RFQ BEAM DYNAMICS DESIGN FOR LARGE SCIENCE FACILITIES AND ACCELERATOR-DRIVEN SYSTEMS

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Abstract

Serving as the front-end of large science facilities and Accelerator-Driven Systems (ADS), the Radio-Frequency Quadrupole (RFQ) accelerator usually needs to reach low beam losses, good beam quality, high reliability, and cost savings such design goals at high beam intensities. To address the challenges for modern RFQs, a special beam dynamics design technique characterized by a reasonable and efficient bunching process with balanced space-charge forces has been developed as an alternative to the classic Four-Section Procedure proposed by Los Alamos National Laboratory (LANL). In this paper, the design studies of some recent RFQ projects will be presented as examples.

BACKGROUND

Particle accelerators were originally invented and are still being mainly developed as exploring tools for the subatomic world. Since 2000, a new generation of large science facilities based on accelerators has been built, e.g. J-PARC [1], SNS [2], and LHC [3], or proposed, e.g. FAIR [4], FRIB [5], and Project-X [6].

Meanwhile, many other important applications taking advantage of accelerators have been also developed quickly. For instance, nuclear waste transmutation using the ADS technology is now being intensively investigated by the EU and China by means of the MAX [7] and China-ADS [8] projects, respectively.

Generally speaking, the driver accelerators of the above-mentioned projects are all started with an RFQ accelerator, accelerate protons or ions up to several hundreds of MeV/u even several tens of GeV/u through a full linac or a combination of linear and circular accelerating structures, and finally bombard a certain target with the output beam to generate various useful secondary particles, e.g. neutrons and radioactive ions.

To increase the production of secondary particles, naturally one needs to increase the current of the primary beam to the target as well. When circular machines are involved, usually the peak beam intensity I_{peak} of the driver accelerator has to be high, as the duty cycle (dc) is limited by the rise-time of magnets. In case of a full linac, high dc even Continuous Wave (CW) operation is feasible so that I_{peak} could be modest.

Therefore, typically modern RFQ accelerators are required to work at high peak beam intensities or at high duty cycles or even in both cases. High I_{peak} will lead to strong space-charge effects, which is especially serious for the RFQ working with low-velocity beams. In this case, certainly, high inter-vane voltage U is desired for sufficient focusing strength. However, high dc operation prefers low U for reducing sparking risks and cooling difficulties. It can be seen that a big challenge to the beam dynamics design of a modern RFQ is how to reach low beam losses, good beam quality, high reliability, and cost savings such design goals at high beam intensities using modest U. It's beyond question that unconventional design and optimization methods have to be developed and applied.

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DESIGN PROCEDURES

For the RFQ beam dynamics design, the LANL Four-Section Procedure (FSP) [9] is a classic technique, dividing an RFQ into four sequential sections: Radial-Matcher (RM), Shaper (SH), Gentle Buncher (GB), and Accelerator (ACC).

The heart of this method is the GB section originally proposed by Kapchinsky and Teplyakov (K-T), in which the longitudinal small oscillation frequency ω_l and the geometric length of the separatrix Z_ψ are kept constant in order to maintain a constant beam density for an adiabatic bunching. ω_l and Z_ψ are determined by Eqs. (1) and (2) [10] with φ_s and ψ as the synchronous phase and the phase width of the separatrix, respectively.

$$\omega_l{}^2 = \frac{\pi^2 qAU \sin(-\varphi_s)}{M\beta^2\lambda^2} \tag{1}$$

$$Z_\psi = \frac{\psi\beta\lambda}{2\pi} \tag{2}$$

$$\tan\varphi_s = \frac{\sin\psi - \psi}{1-\cos\psi} \tag{3}$$

A typical example of the LANL-style design is given in Fig. 1. It's a test design for the FRANZ RFQ [11], a 200mA, CW, proton RFQ planned by Frankfurt University. Clearly, for satisfying the K-T conditions, φ_s and the electrode modulation m are changing very slowly in the GB section, especially at the beginning. For avoiding a too long RFQ, the Shaper with a pushed pre-bunching has to be used, which could be an important source of unstable particles. Another distinctive characteristic of the Four-Section Procedure is that the transverse focusing strength B defined by Eq. (4) is kept invariant after the RM section. The idea is to maintain a constant mid-cell aperture r_0 and consequently a quasi-

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position-independent capacitance along the RFQ channel for easy RF tuning.

$$B \equiv \frac{qU\lambda^2}{Mc^2 r_0^2} \tag{4}$$

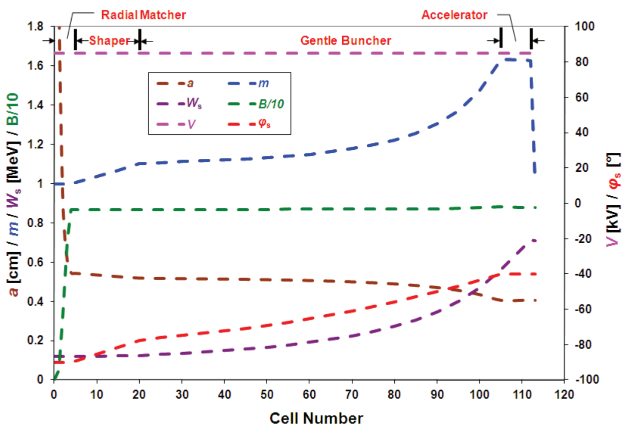

Figure 1: The FSP design for the FRANZ RFQ [11].

The natural beam development process in an RFQ is the following: when the input beam is gradually bunched longitudinally with slight acceleration, the space-charge force is stronger and stronger due to a decreasing bunch size and behaves most significantly at the end of the bunching stage; afterwards, the transverse defocusing force will be naturally weakened when the real acceleration begins. Apparently, B should not be arbitrarily held constant after the RM section, but should be varied according to the changing space-charge situation along the RFQ [12, 13].

Accordingly, the bunching process can be adjusted and improved [12, 13]:

- The main bunching will be more efficient than that in the original GB section, as φ_s and m can rise much more rapidly with the "protection" from an ascending B.
- Therefore, the pushed pre-bunching in the original SH section can be softened by replacing steep "jumping" φ_s and m with gentle increases, respectively. Especially at the beginning, while m is slowly climbing up to produce the longitudinal field gradually, φ_s is kept at -90° for a certain distance to provide the beam a symmetrical bunching with the maximum separatrix.
- After the main bunching, B starts to fall down, φ_s and m can continue increasing at the achieved or slightly lower increment speeds (it depends on the peak intensity of the accelerated beam and the requirements on emittance growths, etc.); this is a stage with a mixture of bunching and accelerating.
- When the beam is well bunched, B, φ_s and m can be held constant – same as in the original ACC section – for a stable acceleration until the required output energy is reached.

This new style of design also divides an RFQ into four sections, but differently. They are:

- Maximum-Separatrix (MS) Section: characterized by φ_s = -90°; besides the functions of the original RM, it performs a symmetrical and soft pre-bunching with a full 360° phase acceptance.
- Main Bunching (MB) Section: it starts from the end of the MS section and stops at where B reaches the maximum.
- Mixed Bunching-Accelerating (MBA) Section: with a decreasing B and keeping increasing φ_s and m.
- Main Accelerating (MA) Section: same to the original ACC section.

Therefore, this design method is named as New Four-Section Procedure (NFSP). For the FRANZ RFQ, a different design made using the NFSP method is shown in Fig. 2, where the MA section is not used, as the total energy increase of the FRANZ RFQ is low.

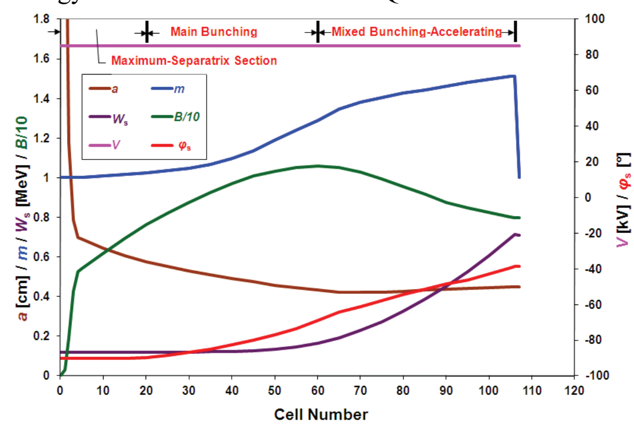

Figure 2: The NFSP design for the FRANZ RFQ [11].

The design and simulation results of the two FRANZ RFQ designs are compared in Table 1. Obviously, the beam losses happened in the conventional design are almost disappeared in the new one. The whole RFQ length is even 10cm shorter. The parameters of another 200mA RFQ, CERN RFQ2 [14], are also listed in the table. This comparable RFQ reaches ~90% of transmission efficiency by almost doubled U, so it cannot be operated at high duty cycles. Therefore, it can be concluded that the NFSP method is an efficient design method for modern RFQs working at high beam intensities and high duty cycles.

Table 1: Design and Simulation Results of 200mA RFQs

Design	f [MHz]	W_{in}/W_{out} [keV]	T [%]	L [m]	U [kV]	dc [%]
FRANZ (FSP)	175	120/700	78.3	2.1	85	100
FRANZ (NFSP)	175	120/700	98.3	2.0	85	100
CERN RFQ2 (FSP) [14]	202.56	90/750	90	1.8	178	< 1

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FAIR PROTON RFQ

As one of the worldwide largest research projects, FAIR will provide antiproton and ion beams with unprecedented intensity and quality. The required 7×10^{10} cooled antiprotons per hour will be produced using the primary protons from a 70 MeV linac.

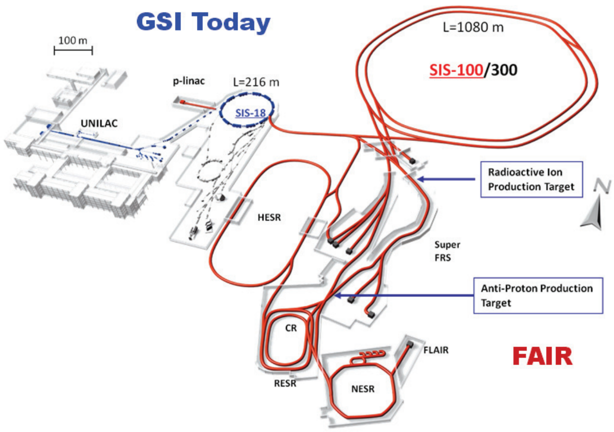

Figure 3: Layout of the planned FAIR facility [4].

In operation, the proton RFQ has been planned to accelerate a 35 mA beam to 3 MeV at 325.44 MHz. For leaving safety margins and enabling future upgrades, three high intensities, 45 mA, 70 mA, and 100 mA, have been used as the design values, respectively. It has been decided to optimize the design at 45 mA that is closest to the operational intensity for the best match, but it should be upgradable from 45 mA to 100 mA.

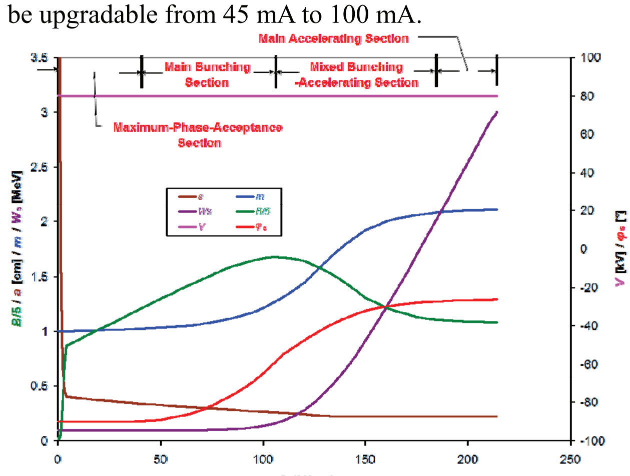

Figure 4: The NFSP design for the FAIR proton RFQ.

The main parameters of the FAIR proton RFQ designed using the NFSP method are shown in Fig. 4 [15]. Table 2 makes a comparison of the design and simulation results between the FAIR proton RFQ and the SNS RFQ [16] which was designed using the classic FSP method. Though the FAIR proton RFQ has lower frequency, higher input and output energies (for RFQs, higher input energy usually results in a longer machine), and lower inter-vane voltage, it achieves better transmission efficiencies over a wide range of intensity from 45 mA to 100 mA with an even 0.5m shorter structure.

Table 2: FAIR Proton RFQ vs. SNS RFQ

Parameters	SNS (FSP)	FAIR (NFSP)		
Ion type	H^-		H^+	
dc [%]	6.2		0.0144	
$I_{operation}$ [mA]	35		35	
I_{peak} [mA]	60	45	70	100
f [MHz]	402.5		325.44	
W_{in} / W_{out} [MeV]	0.065 / 2.5		0.095 / 3	
U [kV]	83		80	
$\varepsilon_{in}^{trans.,n.,rms}$ [π mm mrad]	0.20	0.30	0.30	0.31
$\varepsilon_{out}^{trans.,n.,rms}$ [π mm mrad]	0.21	0.30	0.30	0.31
$\varepsilon_{out}^{longi.,n.,rms}$ [MeV deg]	0.10	0.16	0.15	0.15
L [m]	3.7		3.2	
T [%]	~90	98.7	97.2	95.3

Generated by the design of the ECR ion source and LEBT, the realistic input distributions for the FAIR proton RFQ at 100mA are plotted in Fig. 5. Though many halo particles are already outside of the RFQ design input emittance ellipse, the transmission is still 90.8%.

Clearly the FAIR proton RFQ design realized by the NFSP method is very robust.

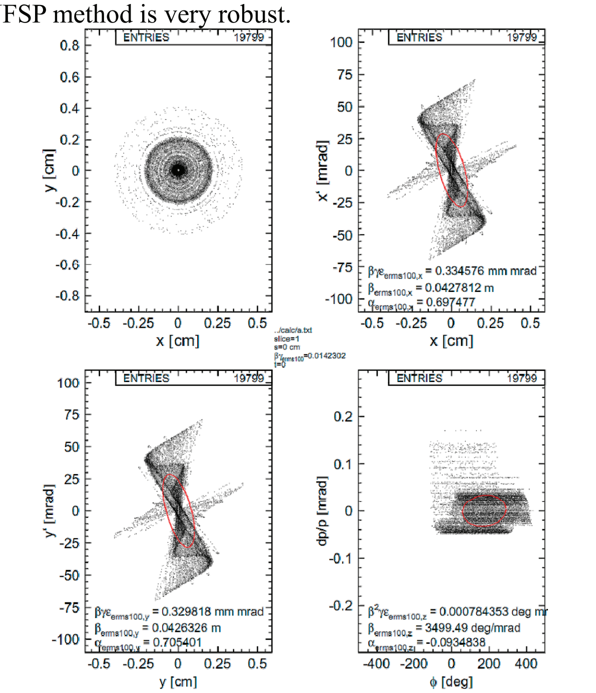

Figure 5: Realistic input distributions for the FAIR proton RFQ (courtesy of L. Groening).

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EUROPEAN ADS RFQ'S

MAX, the ongoing European ADS project, will continue the R&D studies of the EUROTRANS [17] project and deliver an updated consolidated design for the real construction and demonstration in Mol, Belgium. Fig. 6 shows the schematic layouts of the driver linacs for EUROTRANS and MAX.

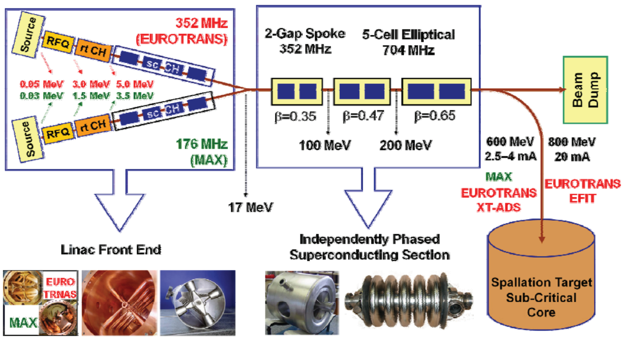

Figure 6: The driver linacs for EUROTRANS and MAX.

Also based on the NFSP method, the EUROTRANS RFQ design [18] is presented in Fig. 7, which shows good performance at both design intensities: 5mA and 30mA.

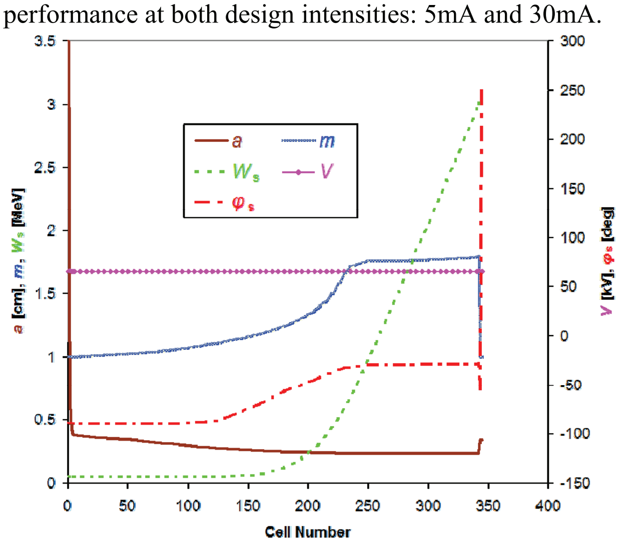

Figure 7: The NFSP Design for the EUROTRANS RFQ.

From EUROTRANS to MAX, the main changes [19] in the RFQ beam dynamics design are: 1) the frequency was lowered from 352 MHz to 176 MHz; 2) the higher design beam intensity, 30 mA, is not necessary any more, so U can be lowered from 65 kV to 40 kV accordingly; 3) the input and output energies of the RFQ were reduced from 0.05 MeV and 3 MeV to 0.03 MeV and 1.5 MeV, respectively, for keeping the RFQ length still at ~4 m.

Figure 8 shows that the R_p value of an RFQ is roughly proportional to $f^{-1.5}$, so that the RF power consumption per unit length could be considably reduced by halving the frequency (see Fig. 9). Some advantages are: 1) cooling will be easier and CW operation will be more reliable; 2) it is feasible to replace the originally adopted 4-vane structure with the simple 4-rod one; 3) the minimum gap between the electrodes will be enlarged and the sparking risk can be reduced.

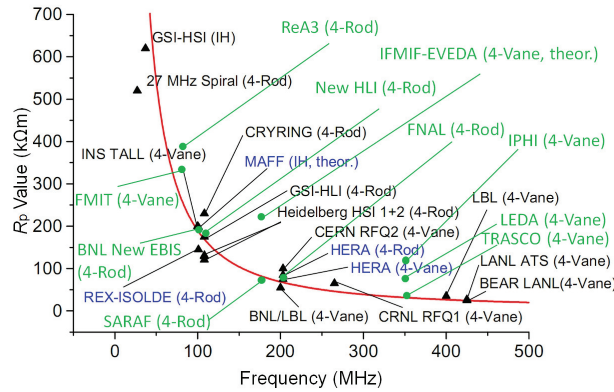

Figure 8: A survey of R_p values for RFQs [20].

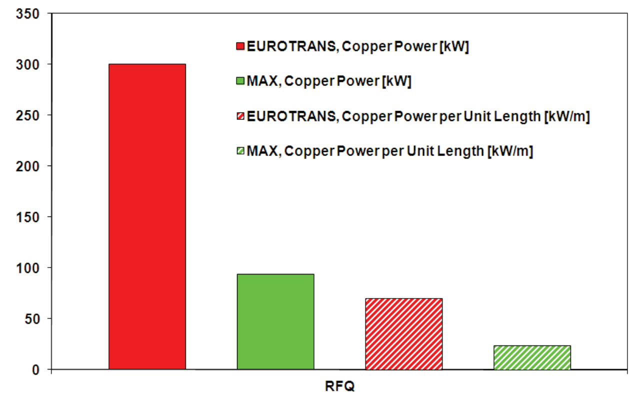

Figure 9: Copper power of EUROTRANS & MAX RFQs.

Table 3 summarizes the design and simulation results of the two RFQs at 5 mA. Clearly, the MAX RFQ design is safer and more reliable for CW operation, while the beam performance is kept still satisfying.

Table 3: MAX RFQ vs. EUROTRANS RFQ

Parameters	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] / E_k	65 / 1.7	40 / 1.0
g_{min} [mm]	2.6	3.6
$\varepsilon_{in}^{trans.,n.,rms}$ [π mm mrad]	0.20	0.20
$\varepsilon_{out}^{trans.,n.,rms}$ [π mm mrad]	0.21 / 0.20	0.22 / 0.22
$\varepsilon_{out}^{longi.,n.,rms}$ [keV deg]	109	64.6
L [m]	4.3	4.0
T [%]	~100	~100

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CHINA ADS RFQ & PXIE RFQ

Given in Table 4, the requirements for the China ADS RFQ and the FNAL PXIE RFQ are very similar. As the superconducting part will be started directly behind the RFQ, very small output longitudinal emittance is allowed. In addition, it has been fixed to use the 4-vane structure with a constant *B*.

Table 4: Requirements of China ADS RFQ & PXIE RFQ

Parameters	PXIE	China-ADS
Ion type	H^-	H^+
f [MHz]	162.5	162.5
W_{in} / W_{out} [MeV]	0.030 / 2.1	0.035 / 2.1
dc [%]	100	100
I_{peak} [mA]	5 (1-10)	15 (1-20)
$\varepsilon_{in}^{trans.,n.,rms}$ [π mm mrad]	0.25	0.30
$\Delta\varepsilon^{trans.}$ [%]	≤10	≤10
$\varepsilon_{out}^{longi.,n.,rms}$ [keV ns]	≤0.8	≤1.0
T [%]	95	95
Twiss α [%]	≤1.5	≤1.5

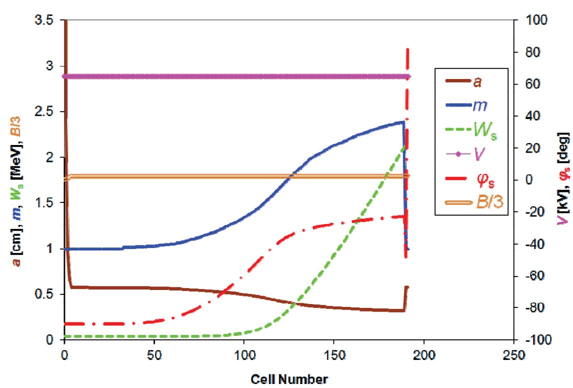

Figure 10: Modified NFSP design for the PXIE RFQ.

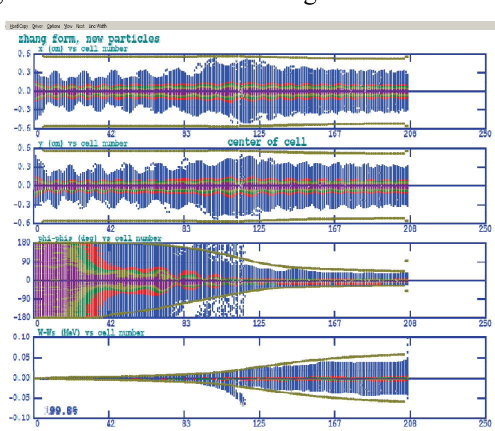

Figure 11: Beam transport plot of the PXIE RFQ.

Therefore, a modified NFSP design shown in Fig. 10 has been made for the PXIE RFQ (the China-ADS RFQ design is almost the identical), where φ_s and m evolve in the NFSP way, but B is constant. Fig. 11 shows the beam transport simulation with realistic input distributions. A small blowup in the middle of the RFQ can be observed, as a result of the application of a constant B, but it's not so bad at low intensities. The design and simulation results satisfy all requirements very well for both RFQs.

CONCLUSIONS

An efficient and general design method so-called New Four-Section Procedure was developed for modern RFQs. It has been used for designing ≥20 RFQs with A/q from 1 to 59.5, f from 36.136 to 352 MHz, I_{peak} up to 200 mA, and dc up to 100%. Two of them, the new EBIS RFQ and the new HLI RFQ, were built for BNL and GSI, respectively, and the BNL one has been successfully tested with intense heavy ion beams. More NFSP RFQs will be built in the near future.

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