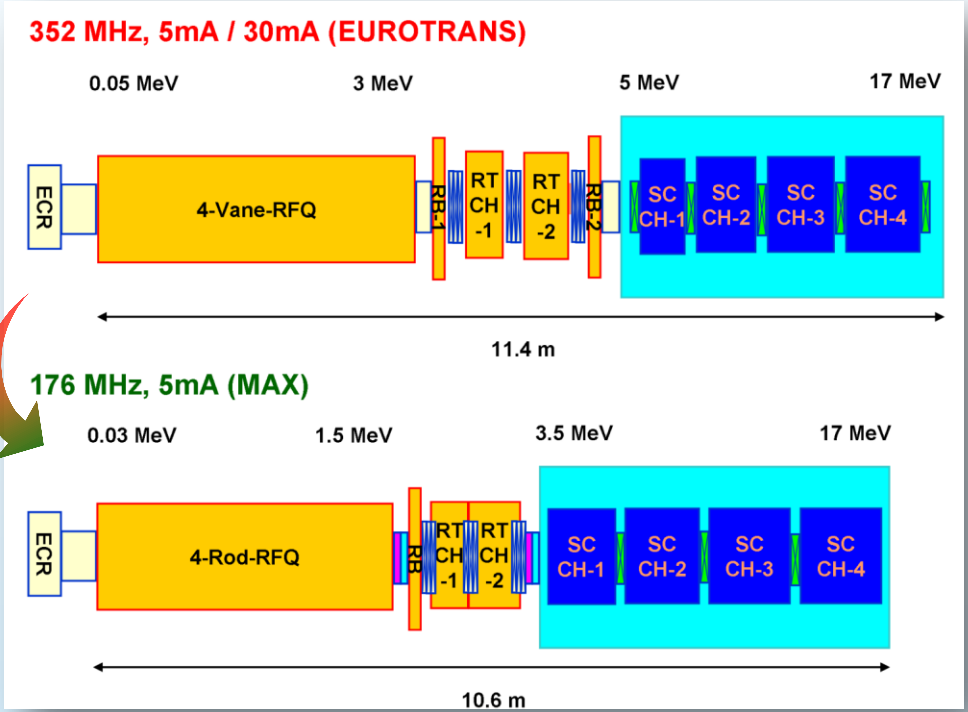


EUROTRANS: a Toy! MAX: a Real Boy !



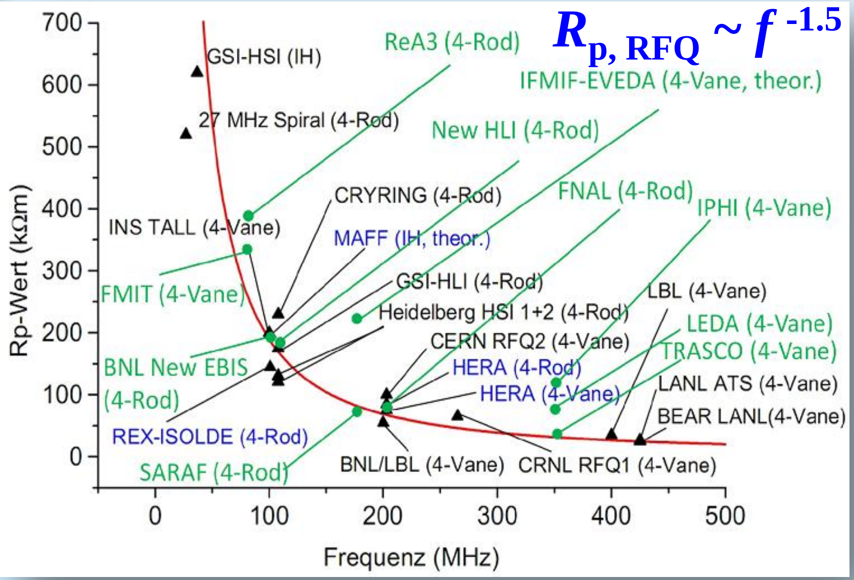


From EUROTRANS to MAX



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

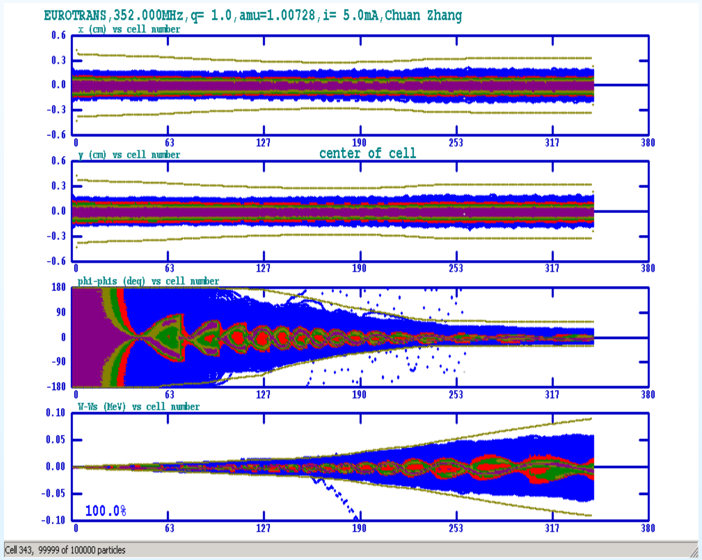
f [MHz] :	352 to 176
RFQ:	4-Vane to 4-Rod
$W_{RFQ,in}$ [MeV]:	0.05 to 0.03
$W_{RFQ,out}$ [MeV]:	3 to 1.5
$W_{RT,out}$ [MeV]:	5 to 3.5
I [mA]:	5/30 to 5



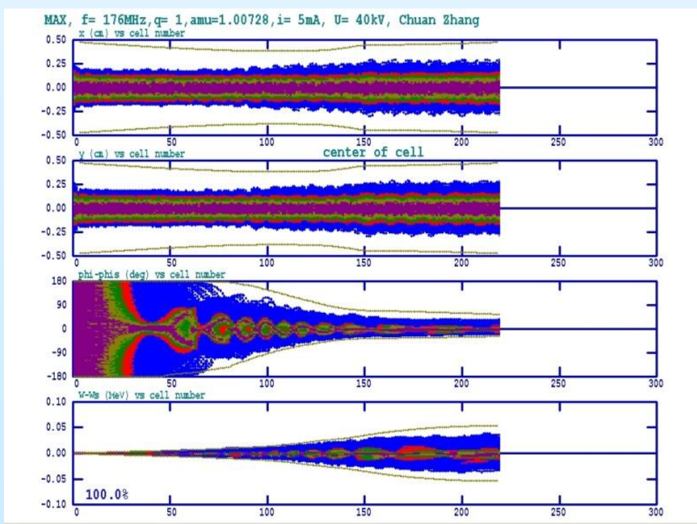
*R*p plot: the data marked in black is from A. Schempp; the data marked in blue was added by T. Sieber; the data marked in green are newly added, where the value for the IFMIF-EVEDA RFQ was kindly provided by Dr. A. Pisent.

EUROTRANS RFQ vs. MAX RFQ

EUROTRANS @5mA



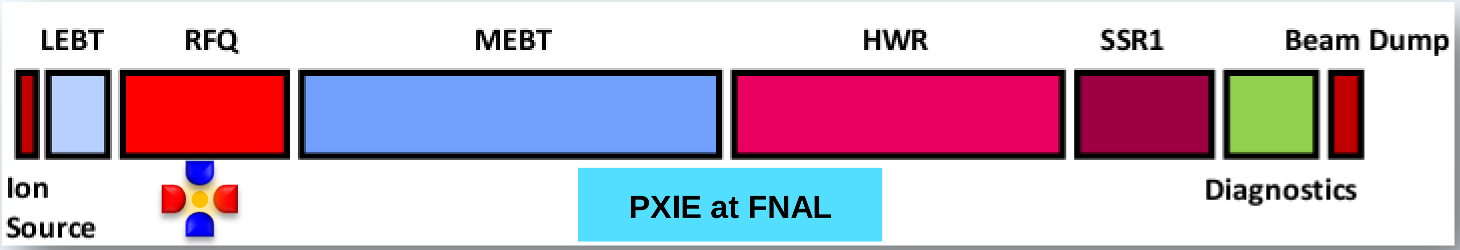
MAX

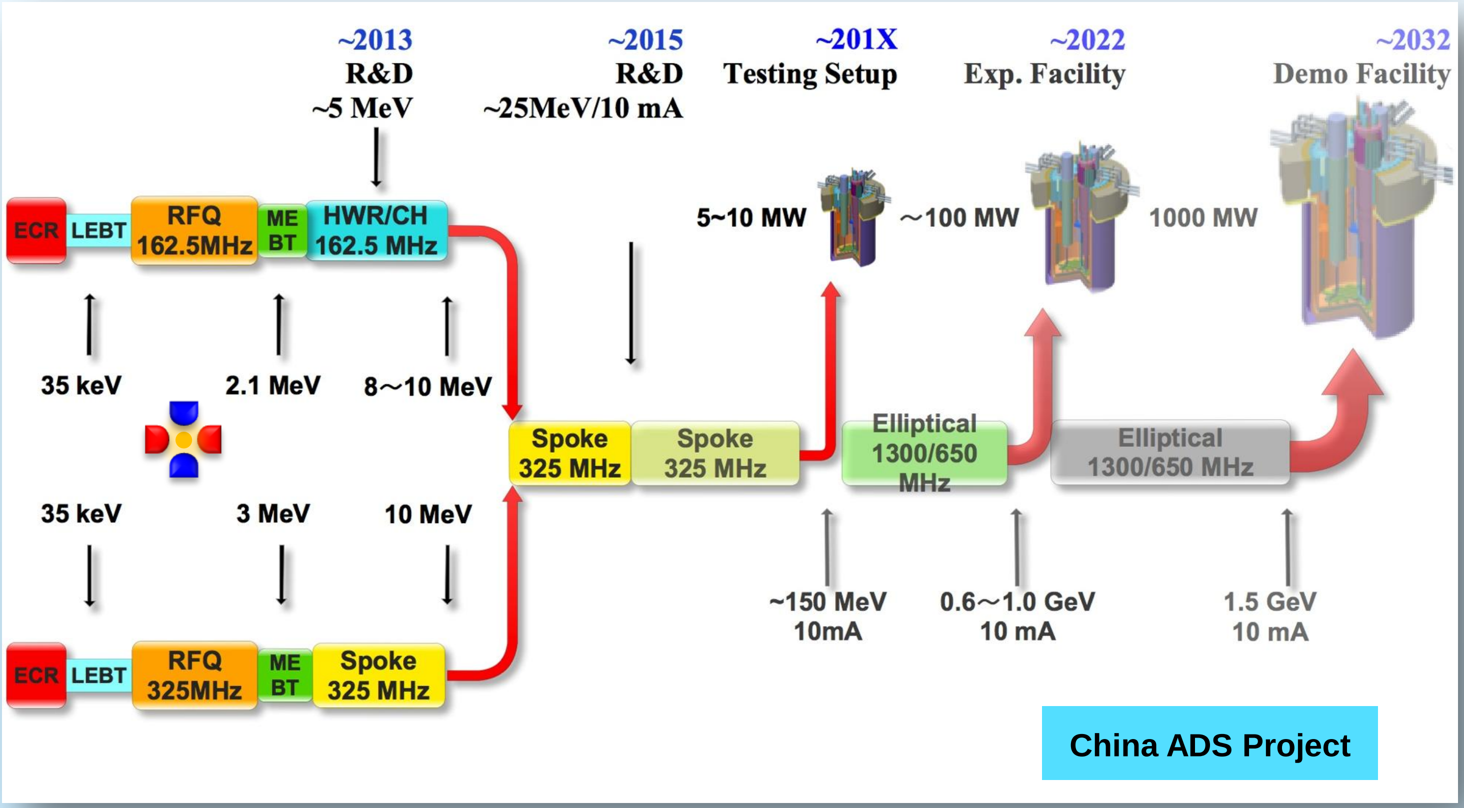


Parameter	EUROTRANS @5mA	MAX
RF Structure	4-Vane	4-Rod
f [MHz]	352	176
W_{in} / W_{out} [MeV]	0.05 / 3	0.03 / 1.5
U [kV]	65	40
E_k	1.7	1
g_{min} [mm]	2.6	3.6
$\varepsilon_{in}^{t., n., rms}$ [π mm-mrad]	0.2	0.2
$\varepsilon_{out}^{t., n., rms}$ [π mm-mrad]	0.21 / 0.20	0.22 / 0.22
$\varepsilon_{out}^{l.,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



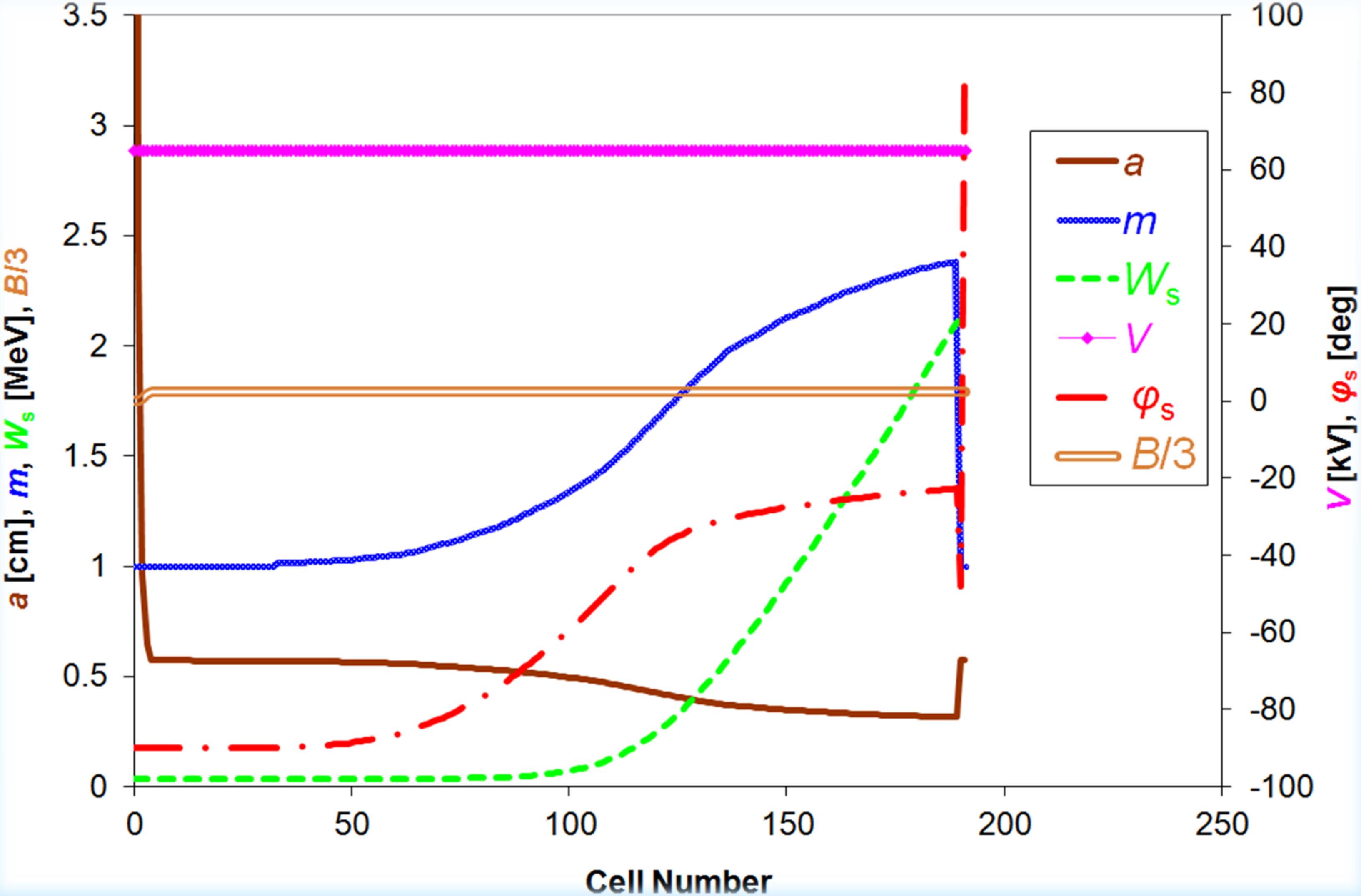


Design Requirements of the PXIE & China ADS RFQs

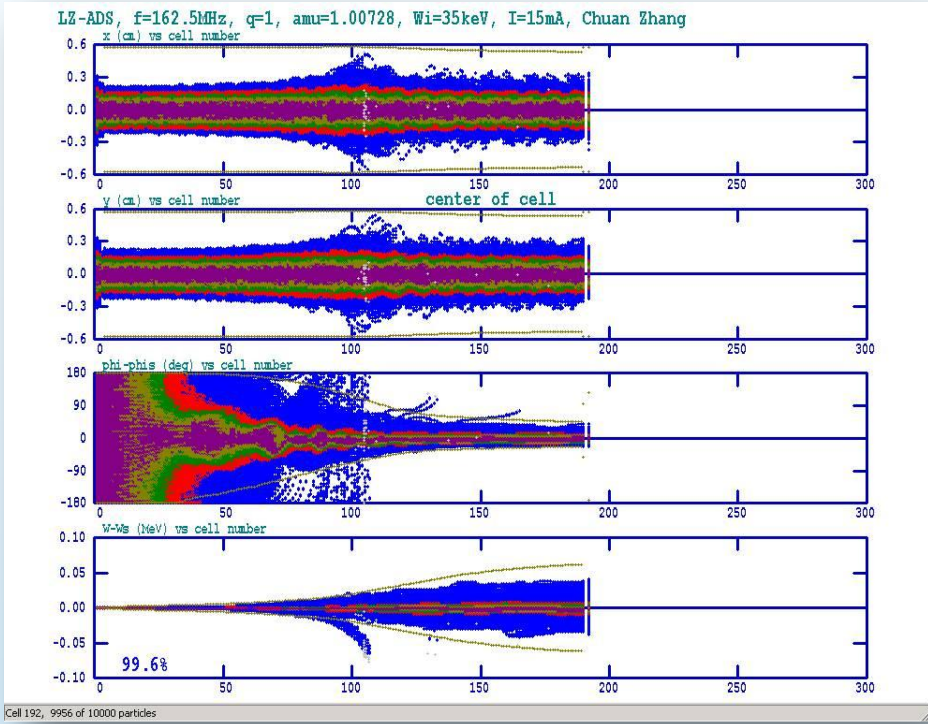
Parameters	PXIE	China ADS
Ion type	H-	H+
Input energy [keV]	30	35
Output energy [MeV]	2.1	2.1
Duty factor [%]	100	100
Frequency [MHz]	162.5	162.5
Beam current [mA]	5 (nominal); 1-10	15 (nominal); 1-20
Input transverse emittance [πmm-mrad]	0.25 (norm. rms)	0.3 (norm. rms)
Transverse emittance growth [%]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

Constant B

Evolutions of Main RFQ Parameters

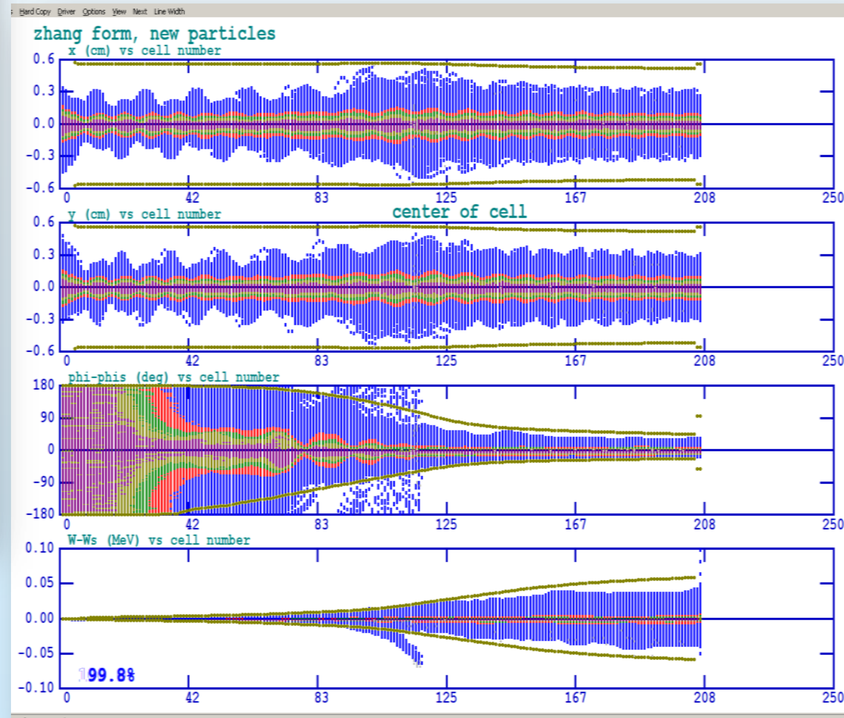


Beam Transport Simulations



China ADS

PXIE



- Vane Length: 444.6 cm and 416.2cm for PXIE and China ADS RFQs, respectively
- Calculated RF Power: 100kW and 110kW for PXIE and China ADS RFQs, respectively

Conclusions

- **The RFQ accelerator is the standard injector.**
- **Characteristics of modern RFQs:**
  - **High beam intensity**
  - **High duty factor even CW**

    CW operation is a different story than the pulsed operation.
- **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

Thank You ☺

Vielen Dank

謝 謝